NOTCH SENSITIVITY OF COMPOSITE SANDWICH STRUCTURES

Dan Adams
Marcus Stanfield
Brad Kuramoto
Martin Raming
Department of Mechanical Engineering
University of Utah
Salt Lake City, UT

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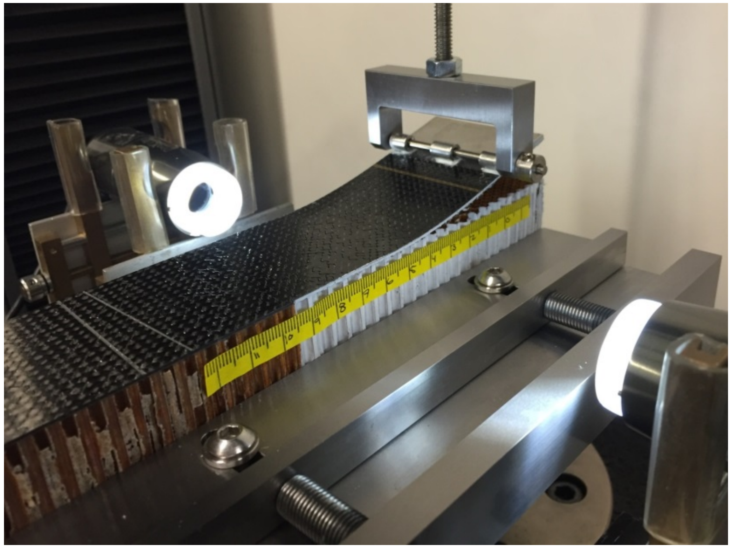
FAA Sponsored Project Information

- Principal Investigators: **Dr. Dan Adams**
  Dr. Mike Czabaj
- Graduate Student Researchers:
  Marcus Stanfield
  Brad Kuramoto
  Martin Raming
- FAA Technical Monitor: **Zhi-Ming Chen**
- Collaborators**:**
  Materials Sciences Corporation
  Boeing (Charles Park)
  ASTM D30 (Composites)

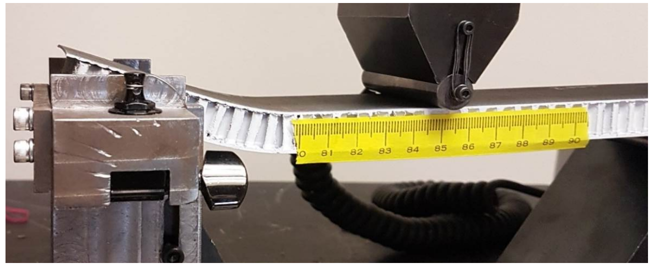
Status Update:
Mode I Sandwich Fracture Mechanics Test Method

- **Recently completed second round of ASTM balloting (September 2018) at D30.09 (sandwich) and D30 (main) levels**
- **Ballot negatives and comments currently being addressed**
- **Will reballot in January 2019 prior to next ASTM D30 meeting in March 2019 (SLC, UT)**



Status Update:
Additional Sandwich Disbond Related Activities

- **Mode I Single Cantilever Beam Fatigue Test**
  - New initiative for 2019
  - Focus on development of ASTM standard practice

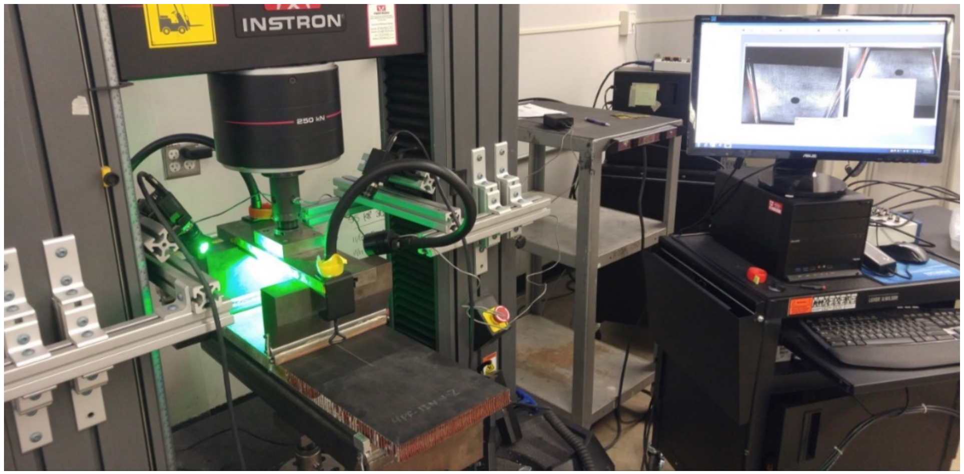


- **Mode II Separated End Notched Flexure Test**
  - Evaluation by working group members

- **Sandwich Mixed Mode Bend (MMB) Test**
  - Evaluation by working group members
- **Sandwich Disbond Building Block Approach and Numerical Analysis Round Robin**
  - Working group focus for 2019

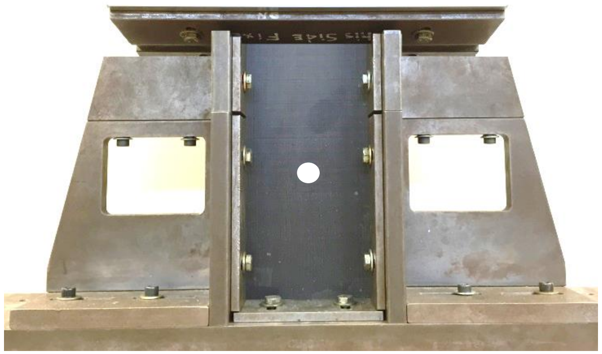
Status Update:
Sandwich Damage Tolerance

- **Draft standard of Sandwich composite Compression After Impact (SCAI) competed**
  - Balloted Spring 2018 ASTM D30 meeting
  - Updates to address negative votes in work
- **Draft practice of 4-Point Flexure After Impact (4-FAI) in progress**

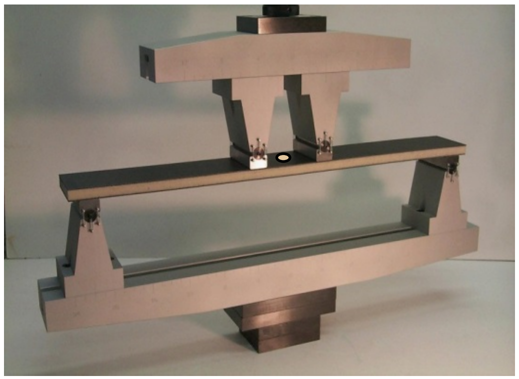


Research Objectives:
Notch Sensitivity of Sandwich Composites

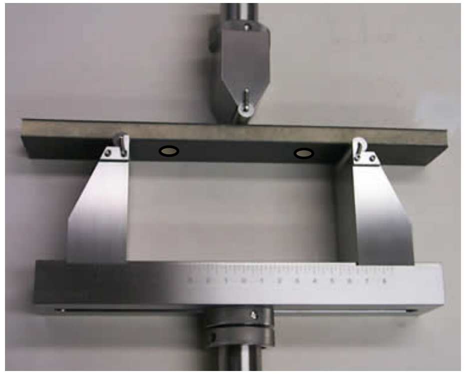
- **Initial development of notched test methods and associated analysis methodologies for composite sandwich panels**
- **Documentation notched testing and analysis protocols in Composites Materials Handbook (CMH-17)**
- **Explore development of new ASTM standards for notch sensitivity of sandwich composites**



Sandwich Open Hole Compression



Sandwich Open Hole Flexure



Sandwich Open Hole Shear

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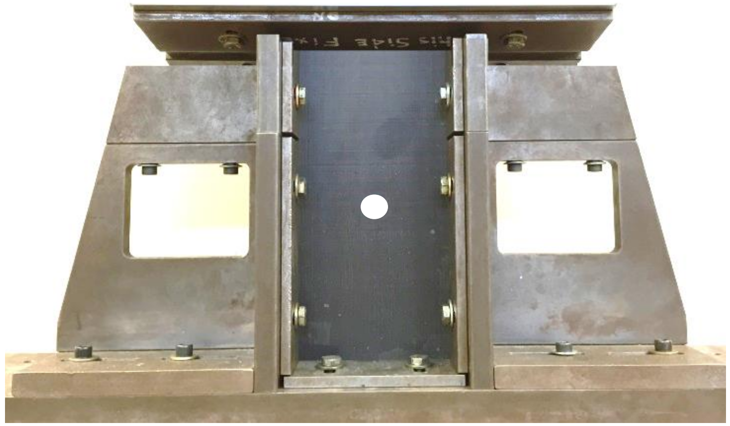
Testing Considerations: Sandwich Open Hole Compression

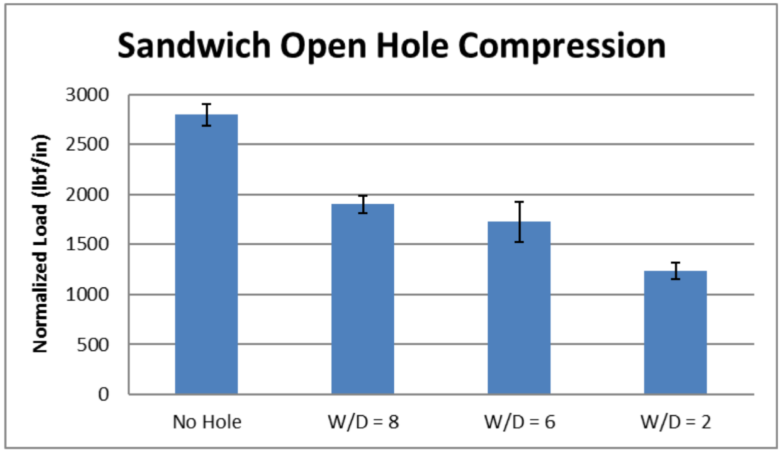
- **Test fixture/Specimen support**
  - End supports
    - Clamping top and bottom
    - Potting
  - Side supports
    - Knife edge
- **Specimen size**
  - Separation of central hole and boundary effects
  - Production of acceptable strength reductions
- **Strain measurement**
- **Specimen alignment**

