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Fracture Mechanics and Notch Sensitivity of Sandwich Composites

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2017 Technical Review

THE UNIVERSITY OF UTAH

FAA Sponsored Project Information

- Principal Investigators:
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- Graduate Student Researchers:
  - **Marcus Stanfield**
  - **Brad Kuramoto**
- FAA Technical Monitor:
  - **Zhi Chen**
- Primary Collaborators:
  - **Materials Sciences Corporation**
  - **ASTM Committee D30**
  - **CMH-17 Sandwich Disbond Working Group**

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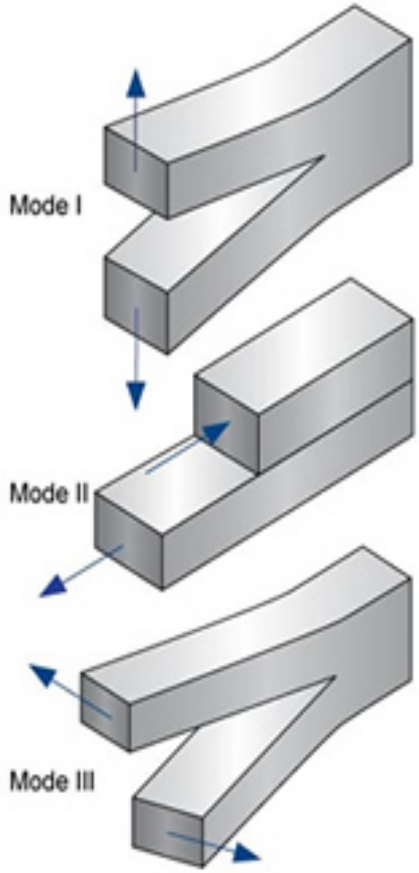
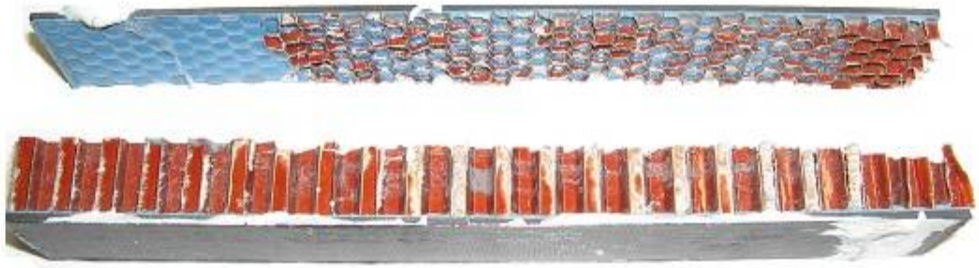
Outline

- **Research updates:**
  - **Sandwich fracture mechanics**
  - **Sandwich damage tolerance**
- **Notch sensitivity of sandwich composites**
  - **Sandwich notch sensitivity testing**
  - **Numerical modeling – progressive damage analysis**

Fracture Mechanics Test Method Development for Sandwich Composites

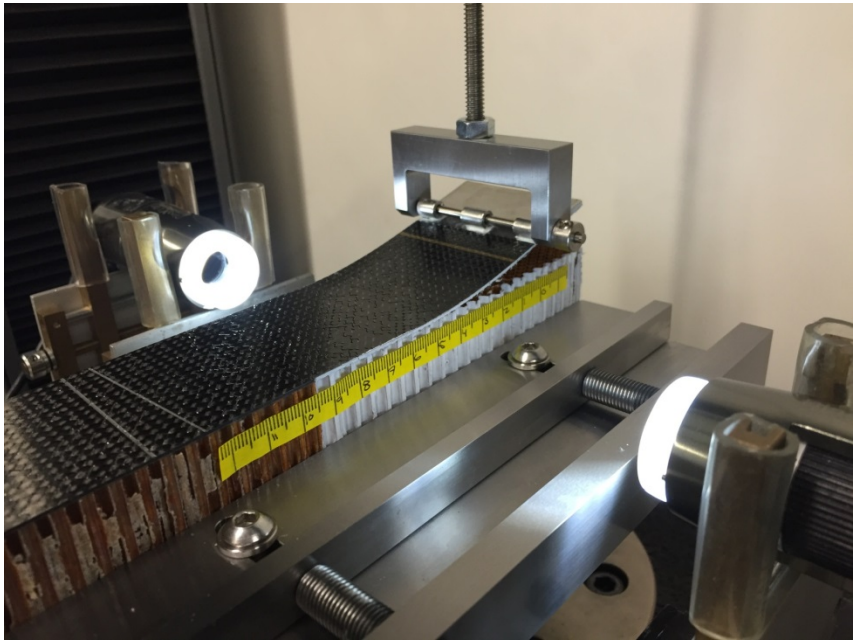
- **Focus on facesheet-core disbonding**
- **Mode I and Mode II loading**
  - **Identification and initial assessment of candidate test methodologies**
  - **Selection and optimization of best suited Mode I and Mode II test methods**
  - **Development of draft ASTM standards**

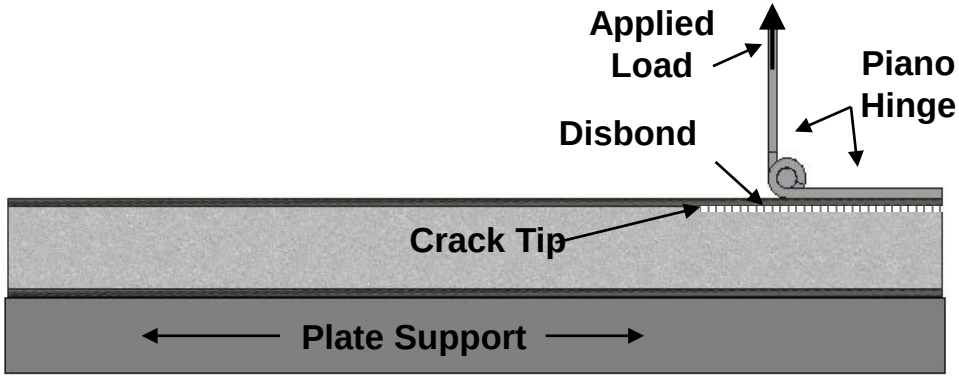




Mode I Test Method:
Single Cantilever Beam (SCB) Test

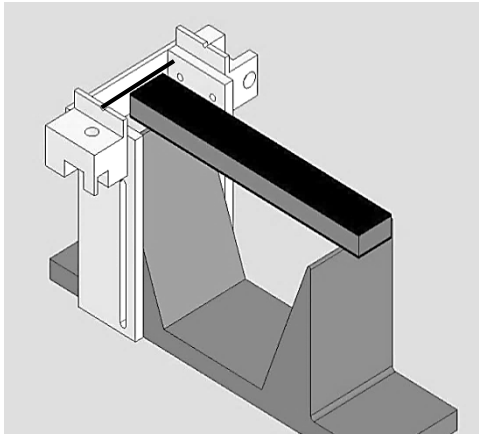
- Sandwich specimen pre-cracked at one end
- Specimen secured to fixture base plate
- Upward loading of upper facesheet using bonded hinge
- Measurement of applied load, crosshead displacement, crack length
- Calculation of fracture toughness, G_c





