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Notch Sensitivity and Damage Tolerance of Composite Sandwich Structures

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2018 Technical Review

THE UNIVERSITY OF UTAH

FAA Sponsored Project Information

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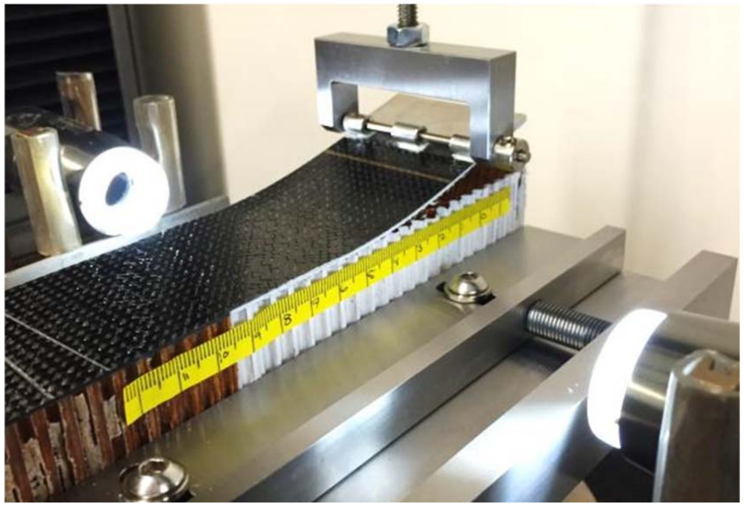
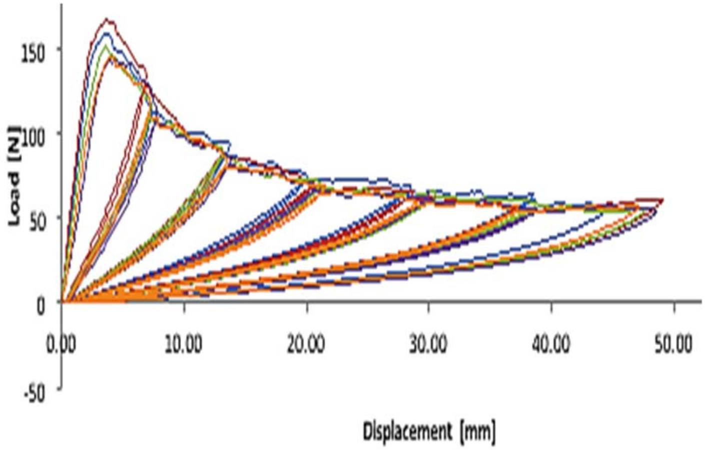
- Graduate Student Researchers:
  - **Marcus Stanfield**
  - **Brad Kuramoto**
  - **Martin Raming**
- FAA Technical Monitor:
  - **Zhi-Ming Chen**
- Primary Collaborators:
  - **Materials Sciences Corporation**
  - **Boeing (Charles Park)**
  - **ASTM D30 (Composites)**

Status Update:
Mode I Sandwich Fracture Mechanics Test Method

Standardization of Single Cantilever Beam (SCB) Test

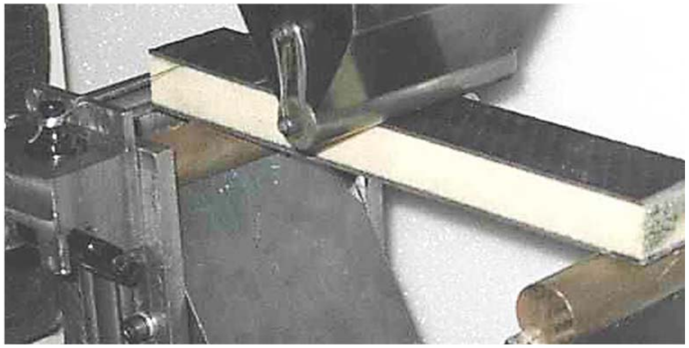
- **Second subcommittee ballot in ASTM subcommittee D30.09**
- **Negative votes discussed at recent ASTM D30 meeting and follow-on teleconference**
  - **Mode mixity: “Mode I dominant”**
  - **Acceptable disbond location: within top one-fourth of core**
- **Additional details to be included in CMH-17**
- **Concurrent D30 subcommittee & main committee ballot in June**