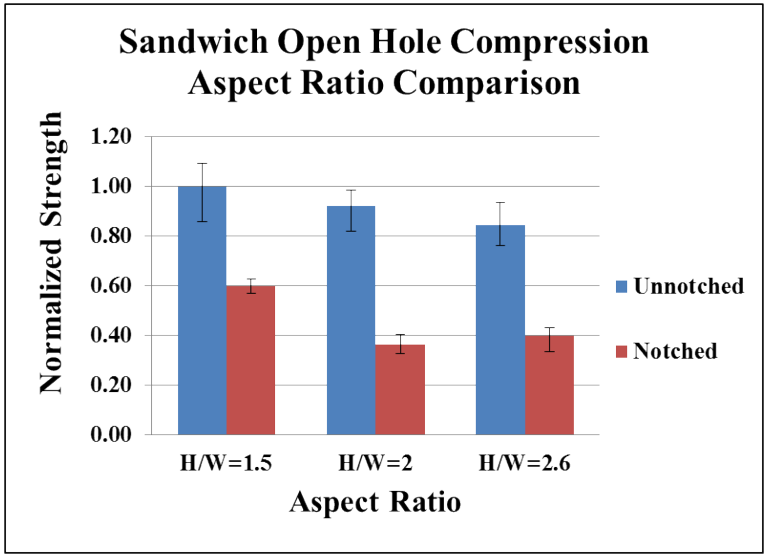


Open hole compression fixture for monolithic composites

Previous Work: Specimen Size

- **Hole Diameter (W/D)**
  - Legacy: W/D = 6
  - Acceptable strength reduction
  - Minimal finite width effects
- **Aspect Ratio (H/W)**
  - H/W = 2
  - Acceptable strength reduction
- **Standard Configuration**
  - Width: 4 in.
  - Height: 8 in.
  - Hole Diameter: 0.67 in.





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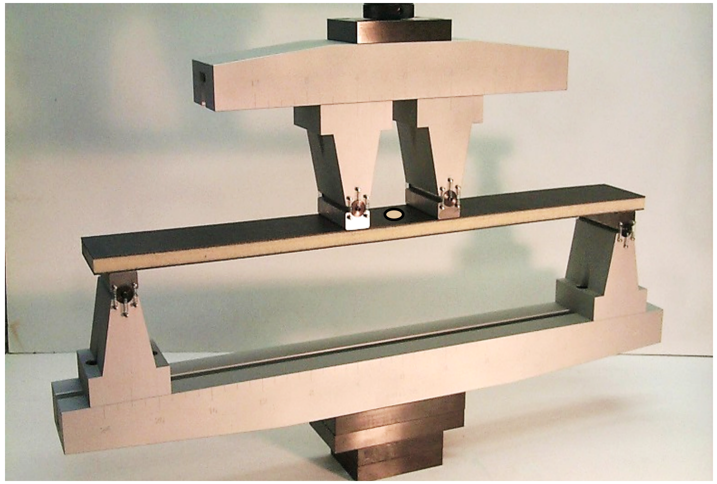
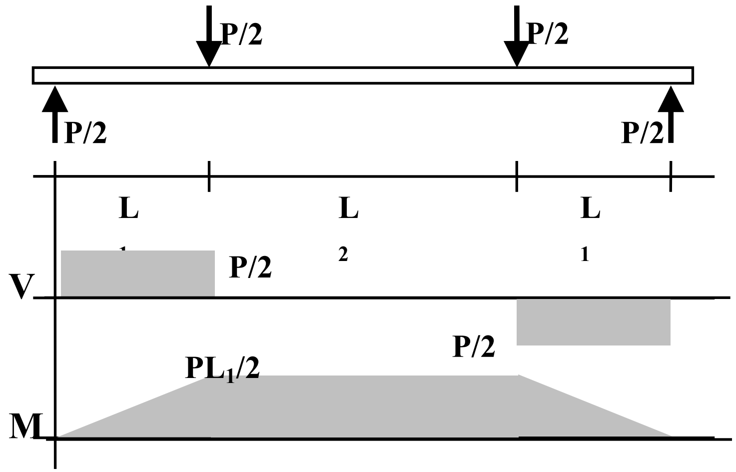
Testing Considerations:
Sandwich Open Hole Flexure

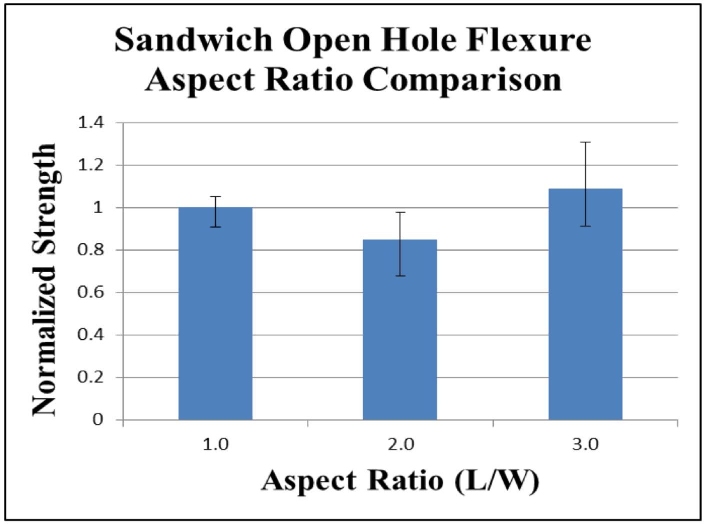


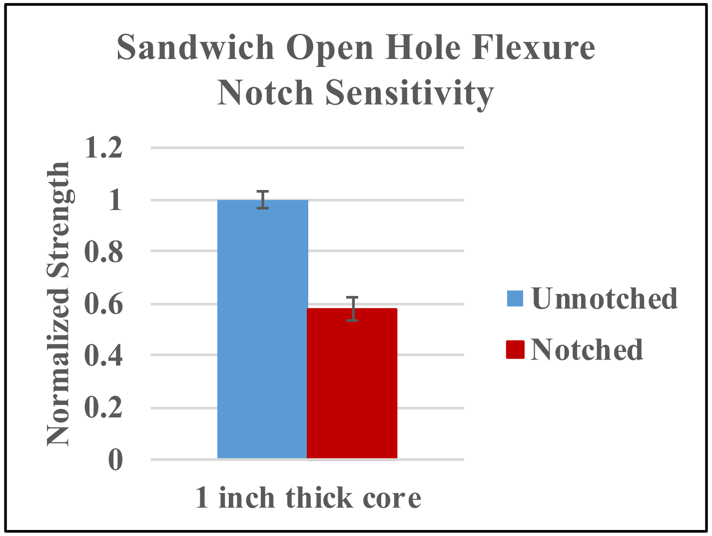
- Test fixture/specimen support
  - Inner span
    - Separation of notch and loading boundary effects
  - Outer span
    - Develop sufficient bending moment
    - Ensure failure in inner span
- Required specimen width
  - Separation of central hole and specimen edges
  - Production of acceptable strength reduction



Previous Work: Specimen Size

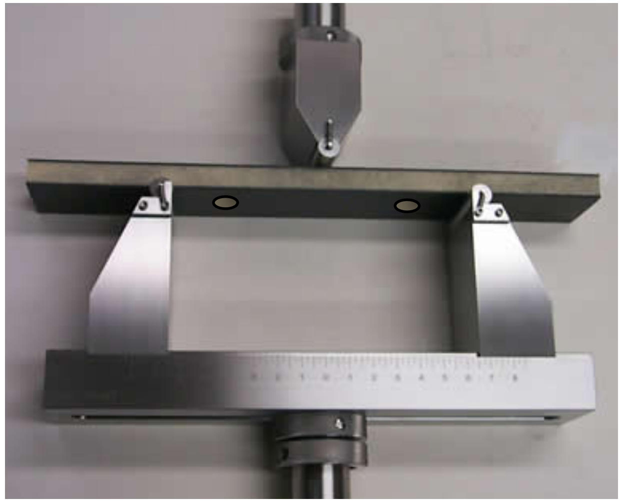
- **Standard configuration**
  - Specimen width W = 3 in.
  - Hole diameter D = 0.5 in.
  - Inner span L = 4 in.
  - Outer span sized to ensure inner span failure
- **No inner span aspect ratio sensitivity (L/W)**
  - Inner span can be increased for measurement purposes

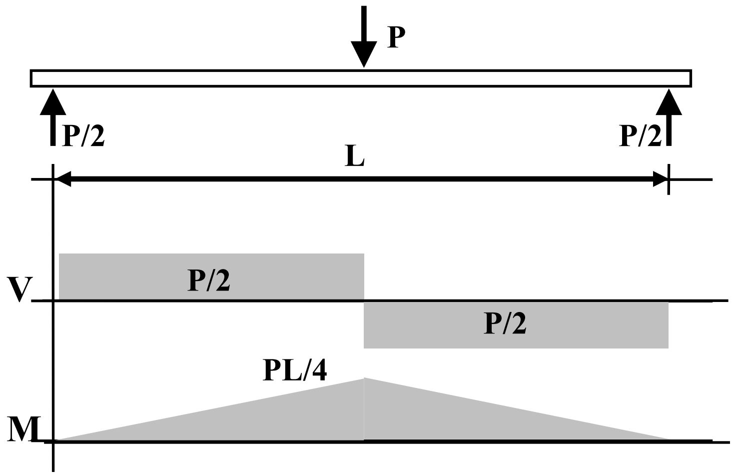




Testing Considerations: Sandwich Open Hole Shear

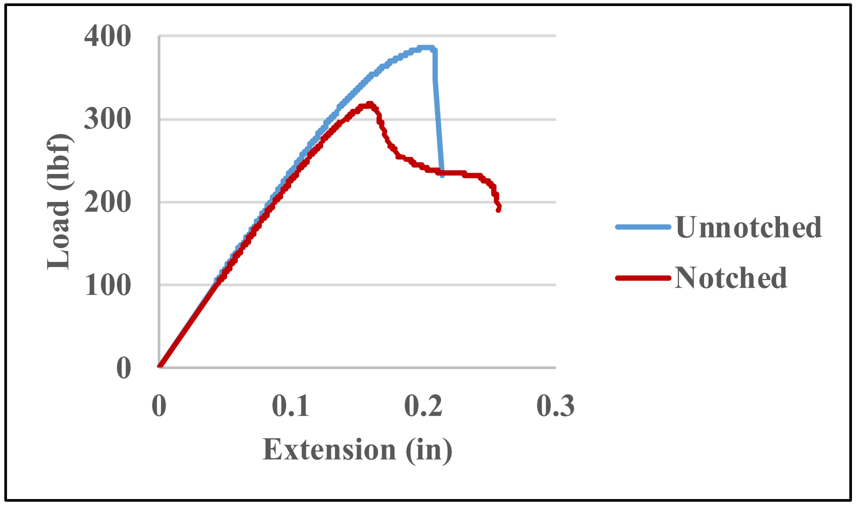
- Test fixture/specimen support
  - Span
    - Locate notch to ensure shear failure in core at notch
- Required specimen width
  - Separation of central hole and specimen edges
  - Production of acceptable strength reduction