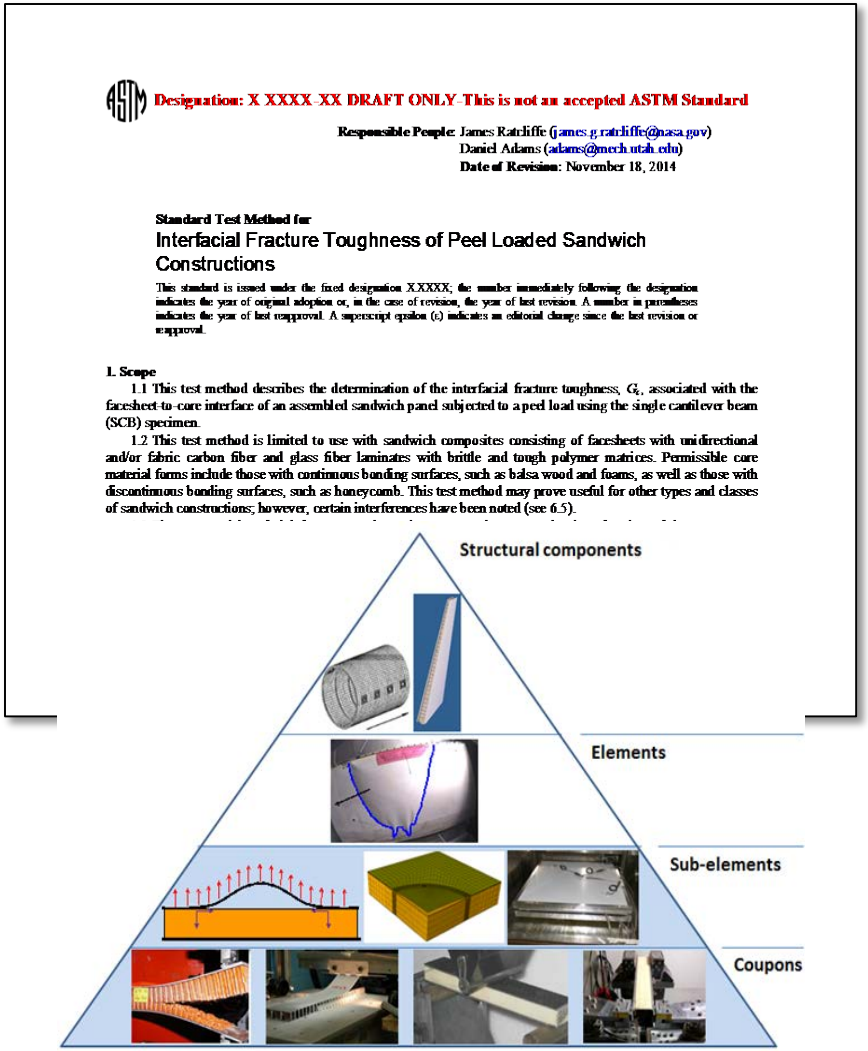
Candidate Mode II Test Method: Separated End Notched Flexure (S-ENF) Test

- Modified three-point flexure test configuration
- High % Mode II (>80%) for all sandwich configurations studied
- Use of tensioned wire to achieve facesheet/core separation
- No core removal required
- Adjustable wire height and span



Recent Developments:
Sandwich Fracture Mechanics

- **Completed seven laboratory international SCB round robin activity**
- **Finalized Mode I SCB draft standard to submit to ASTM Subcommittee D30.09**
- **Progressing with sandwich disbond building block activity (Testing & Analysis)**



Designation: X XXXX–XX DRAFT ONLY–This is not an accepted ASTM Standard

Responsible People: James Ratcliffe (james.g.ratcliffe@nasa.gov)
Daniel Adams (adams@mech.utah.edu)
Date of Revision: November 18, 2014

Standard Test Method for
Interfacial Fracture Toughness of Peel Loaded Sandwich Constructions

This standard is issued under the fixed designation X XXXX; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

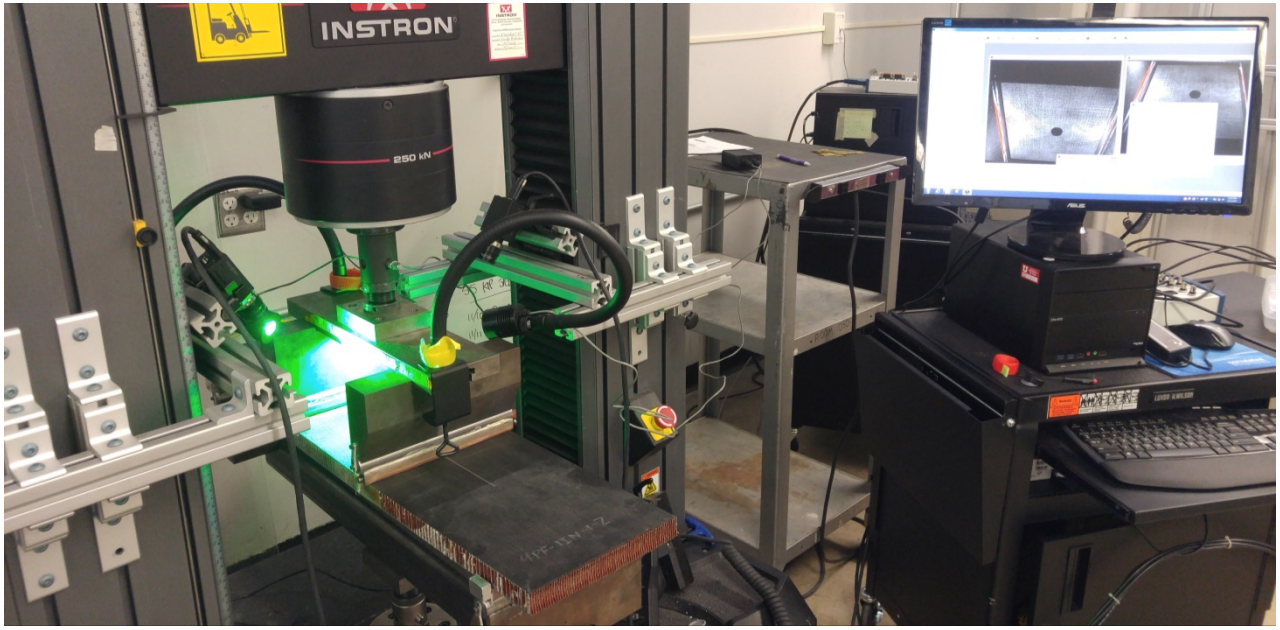
1. Scope

1.1 This test method describes the determination of the interfacial fracture toughness, G_c, associated with the facesheet-to-core interface of an assembled sandwich panel subjected to a peel load using the single cantilever beam (SCB) specimen.

1.2 This test method is limited to use with sandwich composites consisting of facesheets with unidirectional and/or fabric carbon fiber and glass fiber laminates with brittle and tough polymer matrices. Permissible core material forms include those with continuous bonding surfaces, such as balsa wood and foams, as well as those with discontinuous bonding surfaces, such as honeycomb. This test method may prove useful for other types and classes of sandwich constructions; however, certain interferences have been noted (see 6.5).

Status Update: Sandwich Damage Tolerance Test Methods

- **Draft standard of sandwich composite Compression After Impact (SCAI) completed**
- **Draft standard of 4-Pt. Flexure After Impact (4-FAI) in progress**



Outline

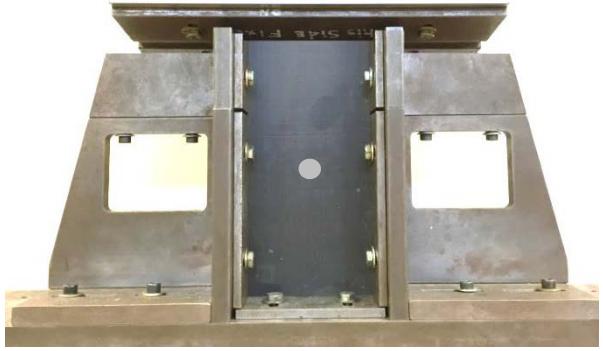
- **Research updates:**
  - **Sandwich fracture mechanics**
  - **Sandwich damage tolerance**

➡ **Notch sensitivity of sandwich composites**

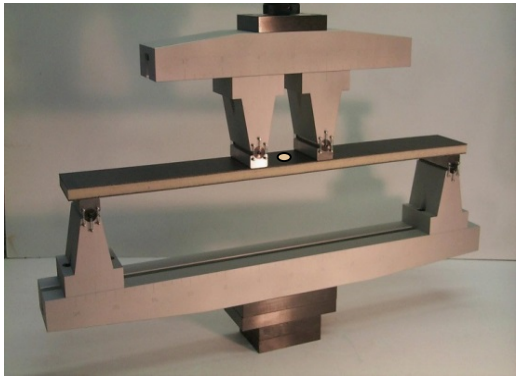
  - **Sandwich notch sensitivity testing**
  - **Numerical modeling – progressive damage analysis**

Research Objectives:
Notch Sensitivity of Sandwich Composites

- **Initial development of notched test methods & assessing analysis methodologies for composite sandwich panels**
- **Explore development of new ASTM standards for notch sensitivity of sandwich composites**
- **Documentation of notched testing and analysis protocols in Composites Materials Handbook (CMH-17) with Parmigiani group (OSU)**



