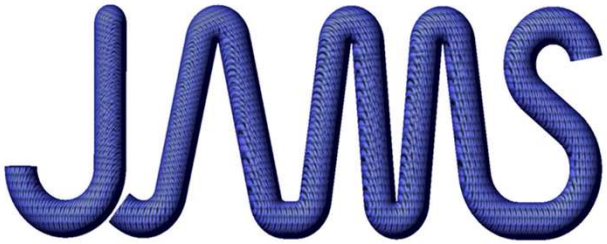
Development and Evaluation of Fracture Mechanics Test Methods for Sandwich Composites

Federal Aviation Administration



Joint Centers of Excellence for Advanced Materials

Presented by:

Dan Adams

University of Utah

JAMS Technical Review

September 22, 2021

Introduction

•Project Title: "Development and Evaluation of Fracture Mechanics Test Methods for Sandwich Composites: Test Method Standardization"

- Project Participants:
  - Principal Investigator: Dr. Dan Adams
  - Graduate Student Researchers: Martin Raming, Brad Kuramoto, Marcus Stanfield
- FAA Technical Monitor: Dave Stanley
- Other FAA Personnel: Larry Ilcewicz, Ahmet Oztekin
- Industry Partnerships/Other Collaborations: Christian Berggreen (DTU), NASA Langley (James Ratcliffe & Ronald Kruegger), Boeing (Charles Park), ASTM Committee D30 (Composites)
- Source of matching contribution for the current award: University of Utah

Background:
Primary Research Emphases

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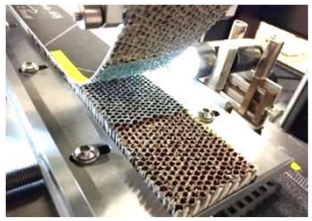
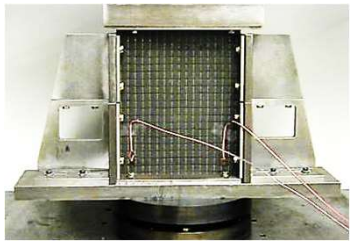
Sandwich Fracture Mechanics

- Development of standardized test methods for facesheet/core disbond growth
- Building block approach for assessment of disbond growth in sandwich structures



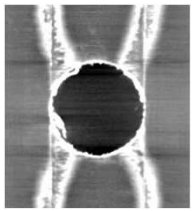
Sandwich Damage Tolerance

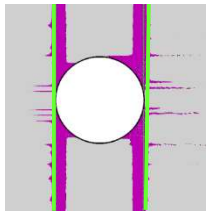
- Assessment of predictive capabilities for damage formation and growth
- Development of standardized test methods for damage tolerance



Sandwich Notch Sensitivity

- Assessment of predictive capabilities for sandwich composite notch sensitivity
- Development of standardized test methods for notch sensitivity





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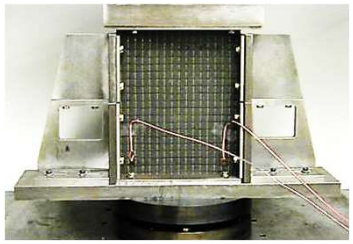