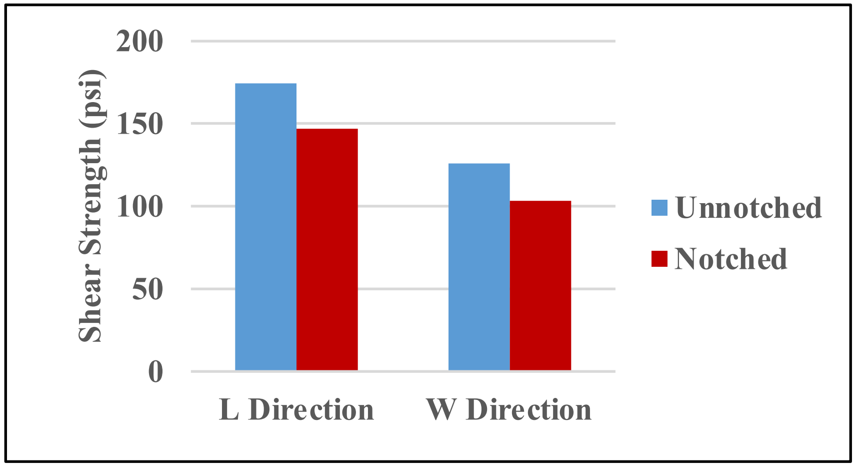




Previous Work: Specimen Size

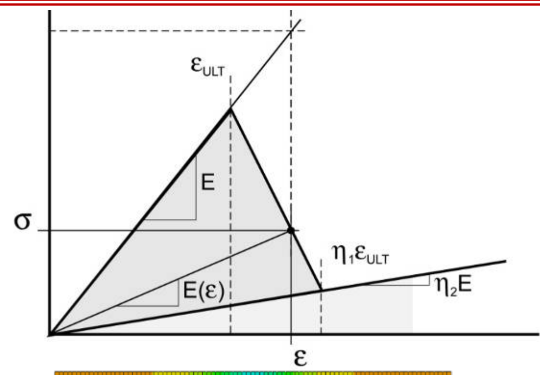
- Standard configuration
  - Specimen width W = 3 in.
  - Hole diameter D = 0.5 in.
  - Span L = 6 in.
  - Notch located at quarter points
- No significant notch effect
- Net section failure
- Similar behavior between ribbon and transverse directions

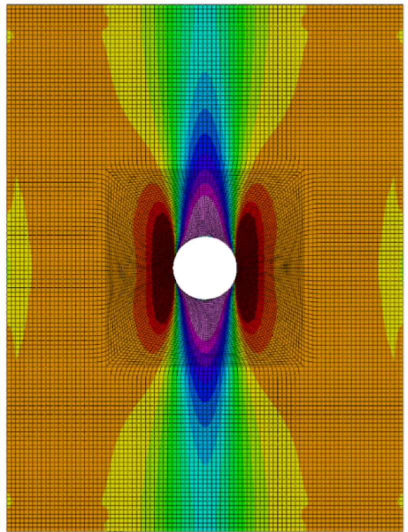




Analysis of Notched Sandwich Specimens
ABAQUS with NDBILIN:

- **User-defined nonlinear material model (UMAT) for ABAQUS**
- **Developed by Materials Sciences Corp.**
- **Stiffness degradation based progressive damage model**
  - **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**



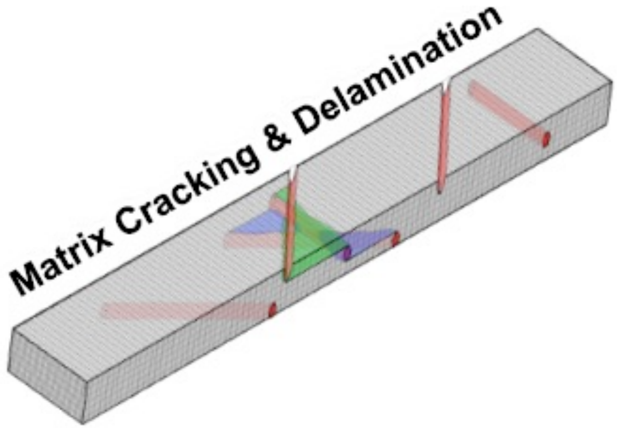


Materials Sciences Corporation

Analysis of Notched Sandwich Specimens

B-Spline Method (BSAM):

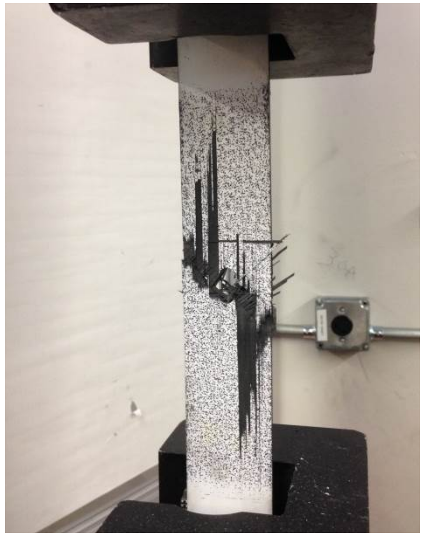
- **Stand-alone software**
- **Developed by AFRL, UDRI, UTA**
- **Discrete damage modeled using Regularized Extended Finite Element Method (Rx-FEM)**
  - **Matrix Cracking**
    - **Multiple failure criteria for damage onset**
    - **Damage propagation using cohesive zone method**
  - **Delamination using cohesive zone method**
  - **Fiber failure using Critical Failure Volume or CDM**

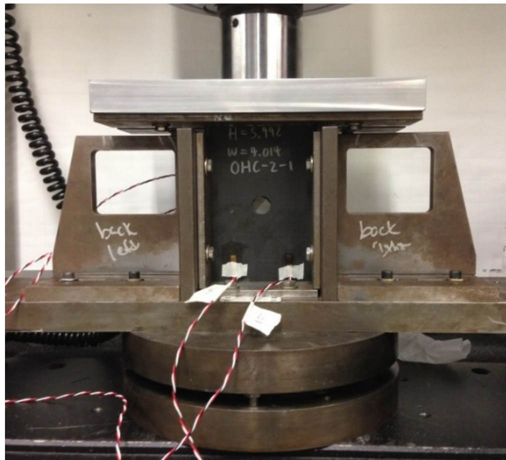


Failure Analysis of Notched Sandwich Specimens

Development of Modeling Approach

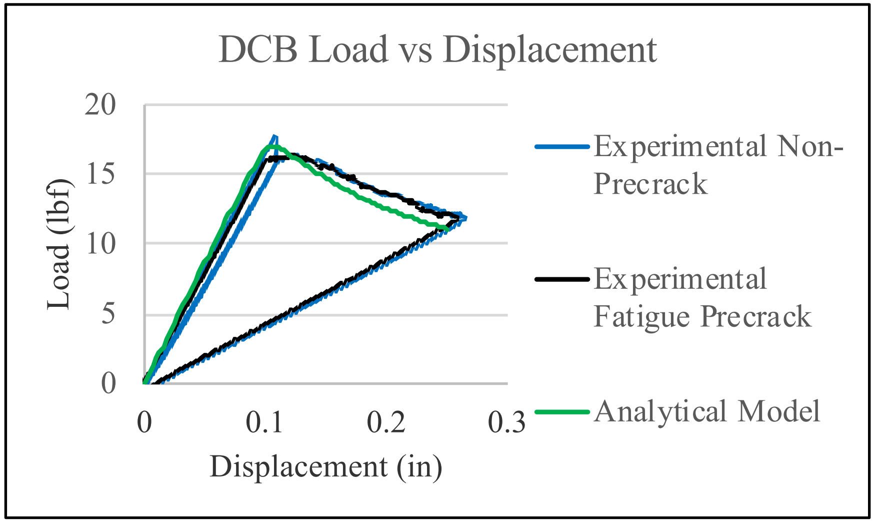
- **Modeling of damage progression in facesheets**
  - Interlaminar disbond (Mode I and II)
  - Laminate tension (+/-45 layup)
  - Open-hole tension
  - Open-hole compression
- **Modeling of damage progression in core**
  - Flatwise compression
  - Flatwise shear
- **Modeling of damage progression in sandwich composites**
  - Sandwich interface disbond (Mode I and II)
  - Sandwich open-hole shear
  - Sandwich open-hole flexure
  - Sandwich open-hole compression