Sandwich Open-Hole Compression



Sandwich Open-Hole Flexure

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

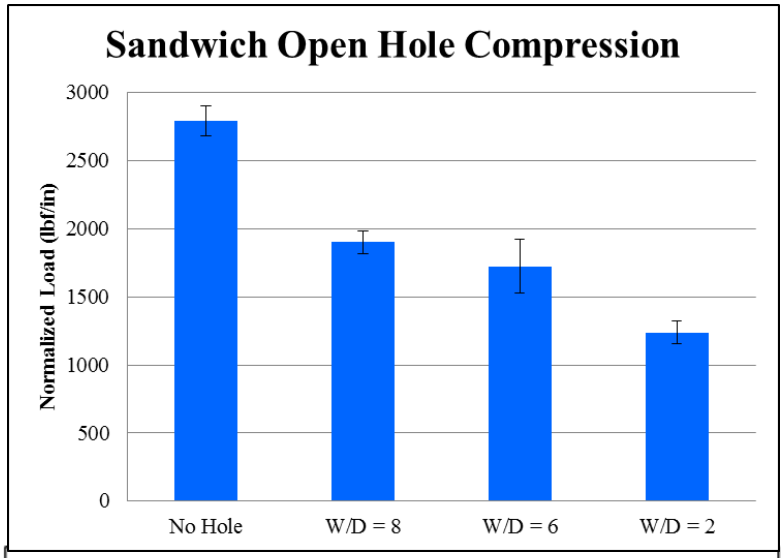
Sandwich Open-Hole Compression: Determination of Sizing Guidelines

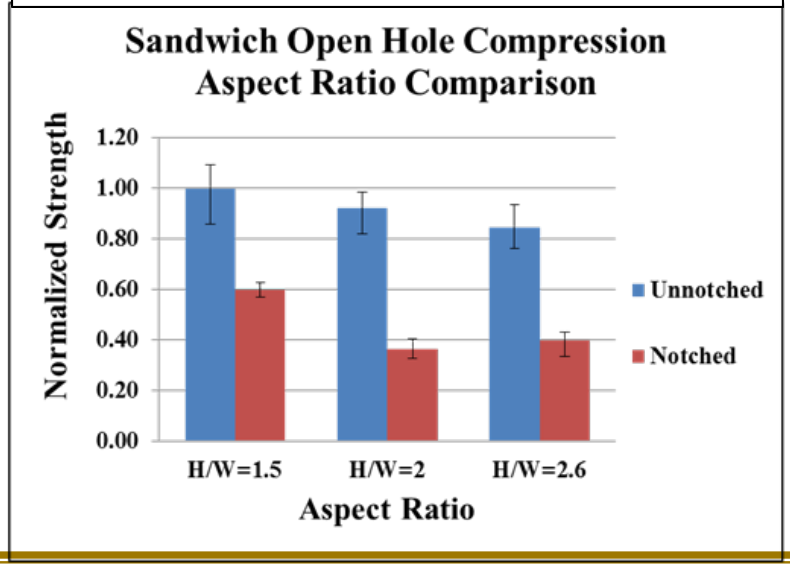
- Hole diameter (W/D)
  - Legacy: W/D = 6
  - Acceptable strength reduction
  - Avoid finite width effects
- Aspect ratio (H/W)
  - H/W = 2
  - Larger strength reduction than H/W = 1.5
  - Avoid finite height effects

H/W = 1.5

H/W = 2.0

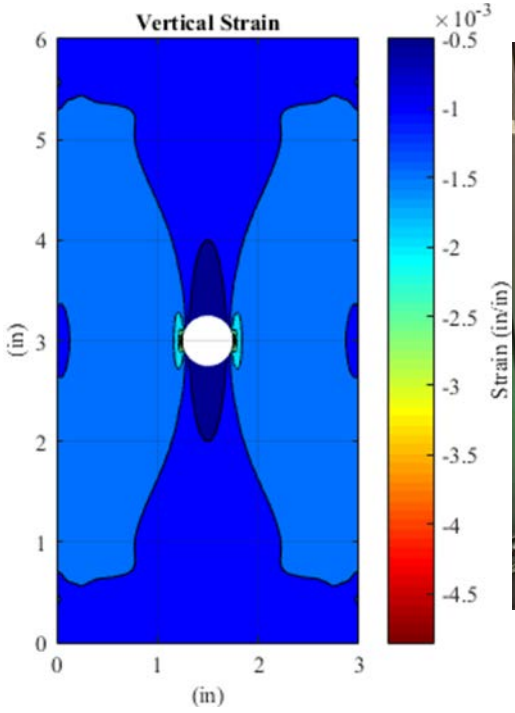
H/W = 2.6

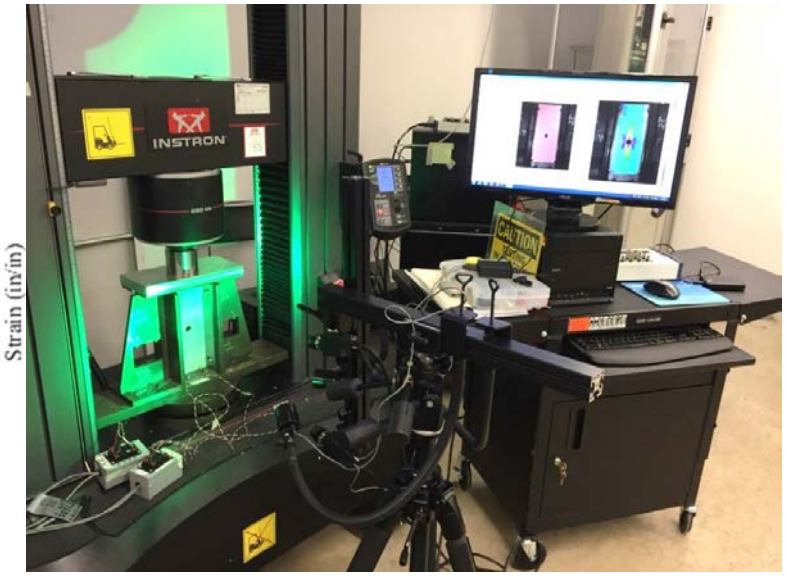


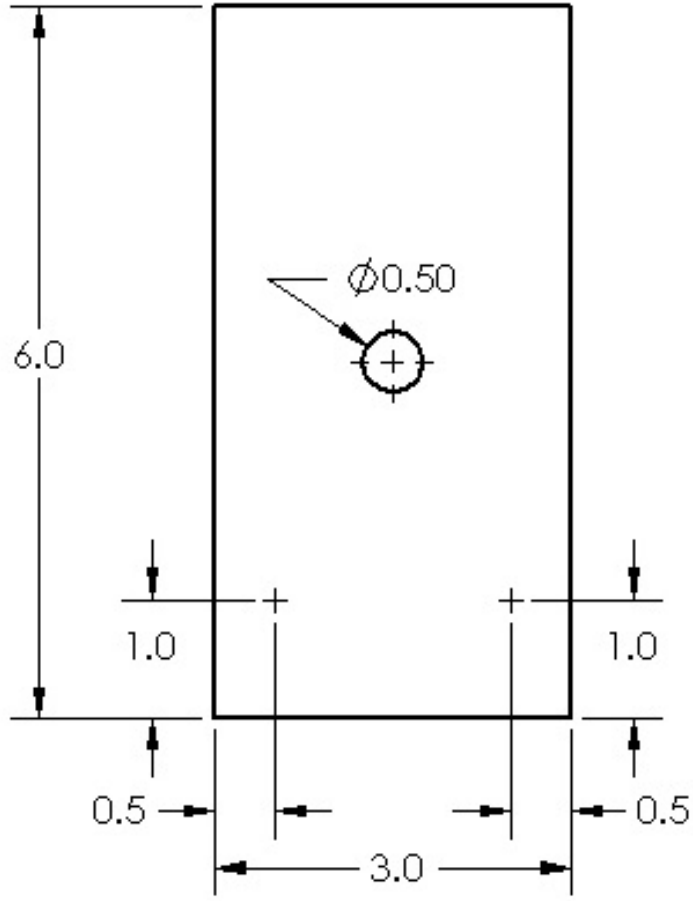


Sandwich Open-Hole Compression: Determination of Sizing Guidelines

- **Minimum size of 3”x6” with ½” hole**
  - **Strain gage placement**
    - **Low strain gradient**
    - **Low shear strain**