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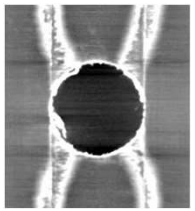
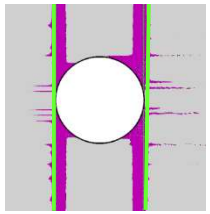
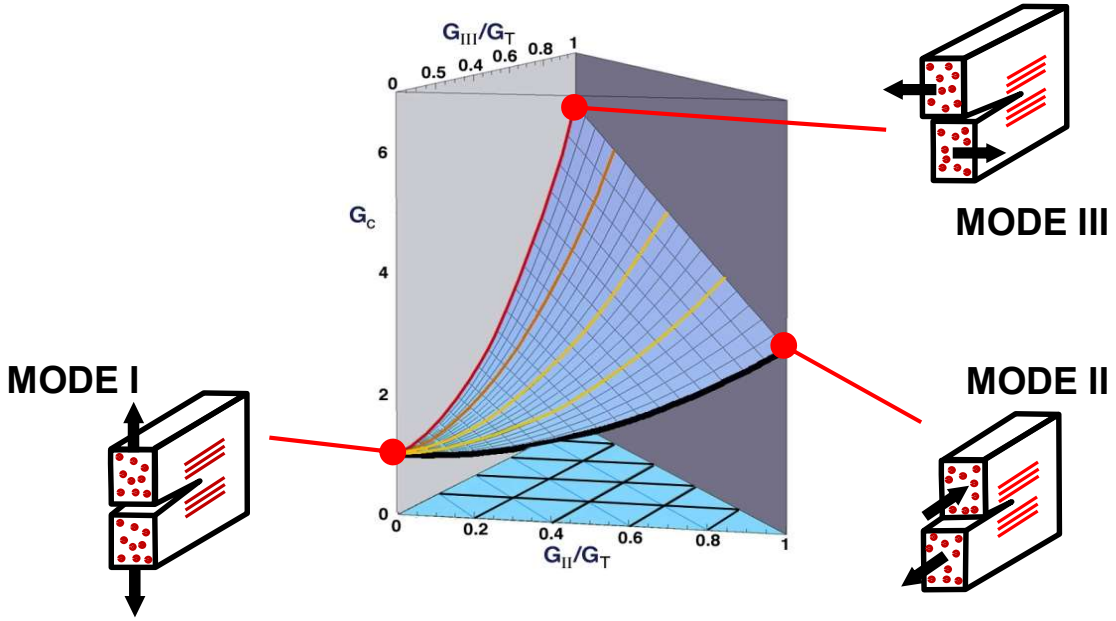


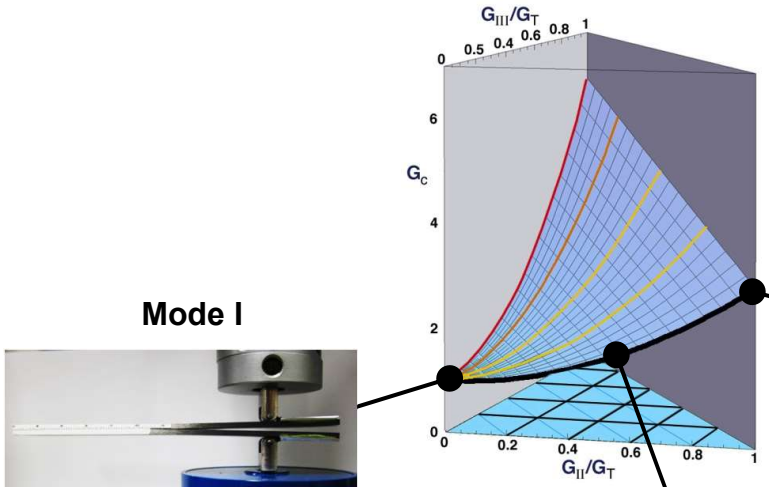


Characterization of Fracture Toughness:
Modes of Fracture



Characterization of Fracture Toughness:

Laminate Fracture Mechanics Tests



Double Cantilever Beam (DCB) test

ASTM D5528

Mixed-Mode Bend (MMB) test

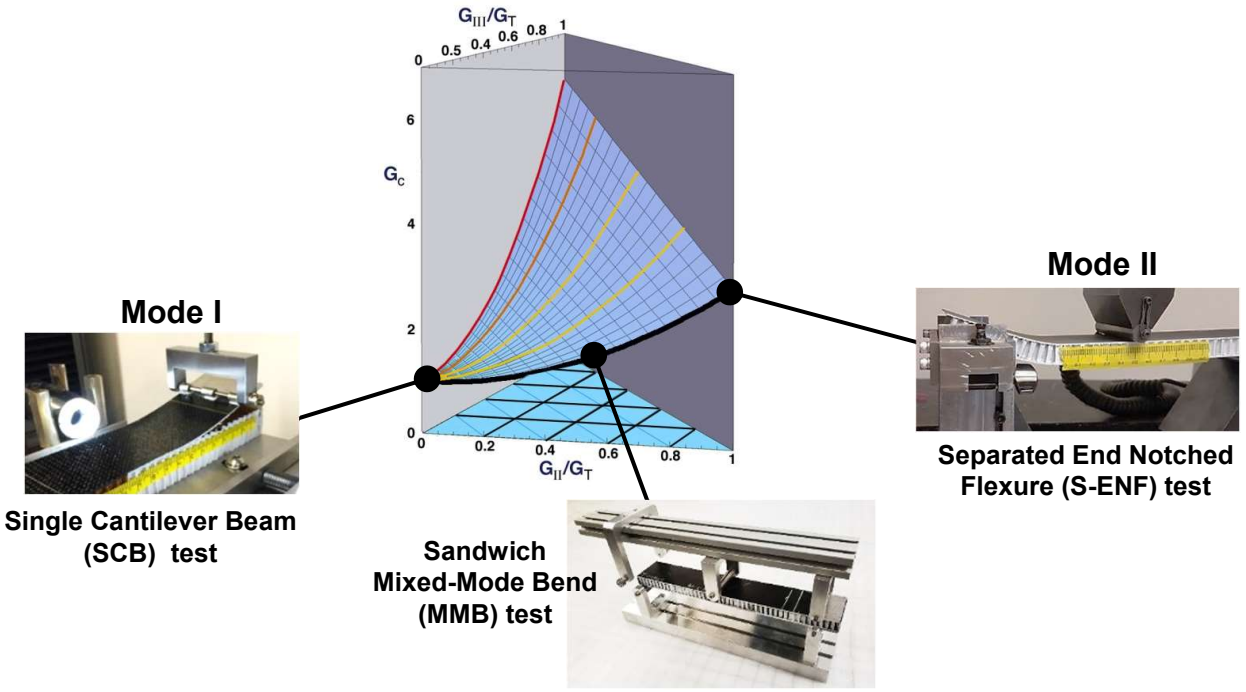
ASTM D6671

End Notched Flexure (ENF) test

ASTM D7905

Previously developed and standardized tests…

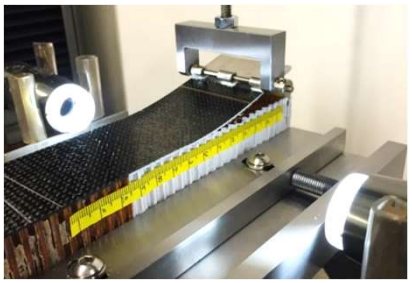
Characterization of Fracture Toughness:
Sandwich Fracture Mechanics Tests in Development

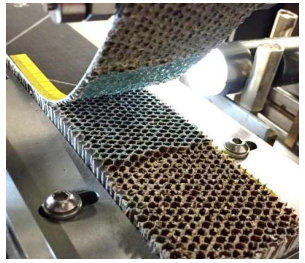


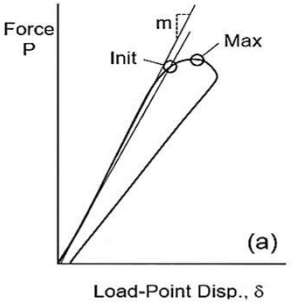
All in development as part of this project

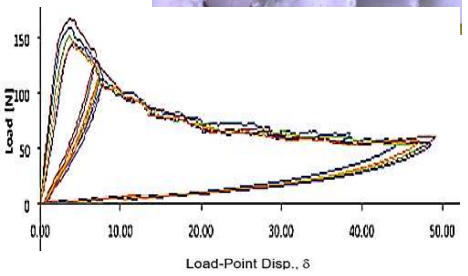
Development and Standardization of Mode I Dominant Single Cantilever Beam (SCB) Test

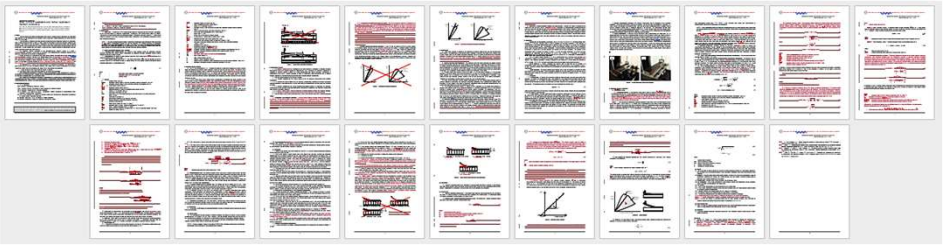
- **Determination of both initiation and propagation fracture toughness**
- **Acceptable "disbond" location: within top one-fourth of core**
- **Remaining issues being resolved:**
  - **Reduction of time required to perform test**
  - **Terminology: "sandwich disbond" vs. "facesheet/core separation"**
  - **Procedure for measurement of final crack length**
  - **Use of Mc/I for bending stress estimates in specimen sizing analysis**