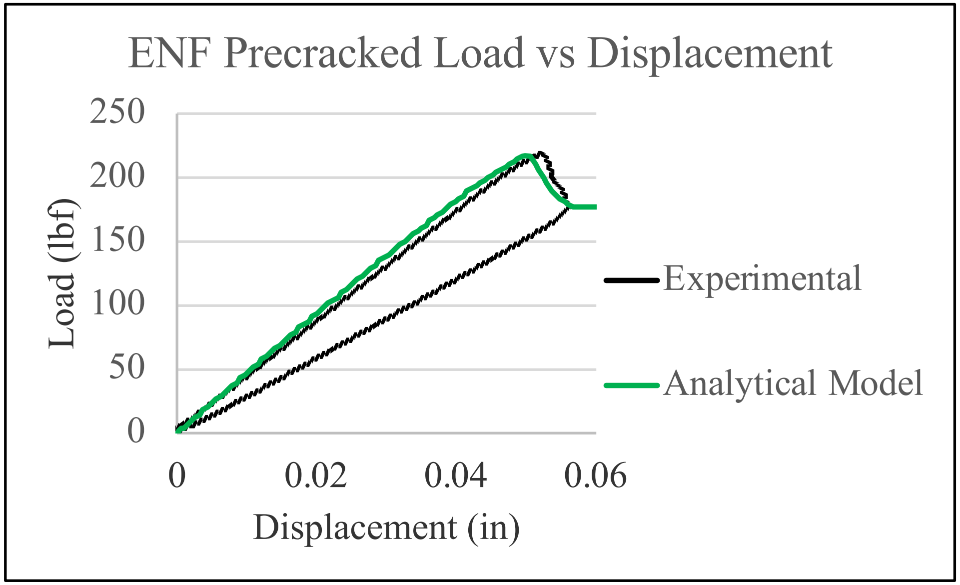


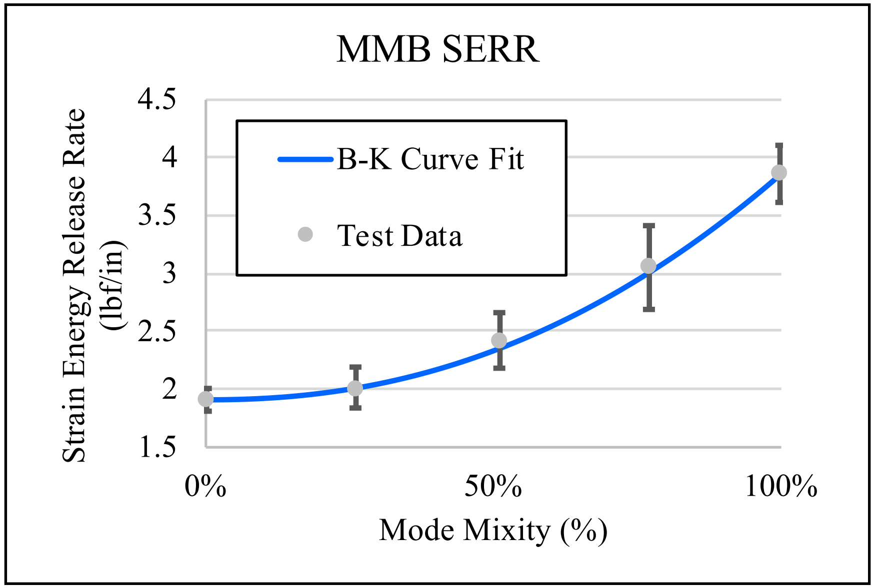


Damage Progression in Facesheets: Analysis of Delamination

- **Calibration of cohesive zone**
  - **Mode I DCB using ASTM D5528**
  - **Mode II ENF using ASTM D7905**
  - **MMB using ASTM D6671**
- **Both modeling approaches use the same damage formulations**

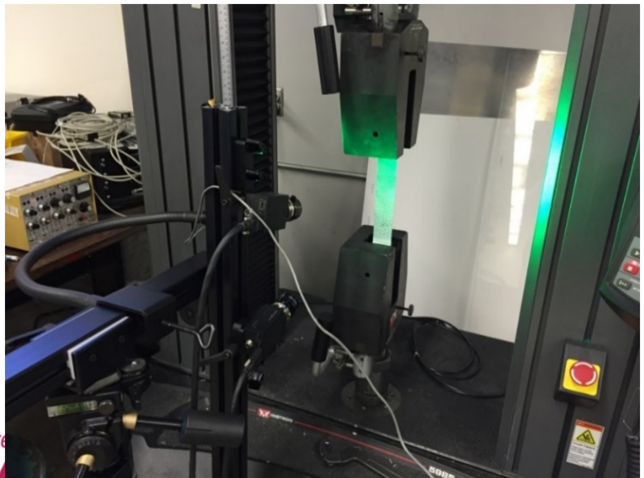


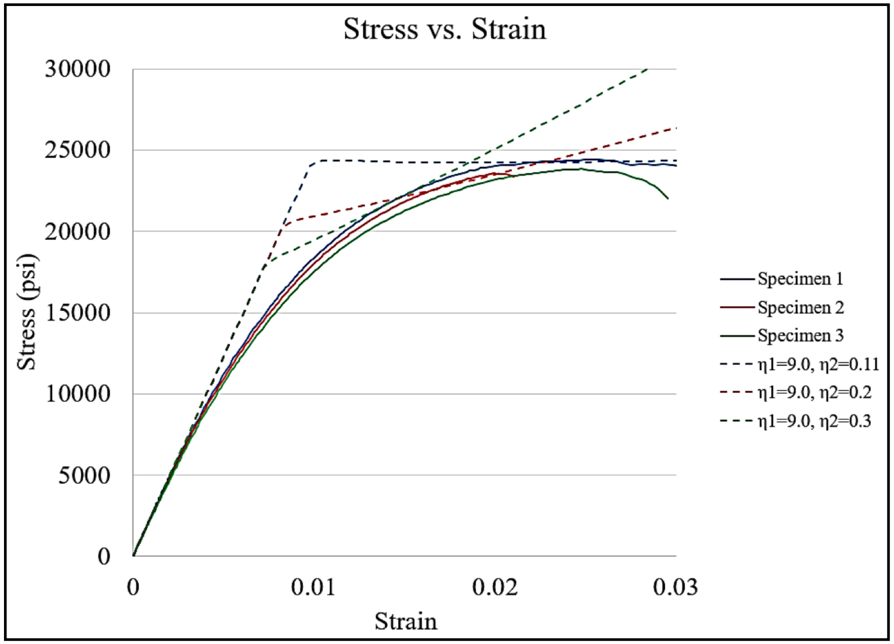




Damage Progression in Facesheets: Analysis of +/-45 Laminates

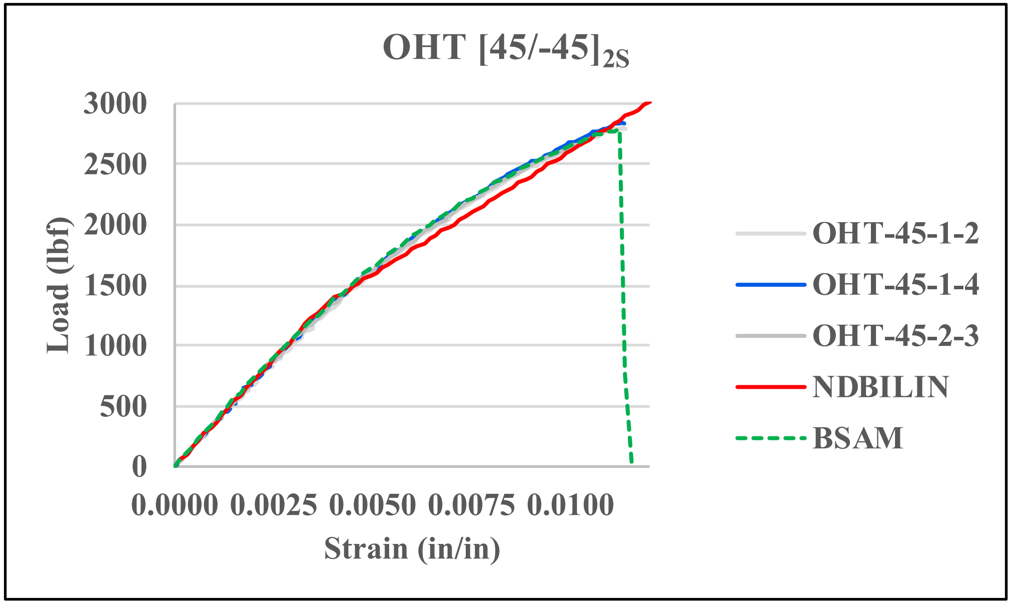
- **Simulation of un-notched and open-hole tension testing**
- **IM7/8552 carbon/epoxy, $[45/-45]_{2S}$ laminates**
- **Matrix shear modulus, strength and damage parameters calibrated using measured stress-strain behavior**
  - NDBILIN: bilinear response
  - BSAM: non-linear response

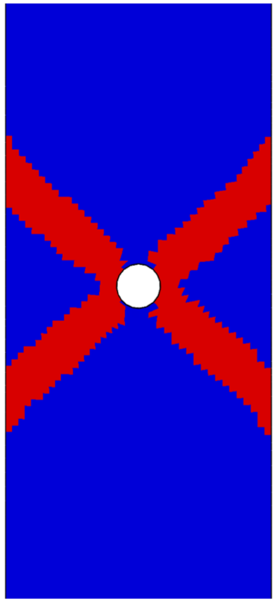




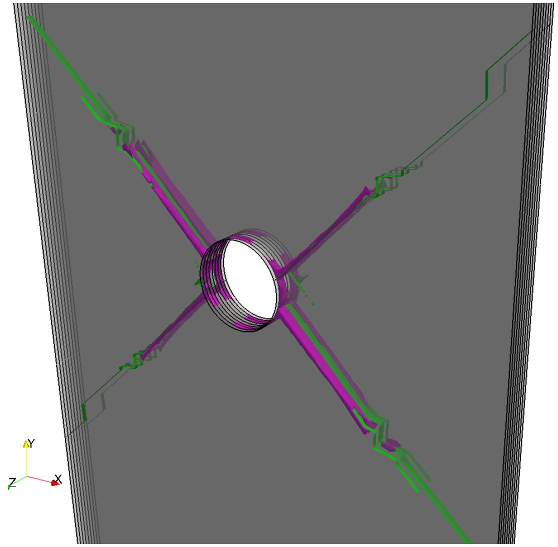
Damage Progression in Facesheets: Laminate +/-45 layup Open-Hole Tension

- **NDBILIN does not predict when failure occurs**
- **BSAM failure strain is sensitive to intralaminar shear strain energy release rate (GIIc)**





NDBILIN
Red = Failed Elements



BSAM
Green = Matrix Cracks
Purple = Delamination

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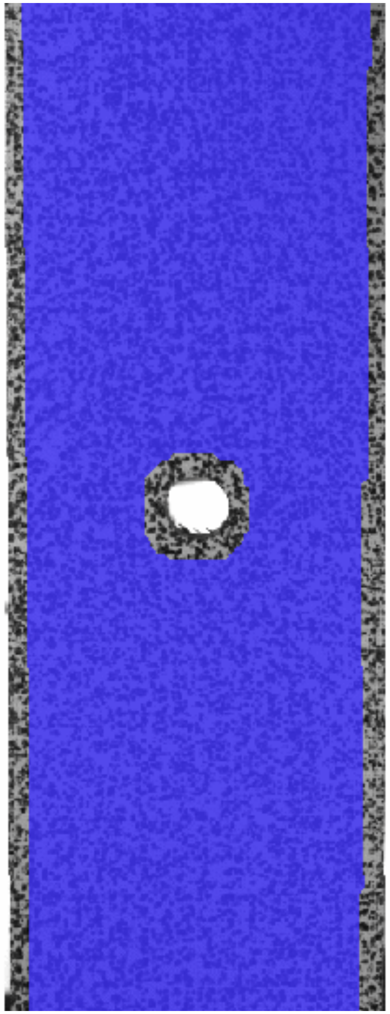
Damage Progression in Facesheets: BSAM +/-45 Open-Hole Tension