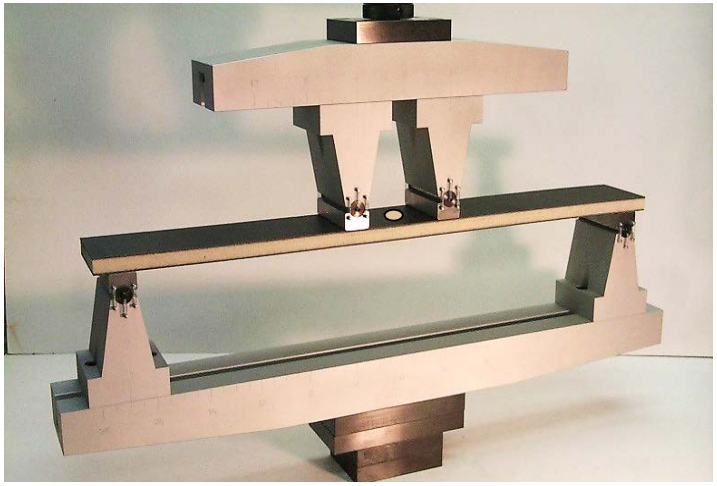


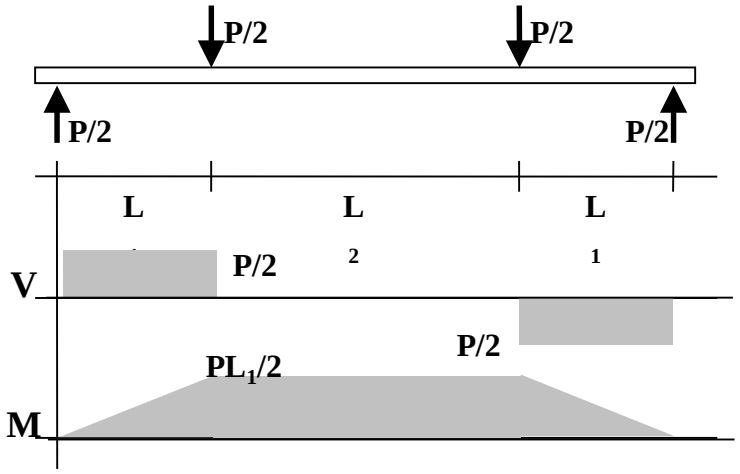




Testing Considerations: Sandwich Open-Hole Flexure Test

- **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**

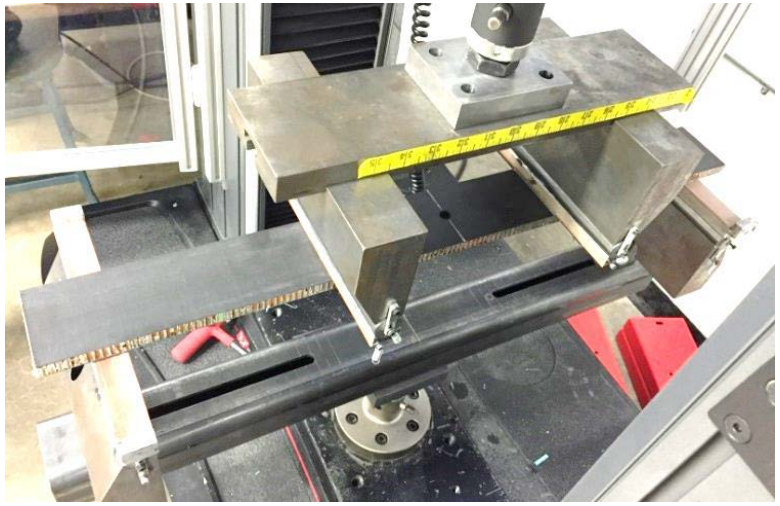


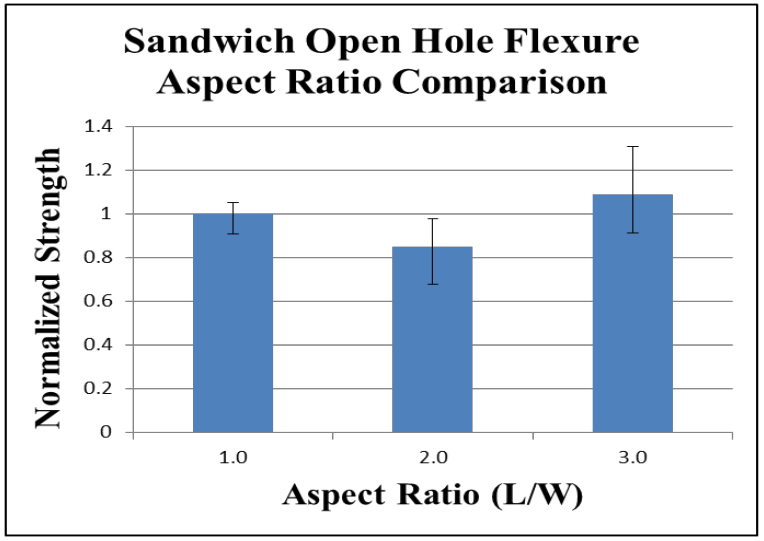


Sandwich Open-Hole Flexure Test: Determination of Sizing Guidelines

Current configuration:

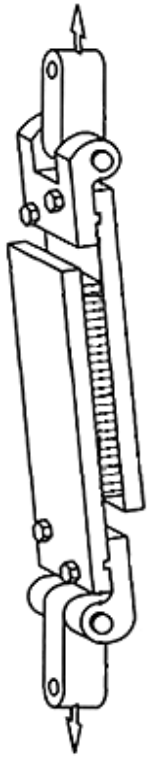
- Specimen width W = 3 inches
- Hole diameter D = 0.5 inch
- Inner span L = 4 inches
- Inner span can be increased to allow DIC to measure far field strains
- No inner span (L/W) strength sensitivity observed
- Outer span sized to ensure inner span failure



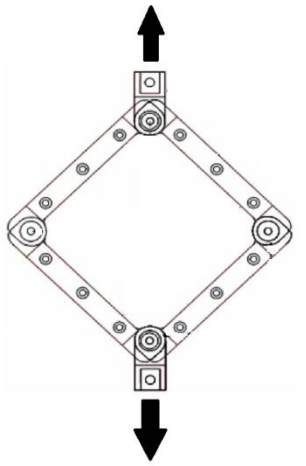


Test Method Development:
Third Loading Configuration

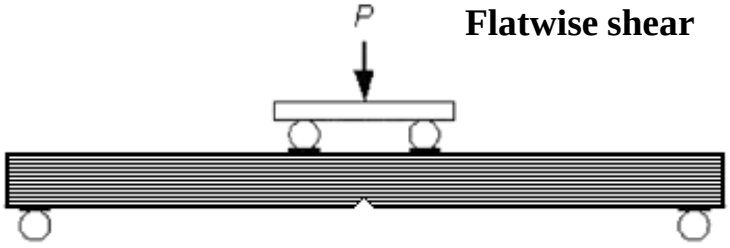
- **Investigate additional notch configurations**
  - **Notched core shear**
  - **In-plane bending edge v-notch**
  - **Compression one sided open hole (single facesheet)**
  - **In-plane shear picture frame**
  - **In-plane biaxial tension/compression**
  - **Out of plane shear (Mode III)**
  - **Open hole tension**