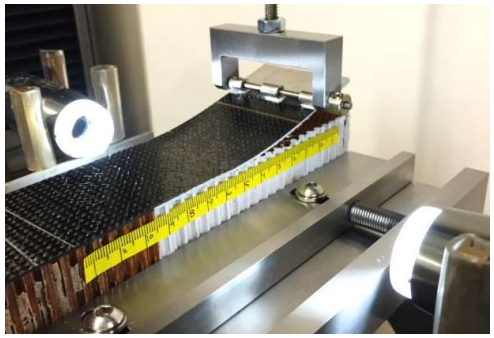






Single Cantilever Beam (SCB) Fatigue Test Development

- Follow-on *Standard Practice* to existing SCB test
- Several previous individual efforts within CMH-17 Sandwich Disbond Task Group
- Draft test procedure identified for incorporation into standard
- Several labs interested in round-robin testing activities
- Coordination through the CMH-17 Sandwich Disbond Working Group



Characterization of Fracture Toughness:
Sandwich Fracture Mechanics Tests in Development

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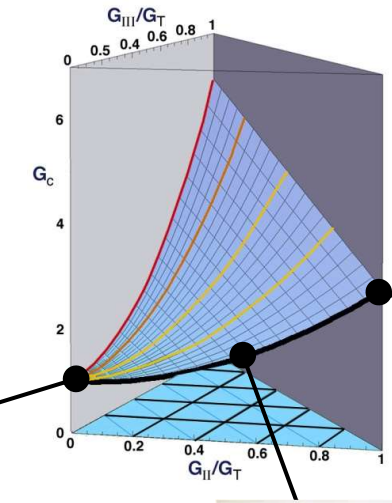
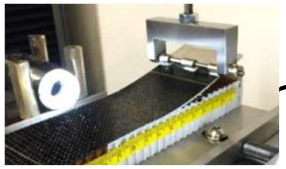
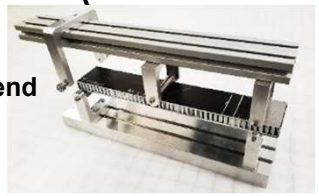


Mode I



Single Cantilever Beam (SCB) test

Sandwich Mixed-Mode Bend (MMB) test

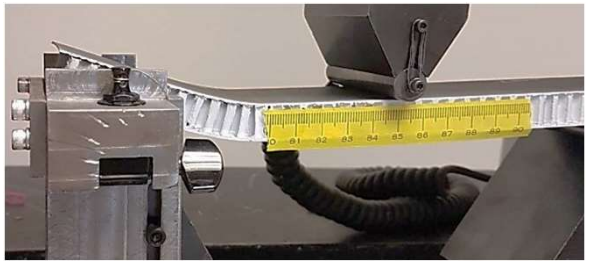


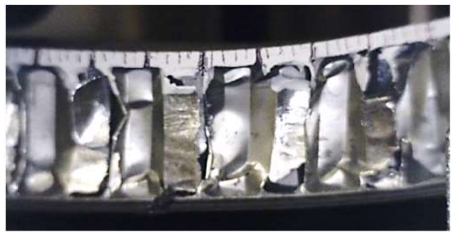
Mode II

Separated End Notched Flexure (S-ENF) test

Development of the Mode II Separated End-Notched Flexure (S-ENF) Test

- Modified three-point flexure test
- Use of tensioned wire to achieve facesheet/core separation and prevent frictional “lock-up”
- No core removal required
- Adjustable wire height and span
- High % Mode II (>80%) predicted for all sandwich configurations investigated
- Cell buckling at crack tip with no crack growth for some honeycomb core configurations
- Collaboration with Florida Atlantic University (Leif Carlsson)





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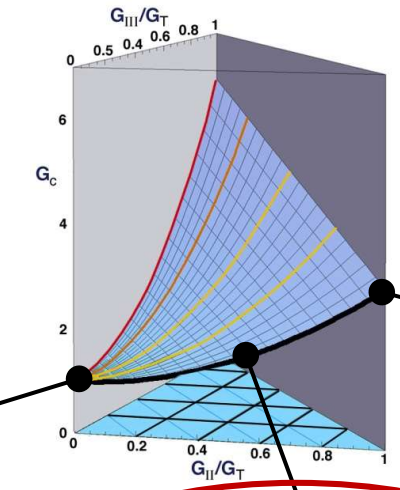
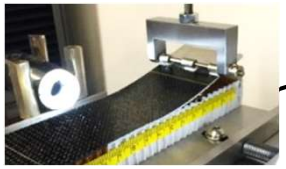