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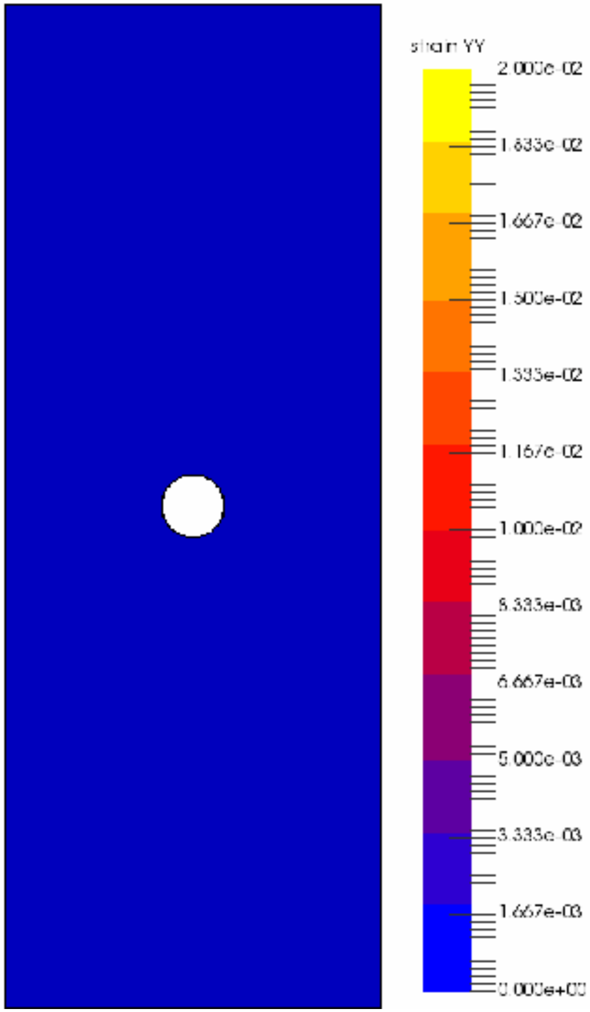
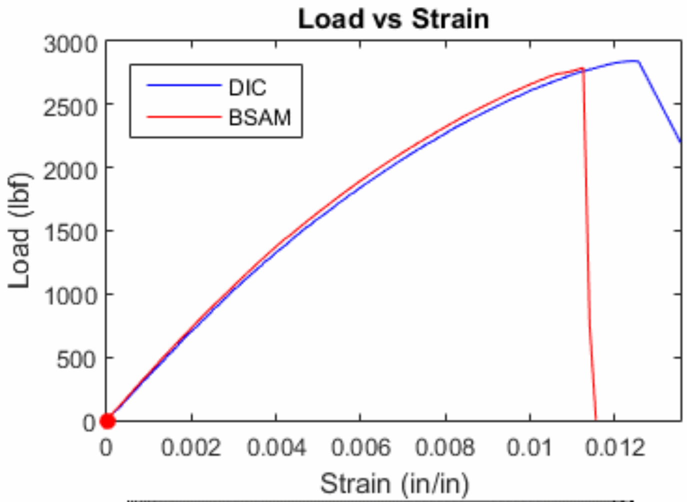
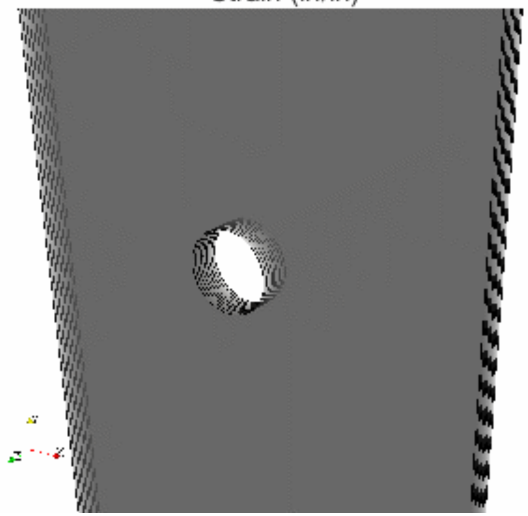


FEM





Damage Progression

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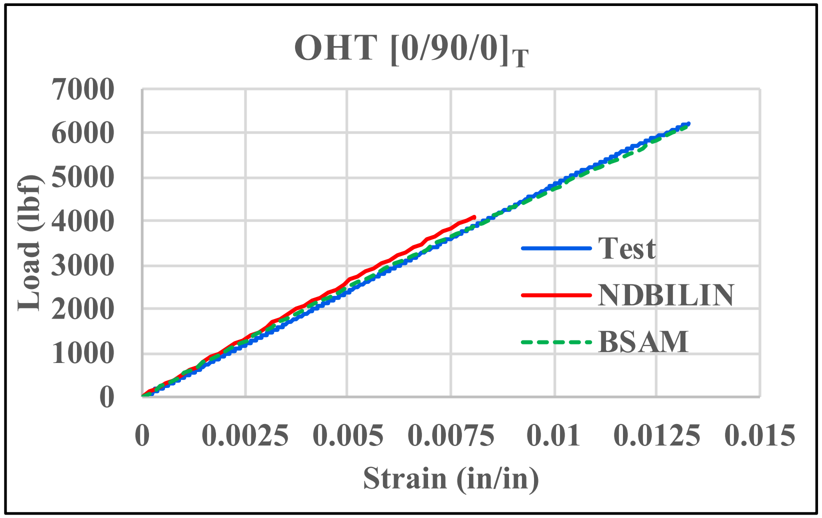
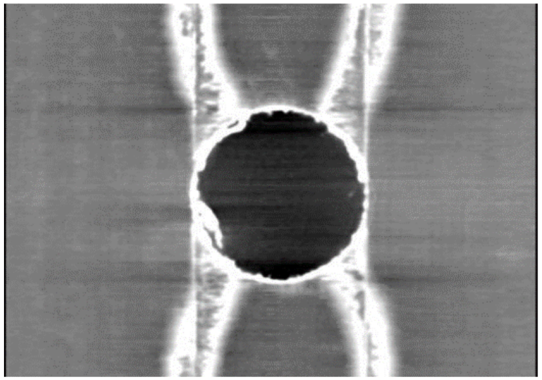
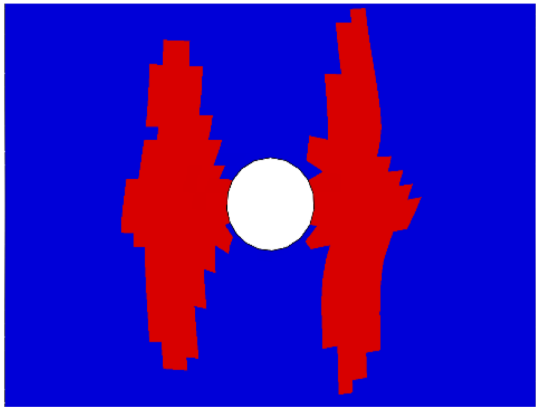
Damage Progression in Facesheets: Cross ply Open-Hole Tension

- **Facesheet layup orientation**
  - $[0/90/0]_T$
- **NDBILIN predicts notch sensitivity**
- **BSAM predicts notch insensitive (<4% difference)**
- **BSAM requires fine mesh for a close to converged solution**