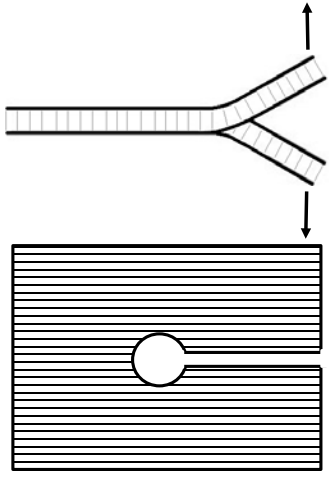
Flatwise shear



In-plane shear



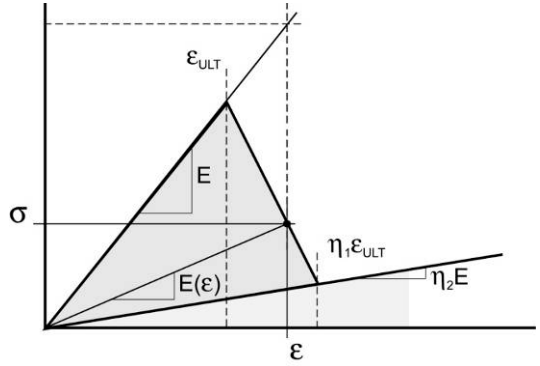
In-plane bending

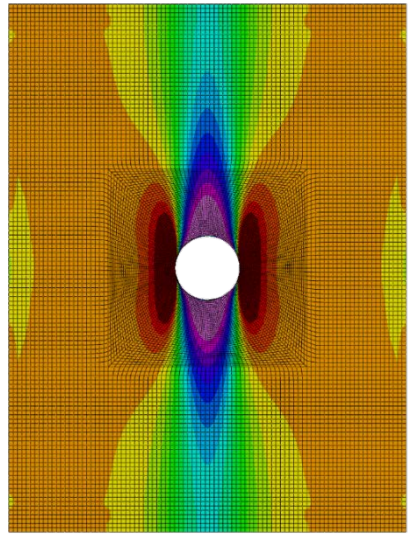


Out-of-plane shear

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**



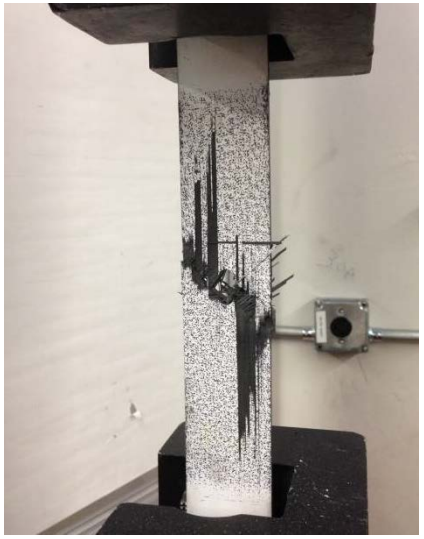


Materials Sciences Corporation

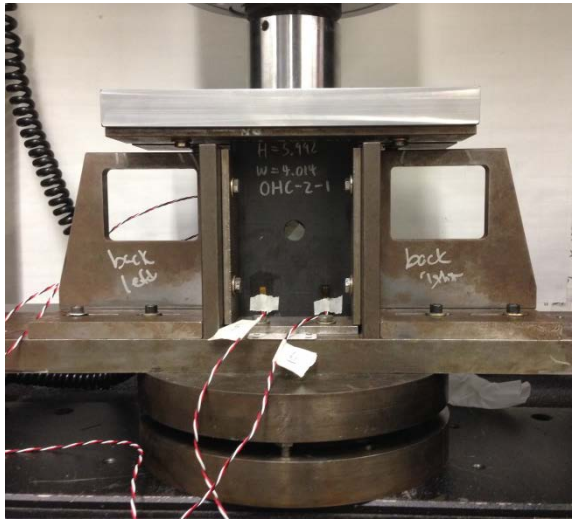
Analysis of Notched Sandwich Specimens

Validation of Modeling Approach

- **Modeling of damage progression in carbon/epoxy facesheet material**
  - **Interlaminar disbond (Mode I and II)**
  - **Laminate tension (+/-45 layup)**
  - **Open-hole tension test**
  - **Open-hole compression test**

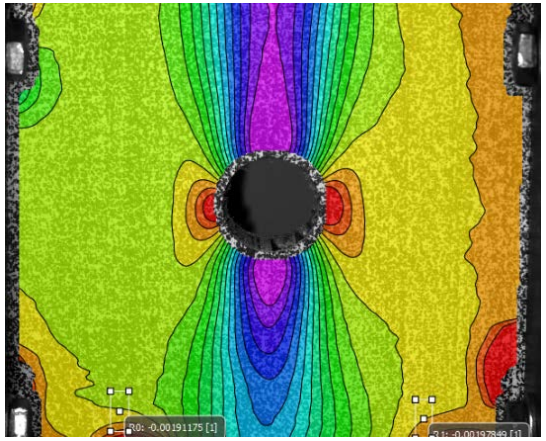


- **Modeling of damage progression in sandwich composites**
  - **Sandwich interface disbond (Mode I & II)**
  - **Sandwich open-hole flexure**
  - **Sandwich open-hole compression**

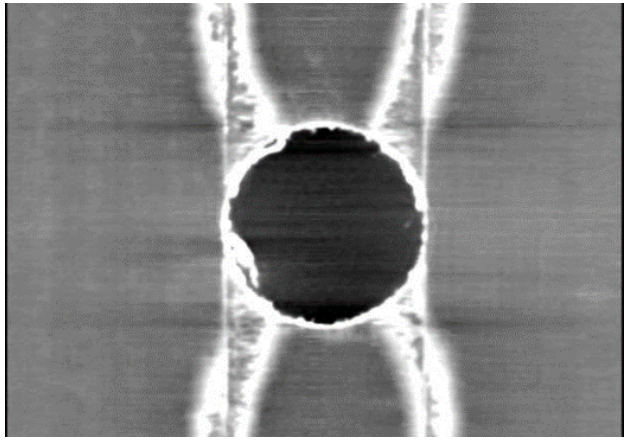


Analysis of Notched Sandwich Specimens
Validation of Modeling Approach

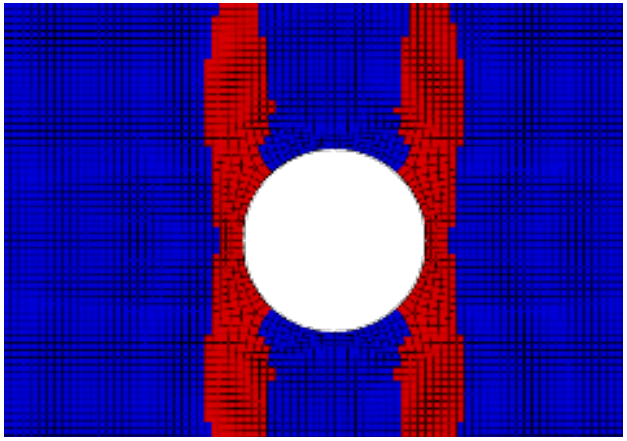
- **Comparison with results from mechanical testing**
  - **Ultimate strength**
  - **Stress vs. strain plots**
  - **Strain fields from Digital Image Correlation**
  - **Damage Progression using X-ray CT**



DIC



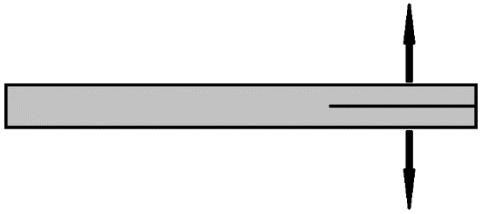
X-ray CT

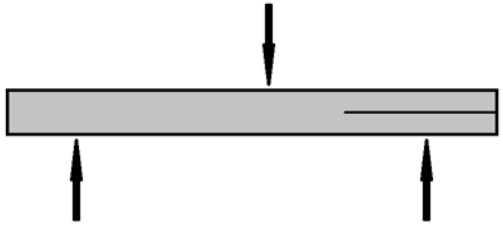


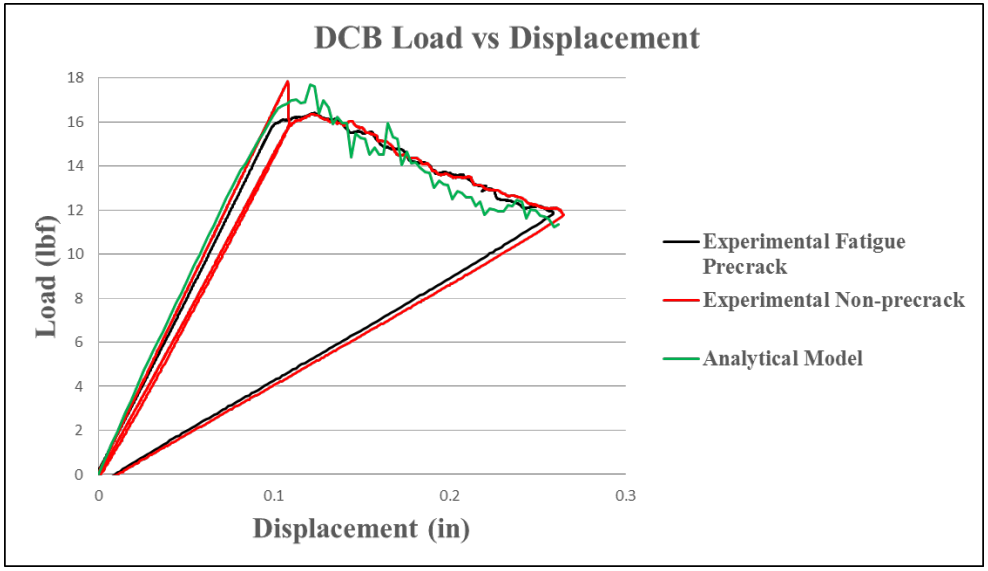
NDBILIN Damage

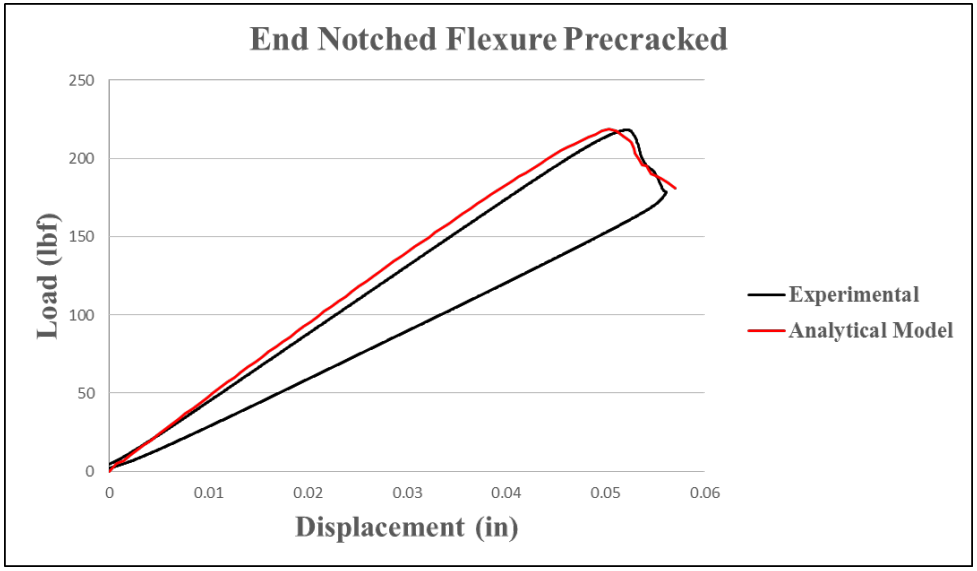
Analysis of Notched Sandwich Specimens
Interlaminar Disbond:

- **Calibration of interlaminar cohesive elements**
  - **Mode I DCB using ASTM D5528**
  - **Mode II ENF using ASTM D7905**



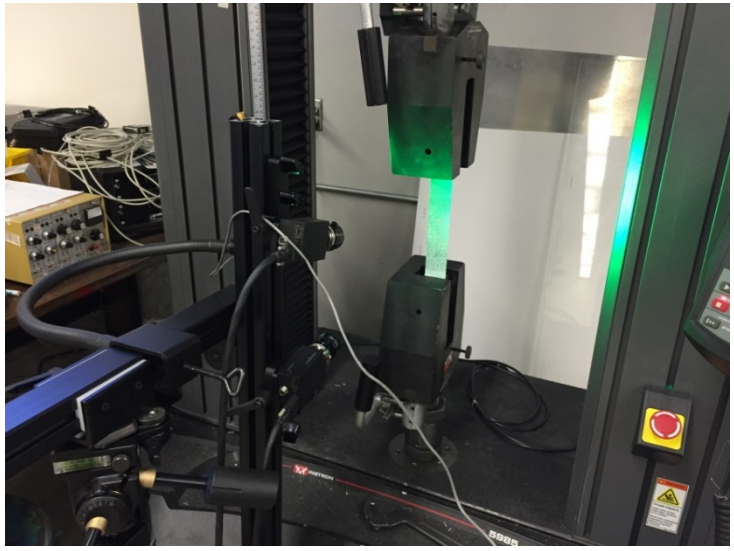


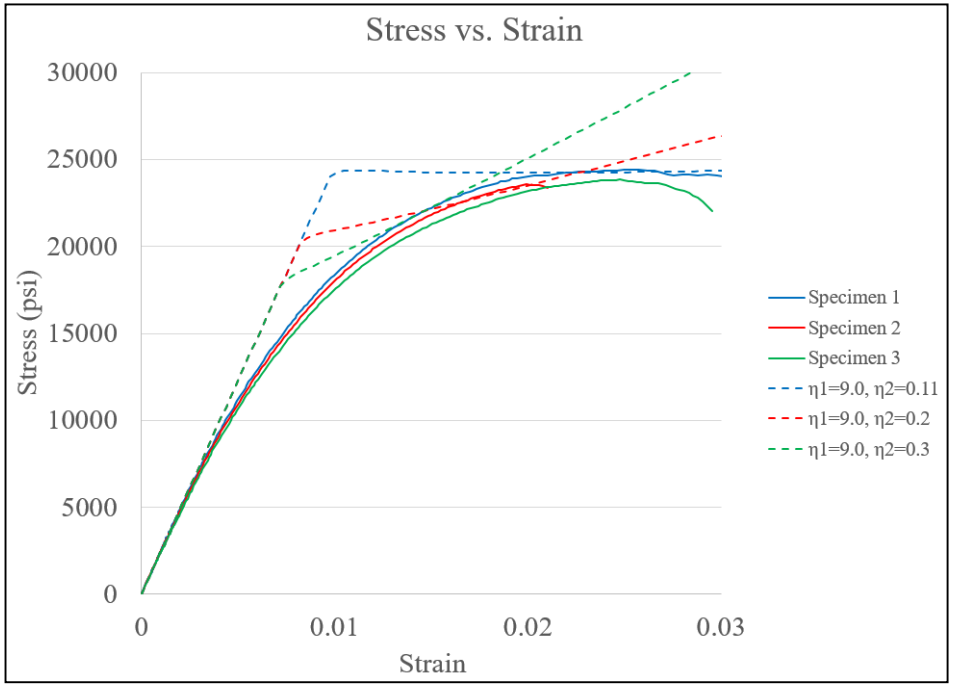




Damage Progression in Facesheets: Analysis of +/-45 Laminates

- **Simulation of tension testing of IM7/8552 carbon/epoxy $[45/-45]_{2S}$ laminate**
- **NDBILIN matrix shear strength and damage parameters modified to model test behavior**





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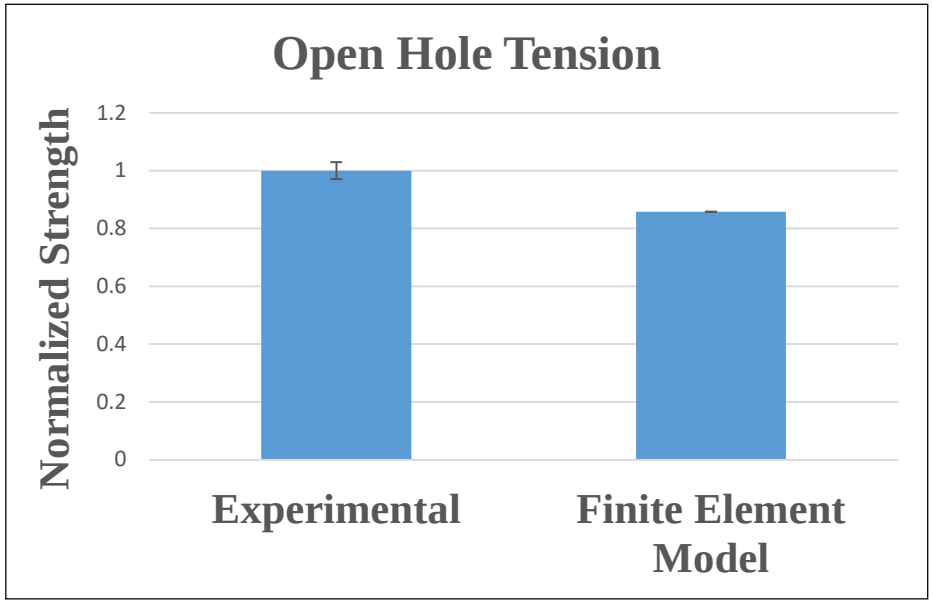
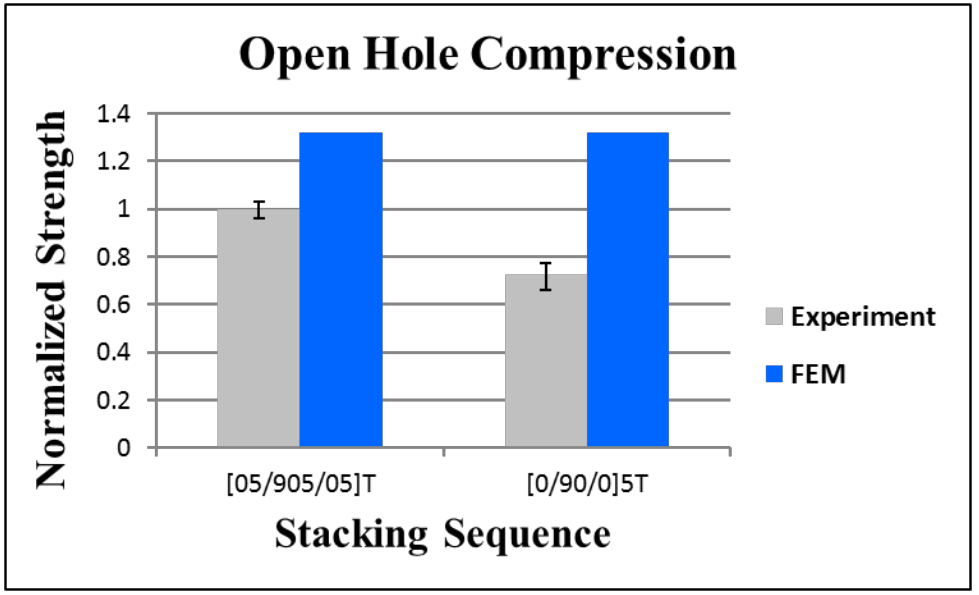
Damage Progression in Facesheets: Analysis of Open Hole Tests