Mode I



Single Cantilever Beam (SCB) test

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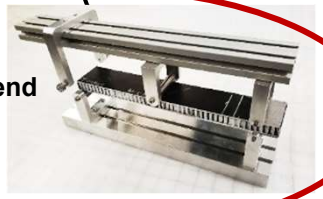


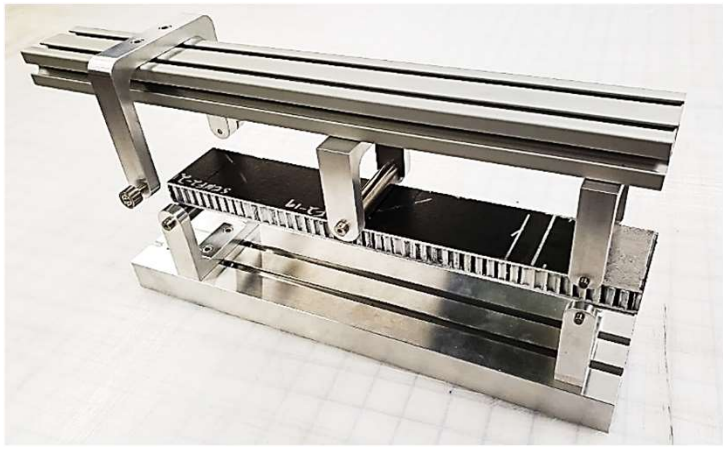
Mode II

Separated End Notched Flexure (S-ENF) test

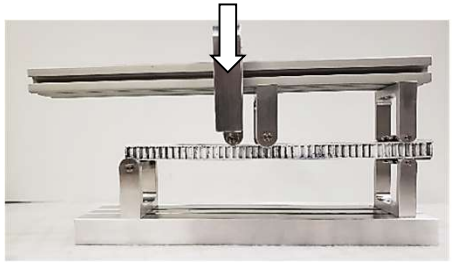
Sandwich Mixed Mode Bend Test Development:

Prototype Univ. of Utah Test Fixture

- Accommodates 2 in. x 12 in. specimens used in SCB testing
- Specimen connections at disbond using bonded hinge halves
- Adjustable position of loading yoke to produce desired mixed-mode loading condition
- Adjustable loading span lengths