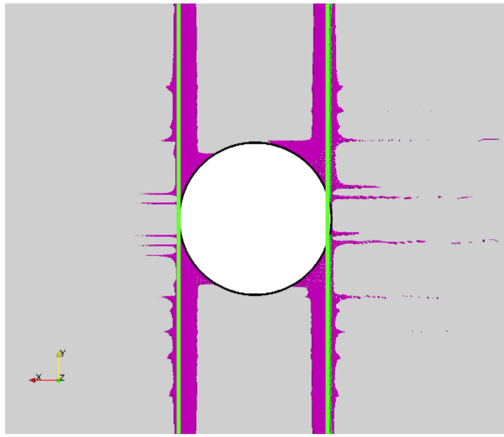




X-Ray CT



NDBILIN



BSAM

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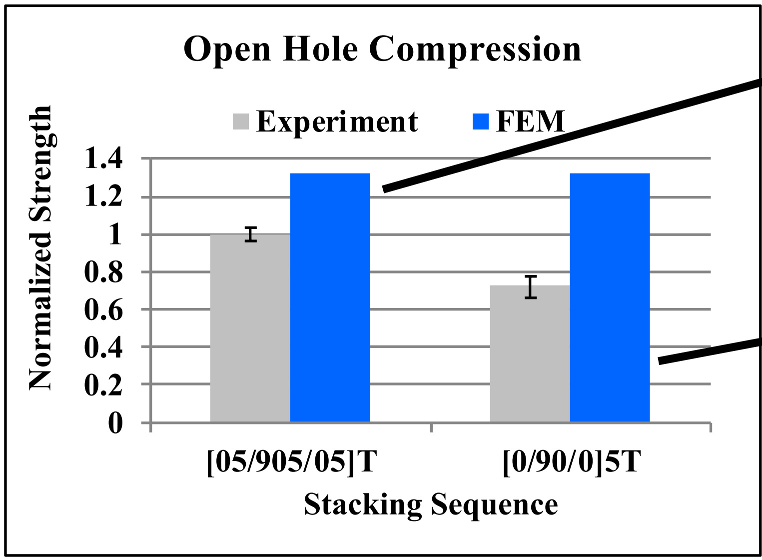
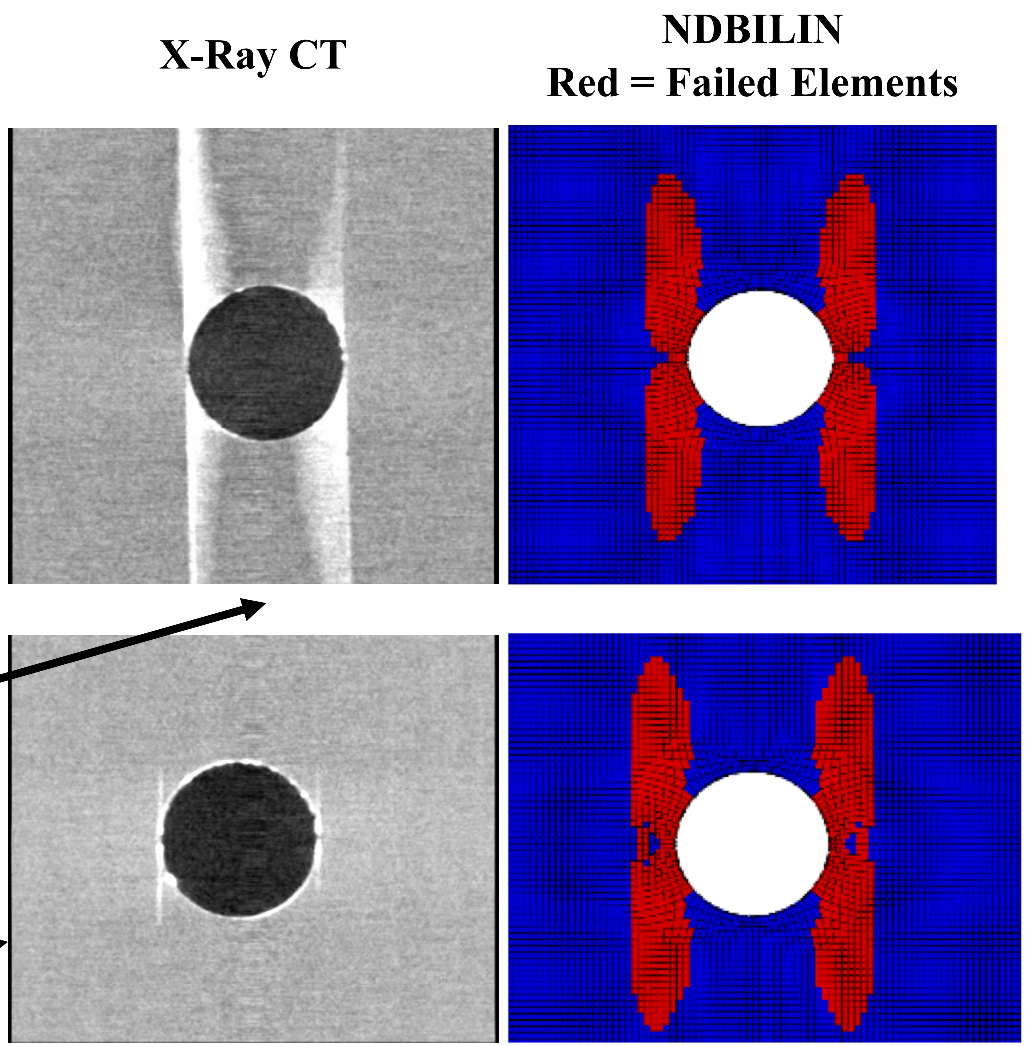
Damage Progression in Facesheets: Open-Hole Compression

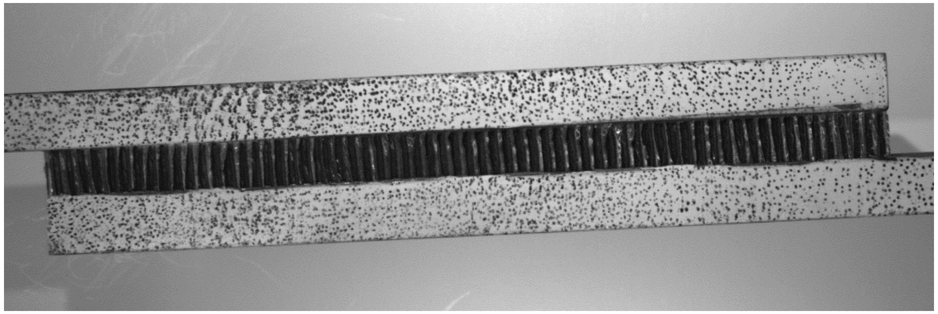
- **Scaled facesheet layup orientation**
  - $[0_5/90_5/0_5]_T$
  - $[0/90/0]_{5T}$
- **NDBILIN predicts similar damage progression and failure loads**



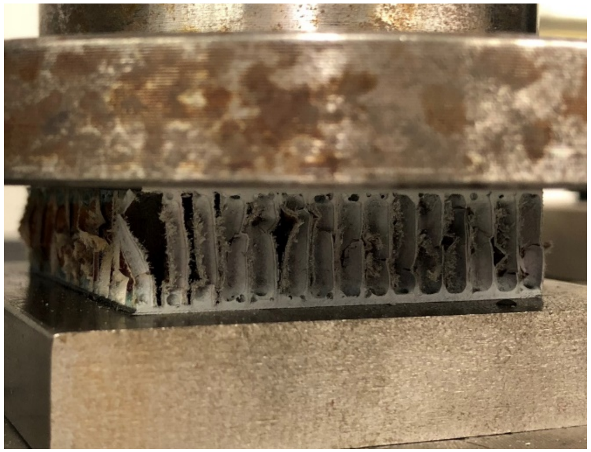


Damage Progression in Core: Flatwise Compression/Shear

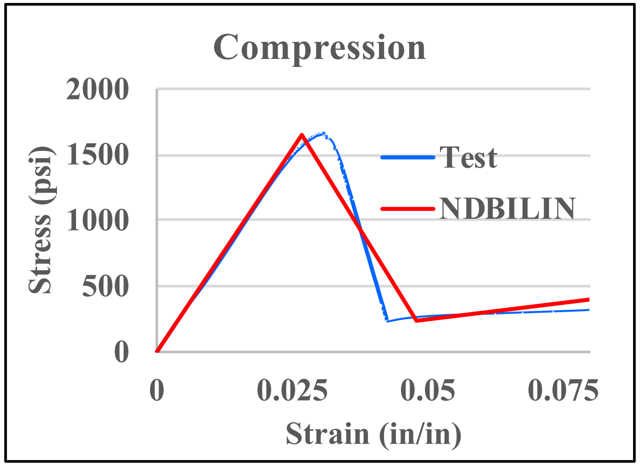
- **Honeycomb core loaded until total core collapse in both compression and shear**
- **NDBILIN parameters fit to material curves**

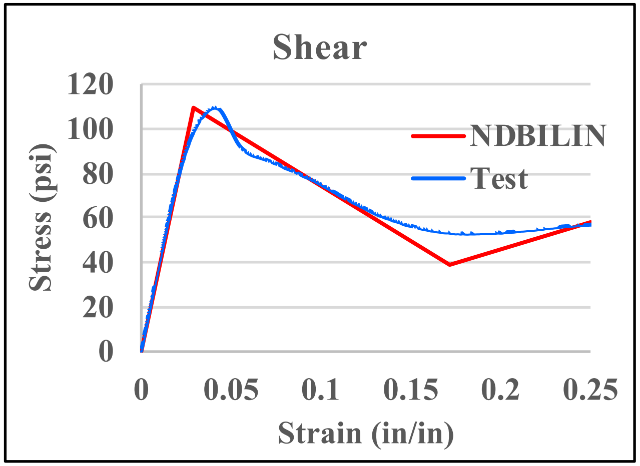


Flatwise Shear Test



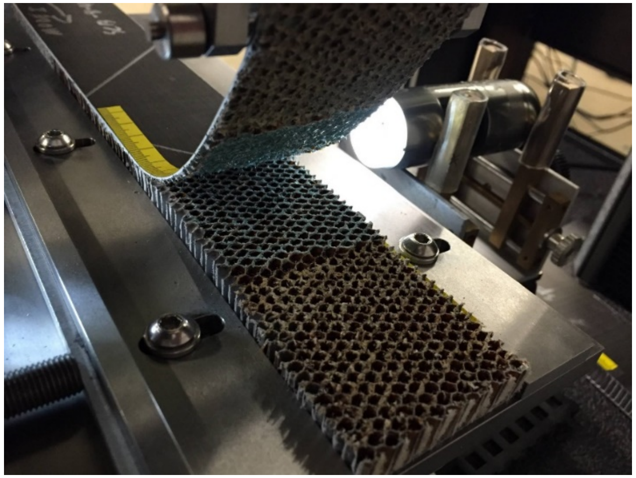
Compression Test



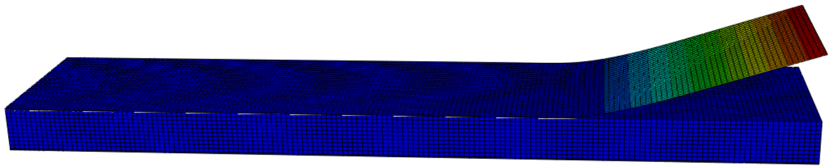


Damage Progression in Sandwich Composites: Analysis of Interfacial Disbond

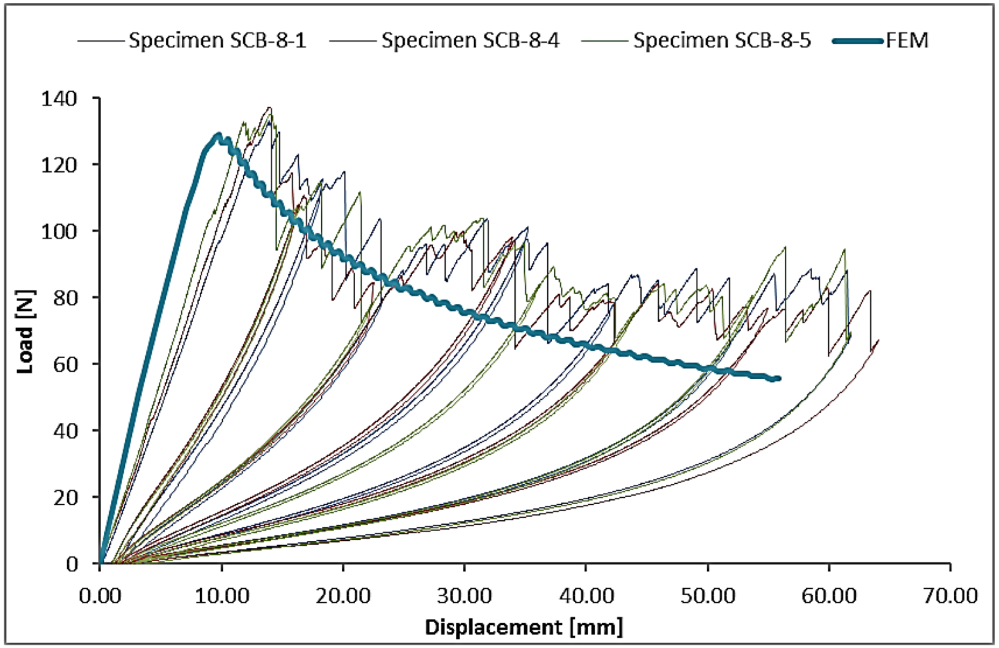
- **Calibration of interfacial cohesive zone**
  - **Mode I Sandwich SCB**