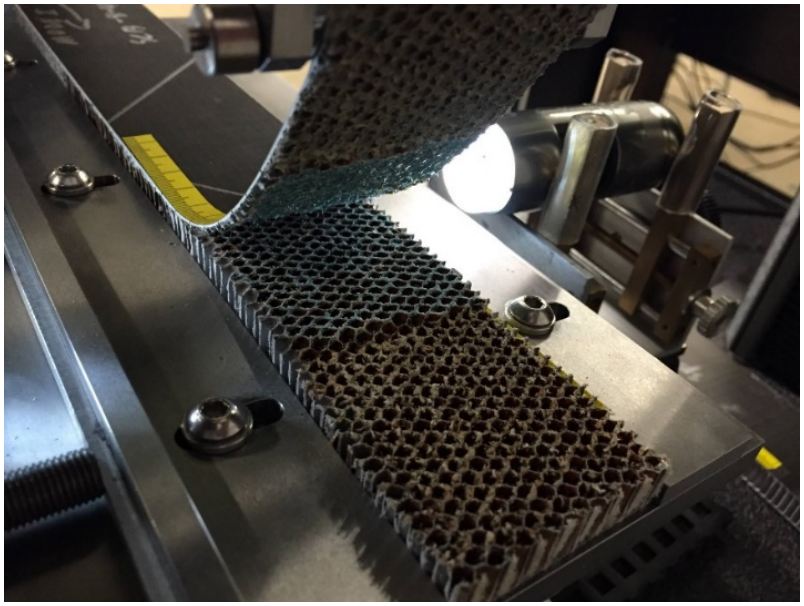
- **Currently, better correlation on failure stress in tension than compression**
- **Revisit open hole results with updated cohesive element parameters and matrix damage parameters to determine NDBILIN best practices**



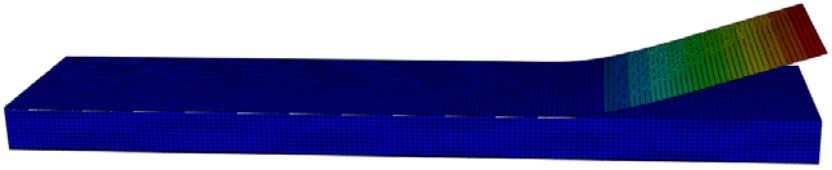


Analysis of Notched Sandwich Specimens
Interface Disbond:

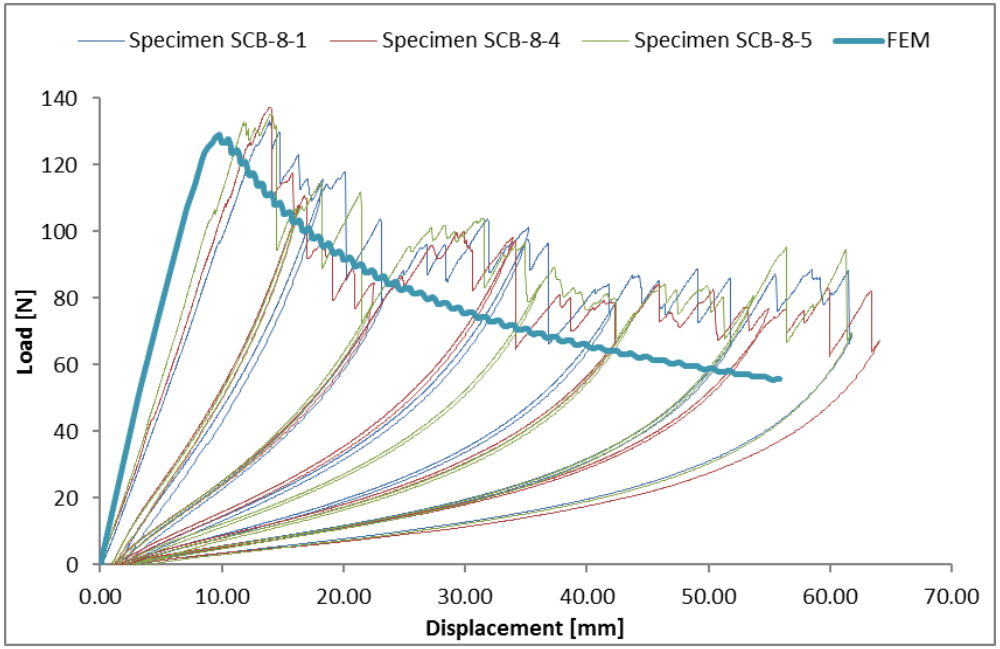
- **Mode I Sandwich SCB**



Single Cantilever Beam Test



Single Cantilever Model Displacements



Load vs Extension Data

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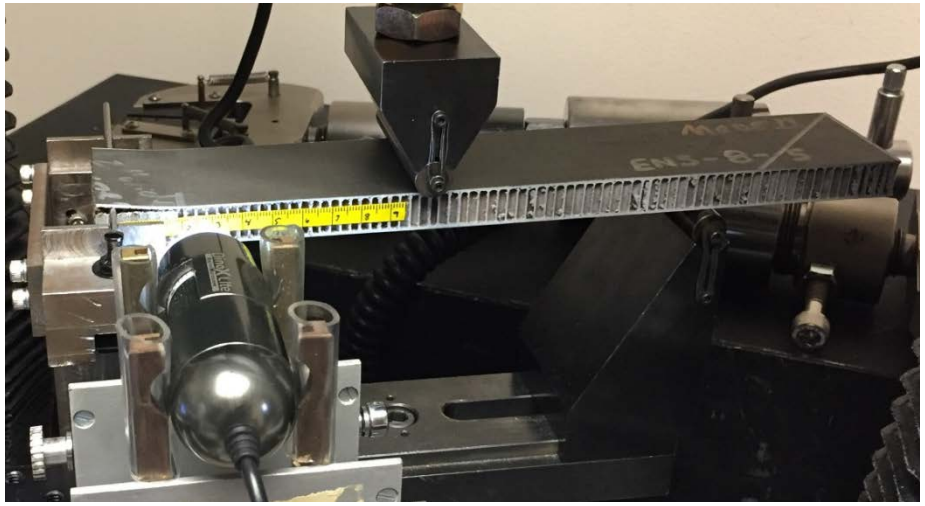
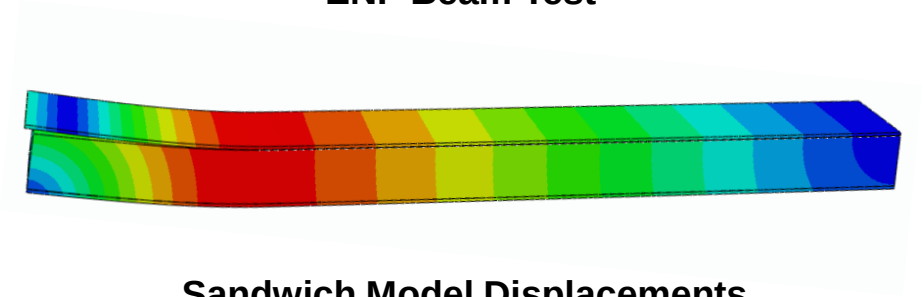
Analysis of Notched Sandwich Specimens
Interface Disbond:

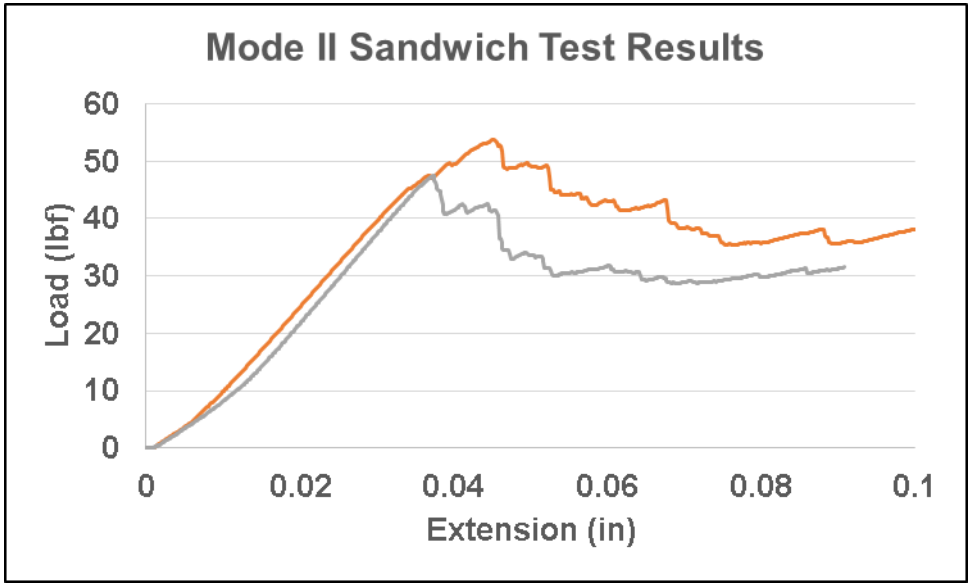
- **Mode II Sandwich ENF**



ENF Beam Test



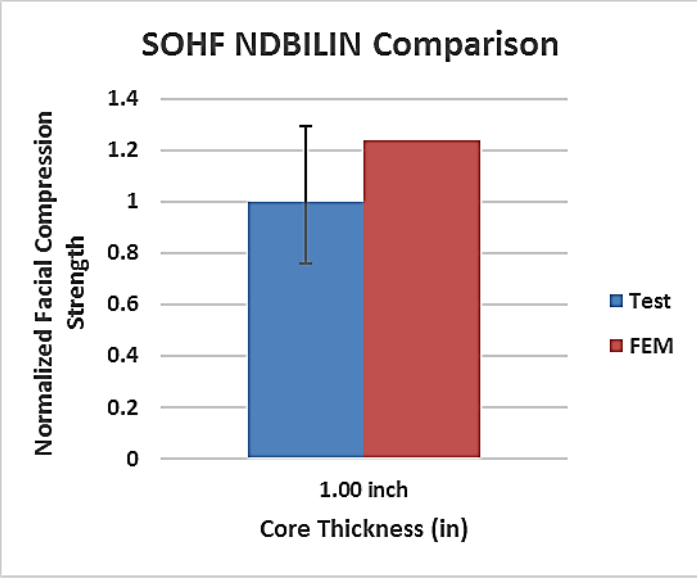
Sandwich Model Displacements

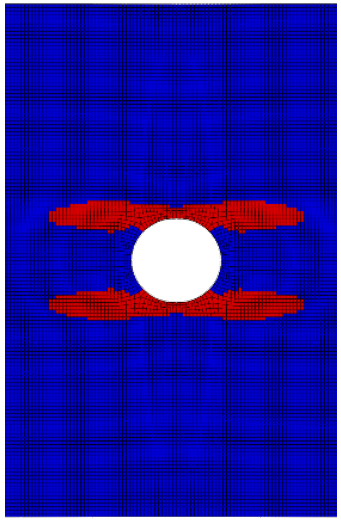


Load vs Extension Data

Damage Progression in Sandwich Composites: Analysis of Sandwich Open-Hole Test

- **Modeling Sandwich Open-Hole Flexure**
  - **Predicted ultimate strength roughly 20% over predicting average but within test scatter**
  - **No instability observed**
  - **Damage progression from X-ray CT (in progress)**
    - **Images captured at 70% and 90% of ultimate load**





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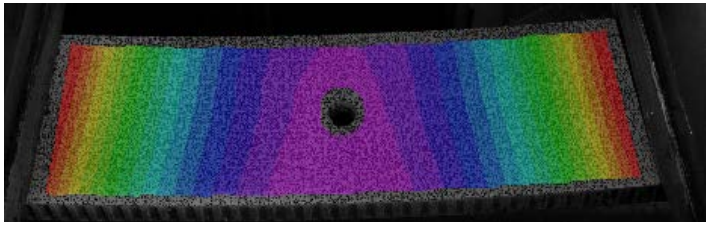
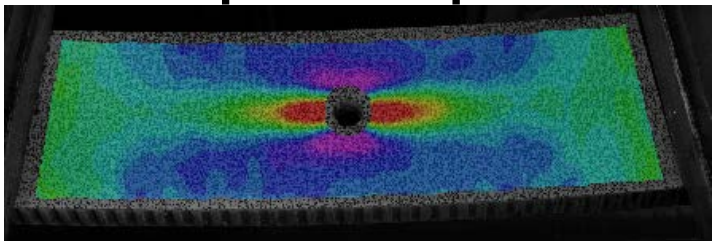


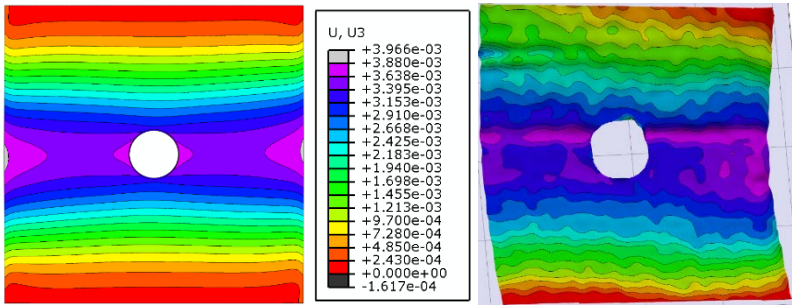
DIC out-of-plane displacements



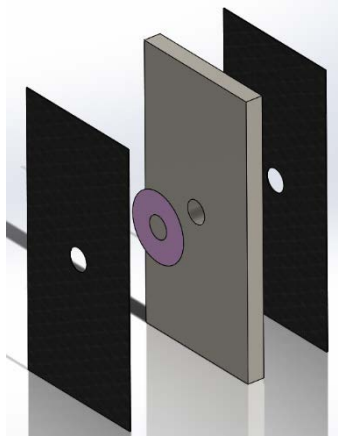
DIC horizontal strain

Damage Progression in Sandwich Composites: Analysis of Sandwich Open-Hole Test

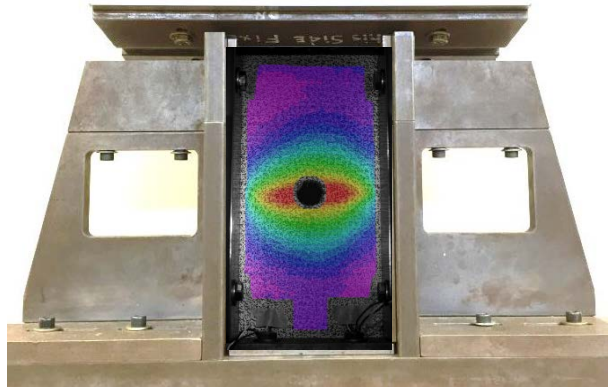
- **Modeling Sandwich Open-Hole Compression**
  - Out-of-plane displacement observed in DIC measurements
  - First mode facesheet buckling observed
  - Investigating facesheet buckling using ABAQUS Riks
  - Progressive approach to validating models
    - Laminate general buckling using IITRI (D3410) for OHC
    - Initial disbond of sandwich tests using Teflon insert



IITRI displacement results (FEM vs DIC)



Initial disbond test



Out-of-plane deformation

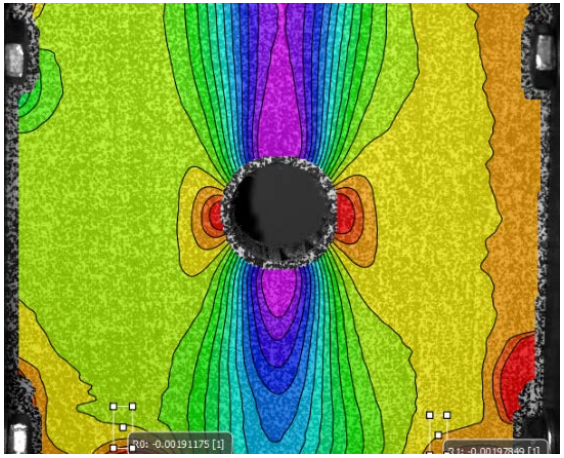
Future Work:
Notch Sensitivity of Composite Sandwich Structures

- **Completion of sizing guidelines for sandwich open hole compression and flexure tests**
- **Incorporate updated material/model parameters in laminate open hole tension/compression simulations**
- **Explore best practices for modeling sandwich core**
- **Investigate buckling predictions of facesheet delaminations under compression loading**

Summary:
Benefits to Aviation

- **Standardized test methods for fracture mechanics, and damage tolerance of sandwich composites**

- **Notch sensitivity test development and analysis assessment for sandwich composites**



Thank you for your attention!

Questions?