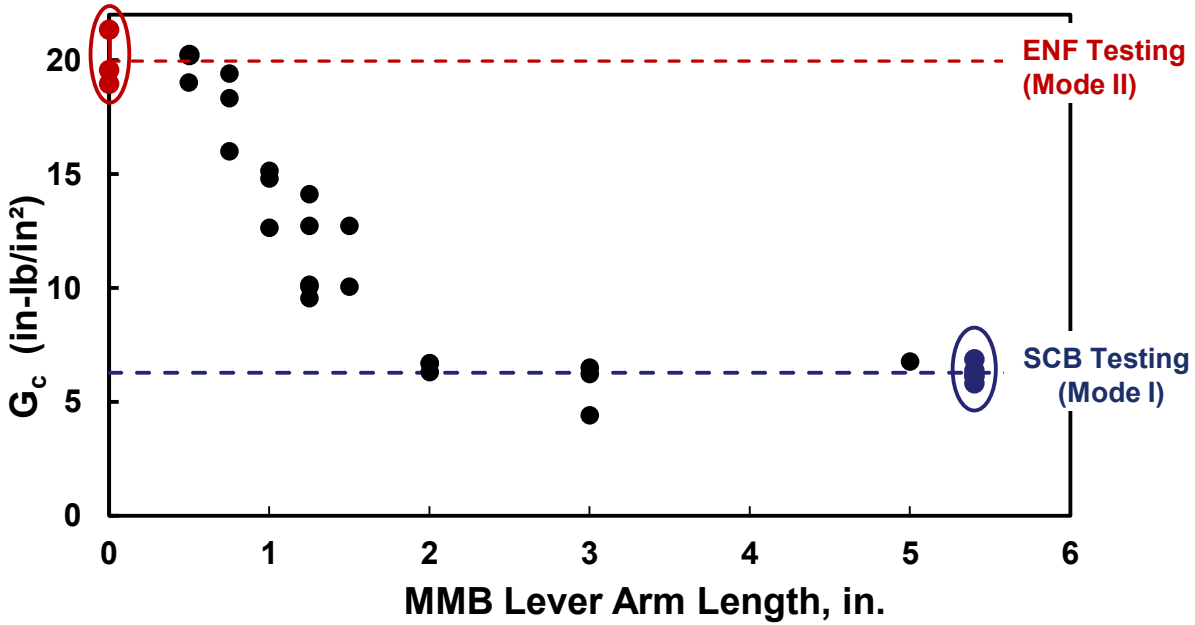


High % Mode I



High % Mode II

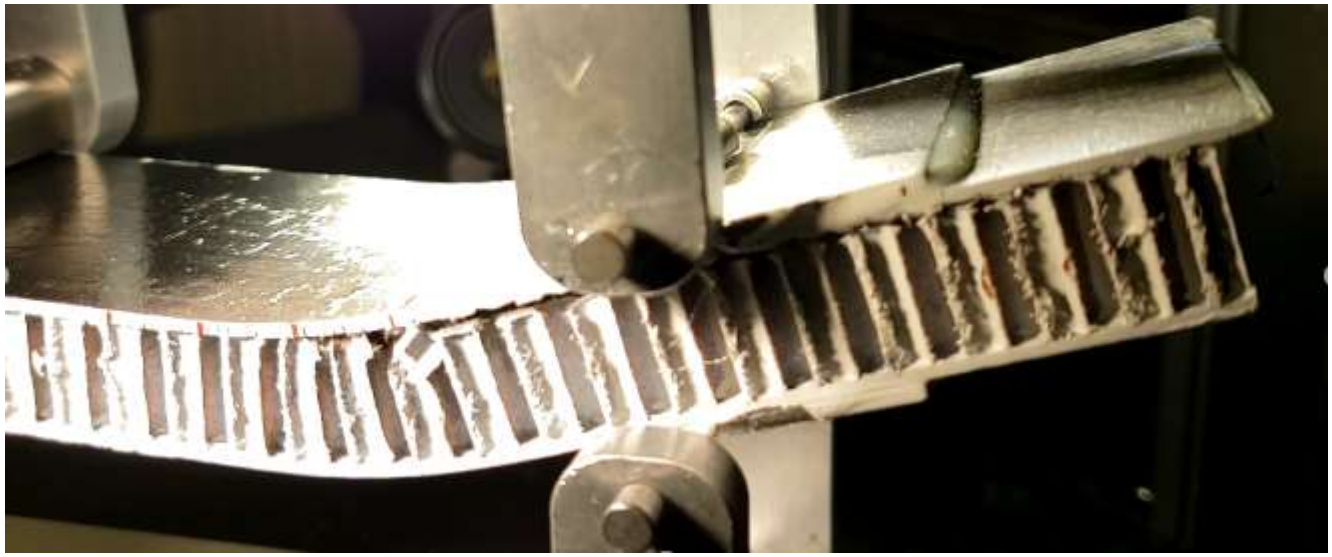
Recent Test Results:
Sandwich Mixed-Mode Bend Test

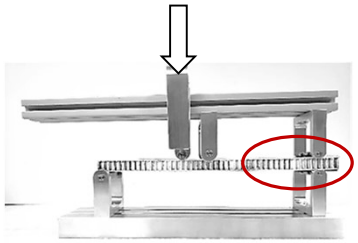


- Carbon/epoxy facesheets, Nomex honeycomb core (8 lb/ft^3, 0.5 in. thick)
- 8 different lever arm lengths (8 different mode mixities)
- Mode I and Mode II tests performed using SCB and ENF test methods for comparison
- 8 in. span length used for both MMB and ENF testing

Sandwich MMB Testing of Nomex Honeycomb Core Sandwich Specimen

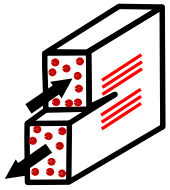
(High percentage Mode II)