Single Cantilever Beam Test



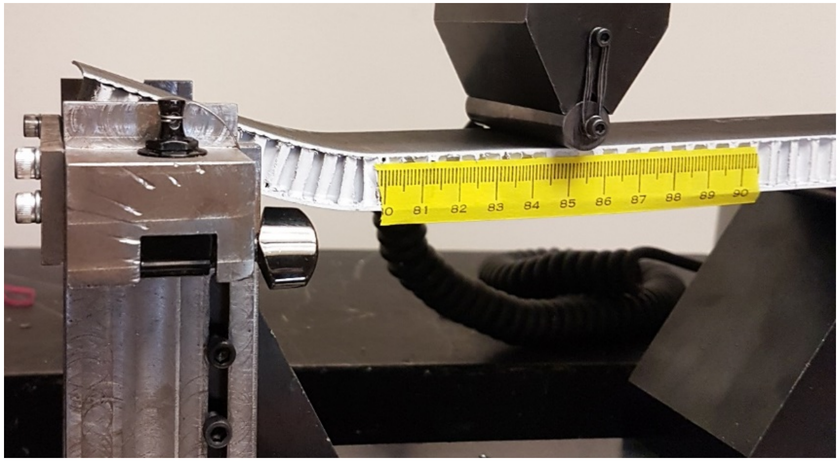
Single Cantilever Model Displacements



Load vs Displacement Data

Damage Progression in Sandwich Composites: Mode II and Mixed-Mode

- **Calibration of interfacial cohesive elements**
  - New failure mode: core cell walls buckle at crack tip, no crack growth
  - Analytical and numerical models do not account for constraint effect on honeycomb core

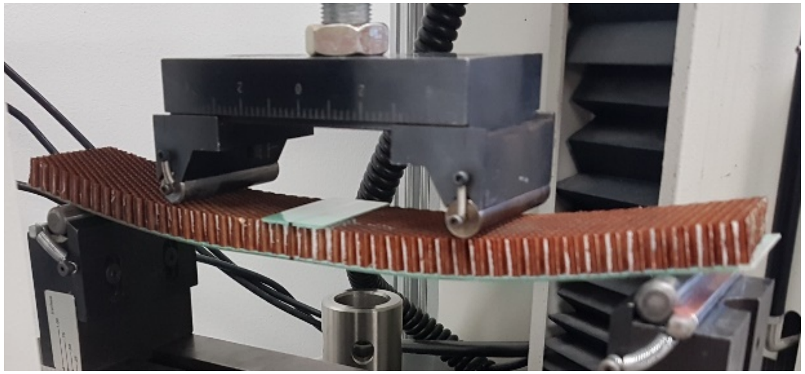


Mode II Sandwich ENF Test

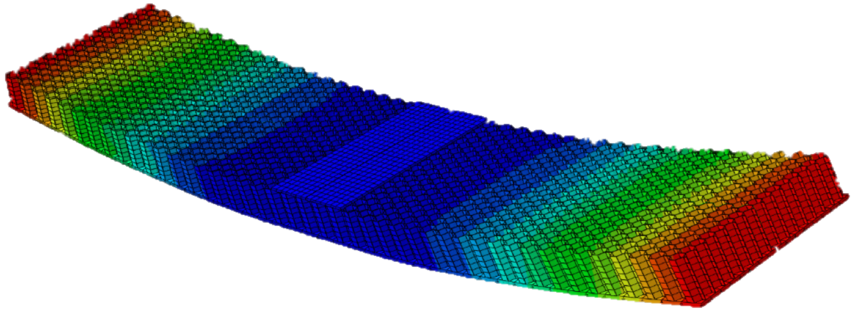
Sandwich Mixed Mode Bend Test

Core Constraint Effect:
Discrete Core Model in Flexure

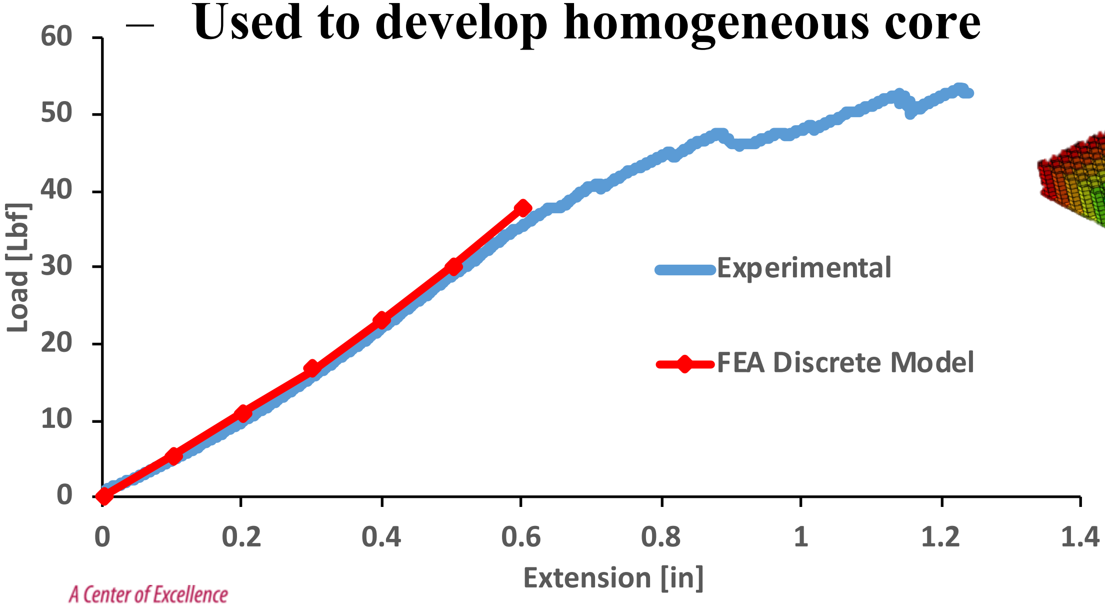
- **Open-Face Flexure**
  - Constraint effects at crack front
  - Ribbon properties calibrated with flatwise compression and shear tests
  - Captures elastic curve
  - Used to develop homogeneous core



Test



FEM



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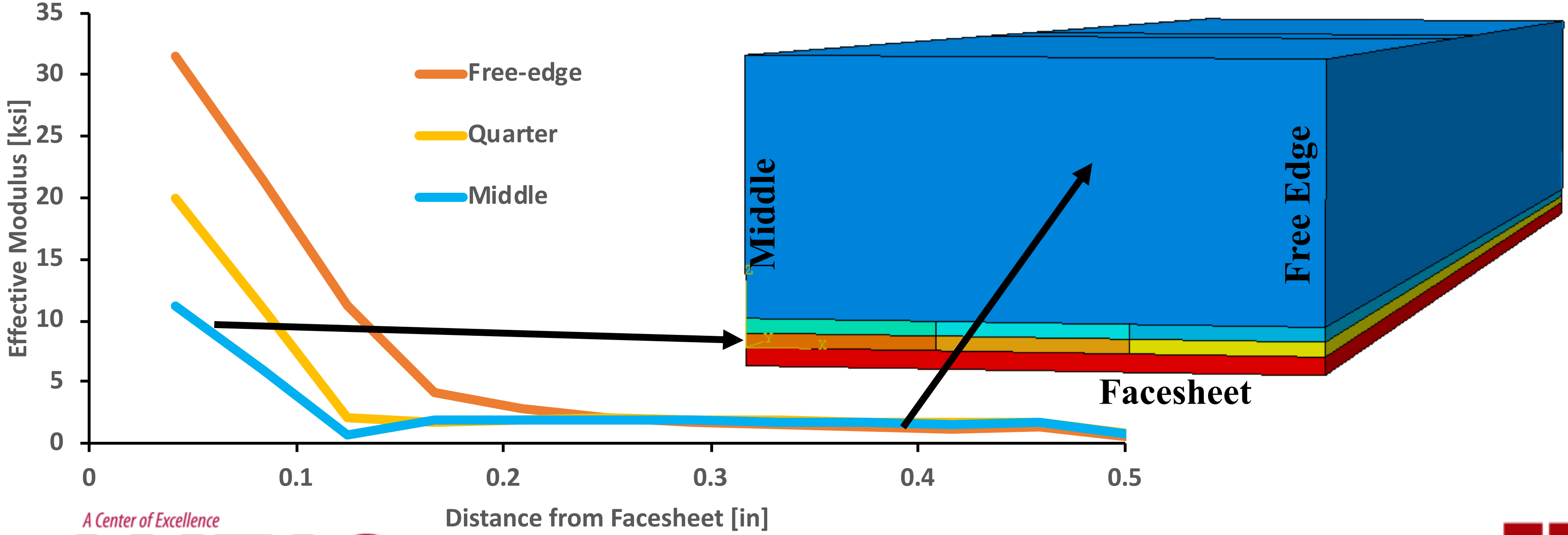
Homogeneous Core: Current Focus

- **Discretized Homogeneous Core**
  - Thickness and free-edge effects
  - Discretize and apply unique material properties and failure parameters
  - Incorporate into sandwich disbond models