High % Mode II Loading

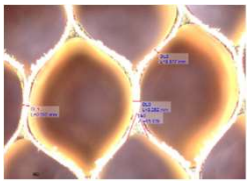
MODE II

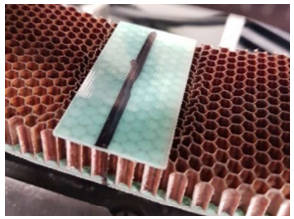


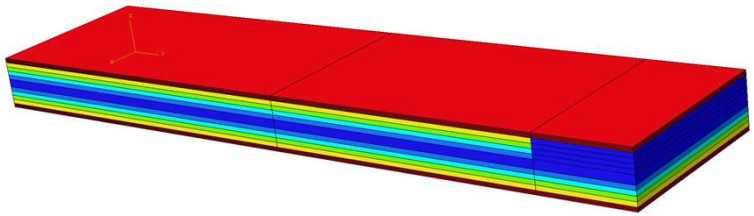
Current Focus:

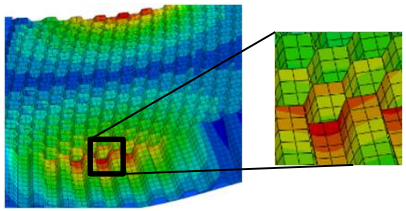
Numerical Investigation of Mode Mixity

- Determine effective core modulus increase due to constraint effects in honeycomb core due to adjacent facesheets
- Develop effective homogenized core model
- Determine stress levels at which core failure/buckling occurs
- Predict mode-mixity using VCCT
  - Single Cantilever Beam test
  - Mixed Mode Bend test
  - End Notched Flexure test





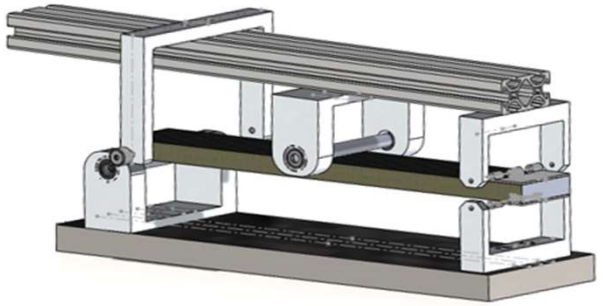




Current Status:

Sandwich MMB Test Development

- Completed exploratory round of sandwich MMB testing
- Initiate MMB "Round Robin" Testing Activity
  - Explore capabilities for high percent Mode II testing
    - Focus on Nomex honeycomb core materials
  - Explore limits of applicability of MMB test configuration
    - Use of other core materials



- Development of closed-form expression for MMB mode mixity

  (Roberta Massabo (U. of Genova), Christian Berggreen (DTU)
- Further development of draft ASTM standard

Background:
Primary Research Emphases

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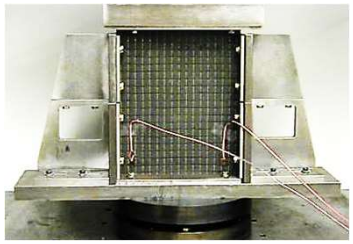
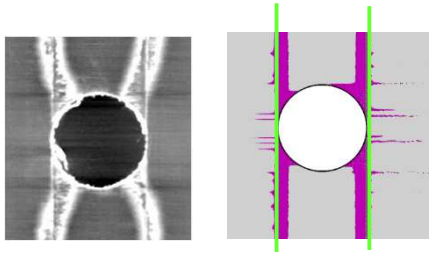
Sandwich Damage Tolerance

- **Assessment of predictive capabilities for damage formation and growth**
- **Development of standardized test methods for damage tolerance**



Sandwich Notch Sensitivity

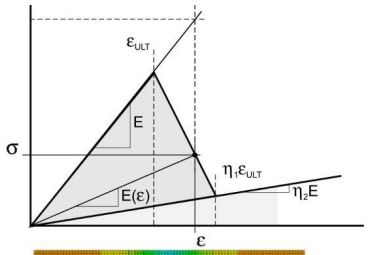
- **Assessment of predictive capabilities for sandwich composite notch sensitivity**
- **Development of standardized test methods for notch sensitivity**

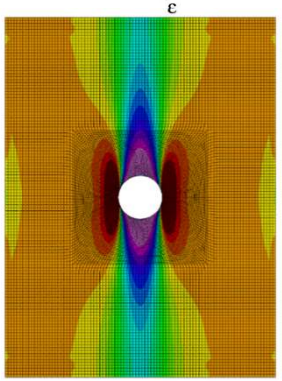


Progressive Damage Analysis of Sandwich Composites

ABAQUS with NDBILIN

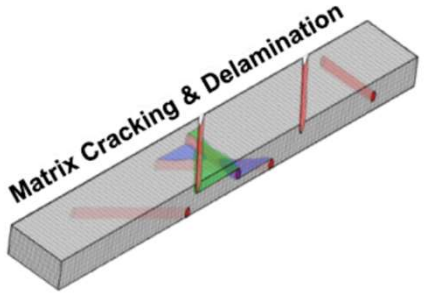
- **User-defined nonlinear material model (UMAT) for ABAQUS**
- **Developed by Materials Sciences Corp.**
- **Stiffness degradation based progressive damage model**
  - **Bilinear stiffness response used to model material damaged state**
  - **"Built in" laminated plate theory for elements**
  - **Lamina level stiffness degradation**
  - **Max. stress, max. strain or Hashin failure criteria for damage onset**





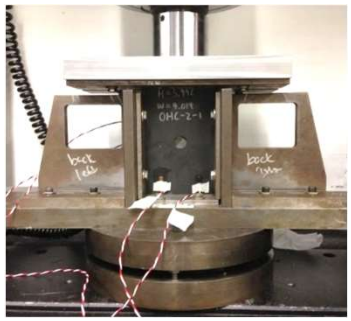
Progressive Damage Analysis of Sandwich Composites
B-Spline Method (BSAM):

- **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 continuum damage model**



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 & compression
  - Compression after impact
- **Damage progression in core**
  - Out-of-plane compression
  - Interlaminar shear
  - Open-face flexure
- **Damage progression in sandwich composites**
  - Sandwich interface disbond (Mode I and II)
  - Sandwich open-hole compression & flexure
  - Sandwich compression-after-impact
  - Sandwich flexure-after-impact



Test Method Development:
Damage Tolerance of Sandwich Composites

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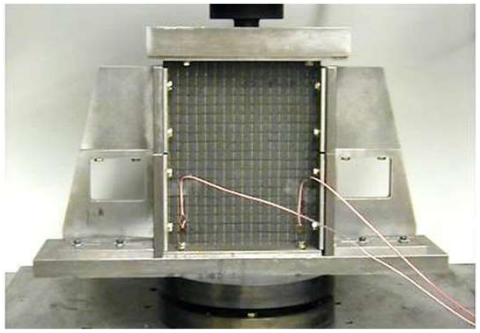
In the final stages of ASTM standardization

Sandwich Compression After Impact



- **Preferred damage tolerance test method for laminates**
- **High interest level for sandwich composites**

Sandwich Flexure After Impact

- **Constant bending moment and zero shear in damaged section**
- **Damaged facesheet can be loaded in compression or tension**

Test Method Development:
Notch Sensitivity of Sandwich Composites

In the final stages of ASTM standardization

Sandwich Open-Hole Compression

- Preferred notched test method for laminates
- High interest level for sandwich composites

Sandwich Open-Hole Flexure

- Four-point flexure
- Constant bending moment and zero shear in notched region

Technical Publications

- *Eight ASTM Standards pertaining to Sandwich Composites*

Sandwich Fracture Mechanics Tests

- Mode I Dominant Single Cantilever Beam Test
- Mixed Mode Bend Test
- Mode II Dominant Separated End Notch Flexure Test
- Single Cantilever Beam Fatigue Test

Sandwich Damage Tolerance Tests

- Compression After Impact Test
- Flexure After Impact Test

Sandwich Notch Sensitivity Tests

- Open-Hole Compression Test
- Open-Hole Flexure Test

Technical Publications (Continued)

- **Journal Publications in progress for several tests**
  - Mode I Dominant Single Cantilever Beam Test
  - Compression After Impact Test
  - Flexure After Impact Test
  - Open-Hole Compression Test
  - Open-Hole Flexure Test

- **FAA Reports in progress (preliminary titles)**

  Development and Evaluation of Sandwich Fracture Mechanics Test Methods

  Development and Evaluation of Sandwich Damage Tolerance Test and Analysis Methods

  Development and Evaluation of Sandwich Notch Sensitivity Test and Analysis Methods

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Thank You For Your Attention!

Questions?