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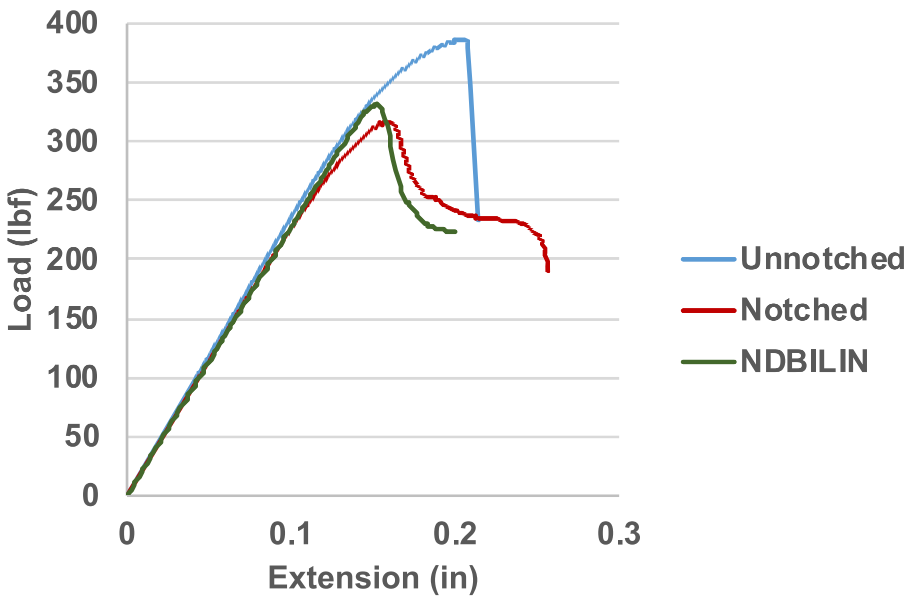
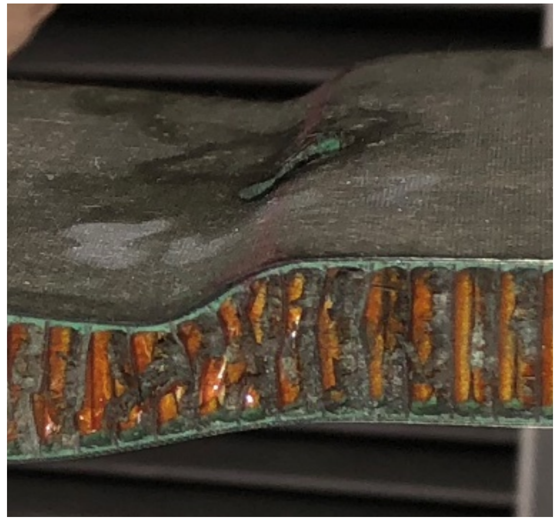
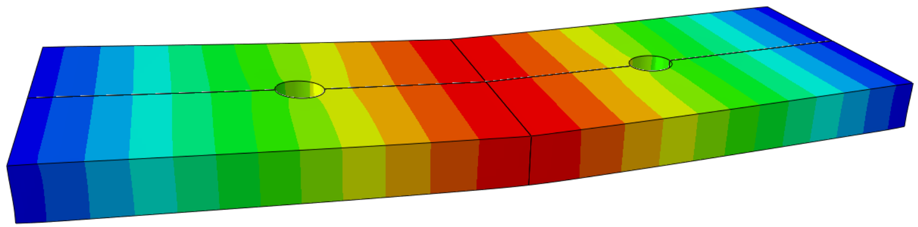
Damage Progression in Sandwich Composites: Analysis of Sandwich Open-Hole Shear Tests

- Core modeled with NDBILIN
- Slight over prediction of max load
- Reload Captured





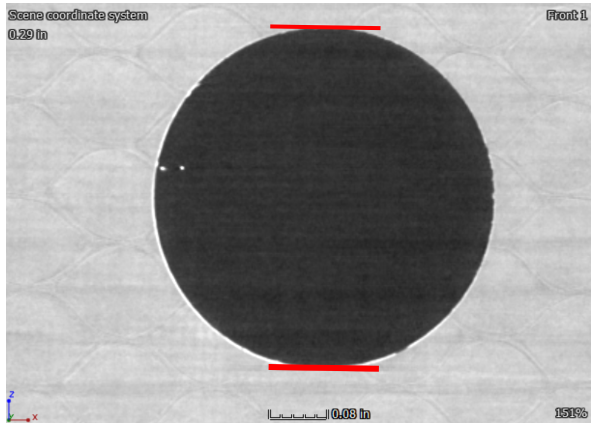
Sandwich Open-Hole Shear Failure



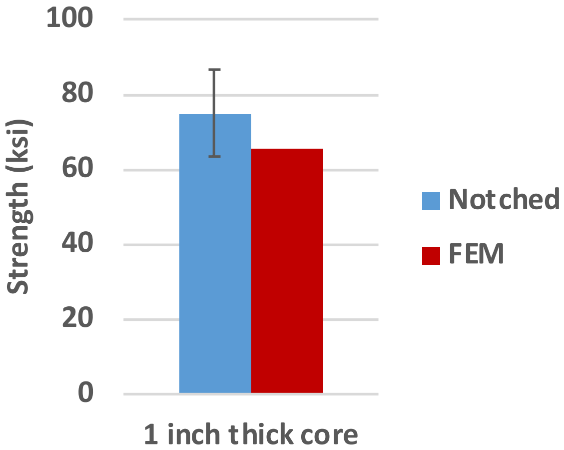
Model Displacements

Damage Progression in Sandwich Composites: Analysis of Sandwich Open-Hole Flexure Tests

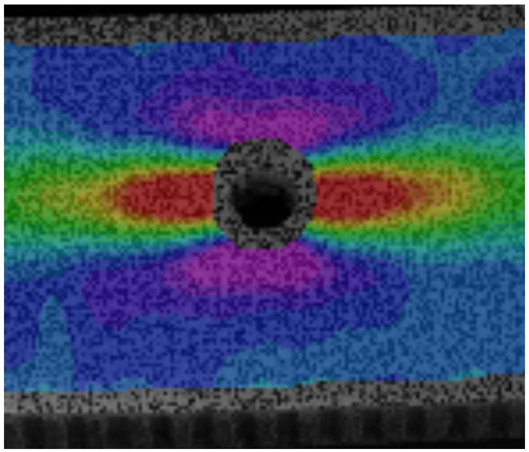
- **90% load X-ray CT shows minimal damage progression**
- **Model over predicting damage and under predicting failure load**



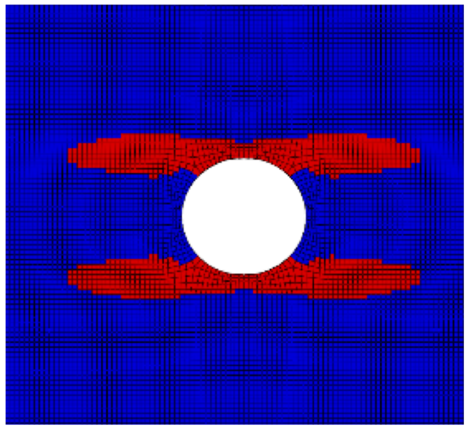
X-Ray CT
(Courtesy of Southwest Research Institute)



Compression Strength Comparison



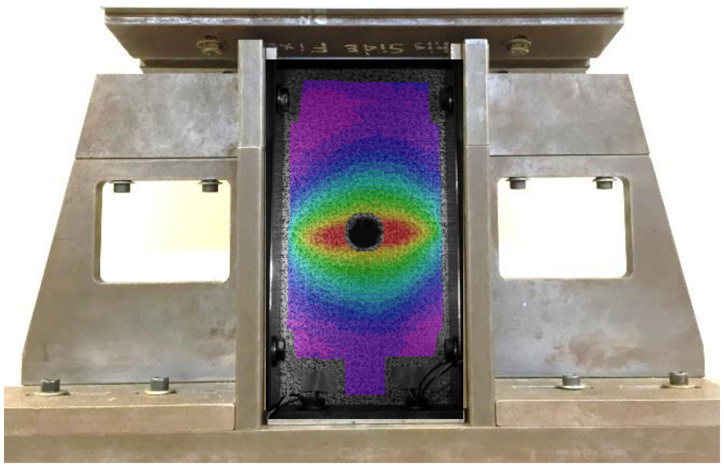
DIC Strain



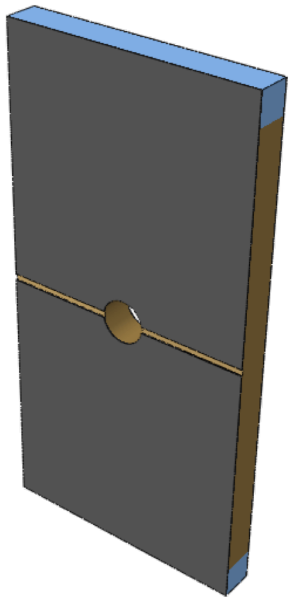
NDBILIN Damage Prediction

Damage Progression in Sandwich Composites: Analysis of Sandwich Open-Hole Compression Tests

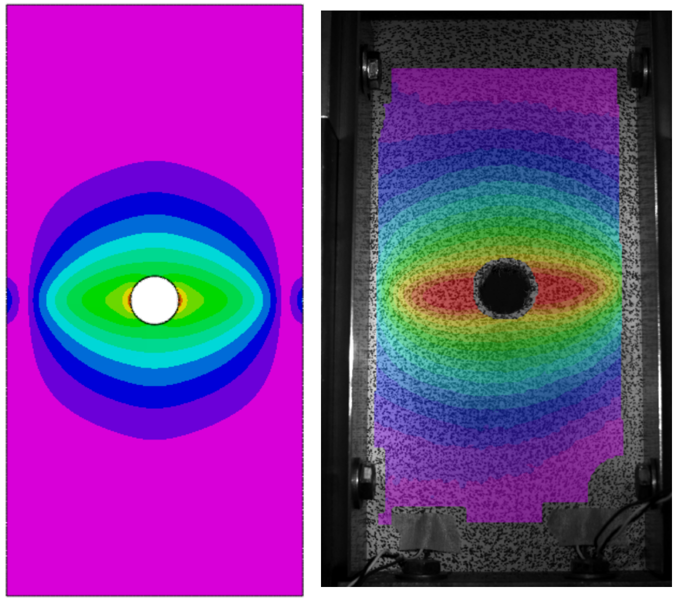
- **Out-of-plane displacements observed in DIC measurements**
- **First mode facesheet buckling observed**
- **Global buckling due to failure on Non-DIC facesheet**
- **Deformation caused by post failure eccentric loading**



SOHC out-of-plane deformation



Idealized Failure



Out-of-plane deformations

FEM DIC

Upcoming Work:
Notch Sensitivity of Composite Sandwich Structures

- **Develop sizing guidelines for proposed notch sensitivity testing methods**
- **Assess discrete damage models for remainder of calibration/validation building block approach**
- **Continue working toward homogeneous core for incorporation into Sandwich Mode II & MMB**
- **Incorporate initial damage from hole drill process on Sandwich Open-hole Compression**

Thank you for your attention!

Questions?

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