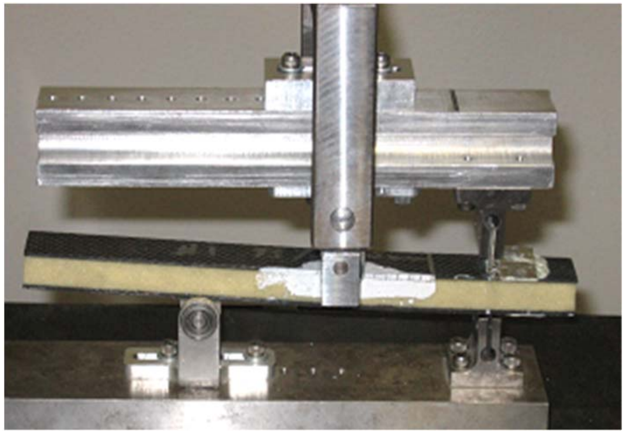




Status Update: Additional Sandwich Disbond Related Activities

- SCB fatigue test method development
- Further Mixed-Mode & Mode II sandwich disbond test method development
- Follow-on U.S. led building block exercise
  - Core, facesheet, and film adhesives obtained
  - Follow-on coupon and sub-element level testing
  - Analysis round-robin
- New content for upcoming revision of CMH-17 Handbook





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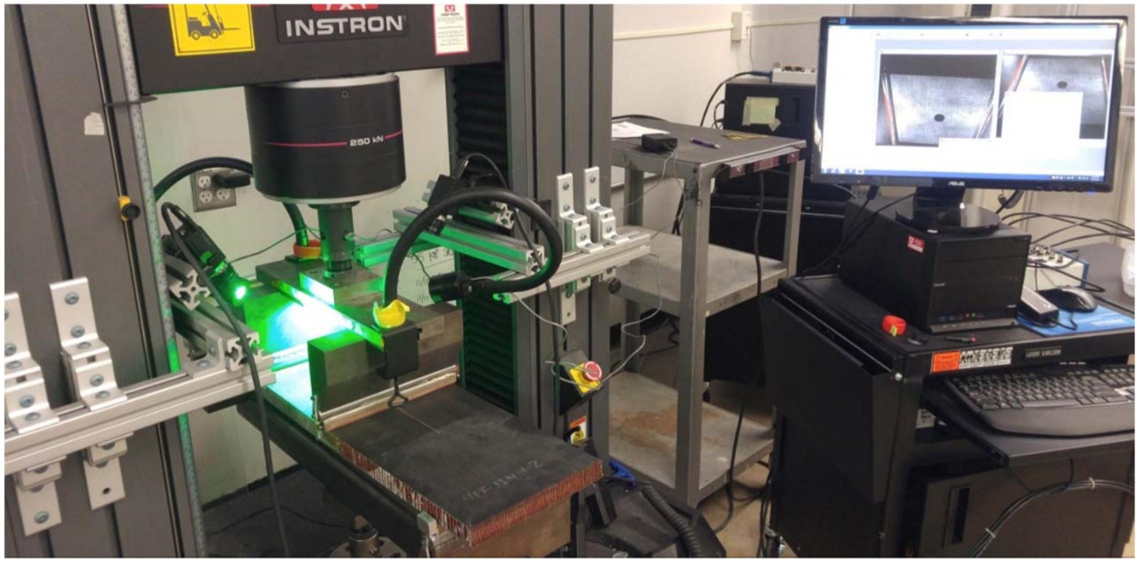
Status Update:
Sandwich Damage Tolerance

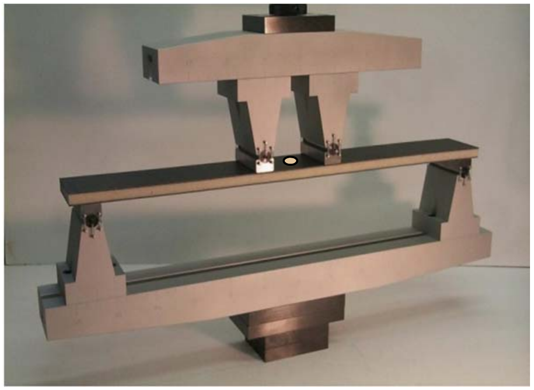
- **Draft standard of Sandwich composite Compression After Impact (SCAI) completed**
  - **Balloted Spring 2018 ASTM D30 meeting**
  - **Updates to address negative votes in work**
- **Draft practice of 4-Point Flexure After Impact (4-FAI) in progress**



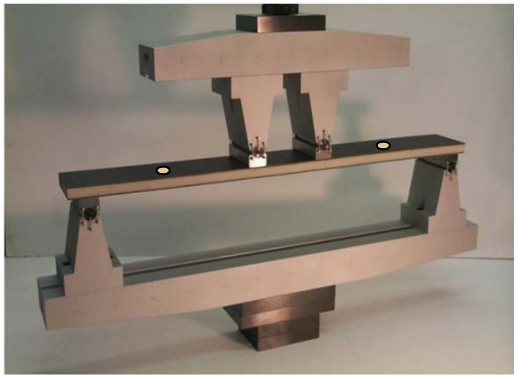
Research Objectives:
Notch Sensitivity of Sandwich Composites

- **Initial development of notched test methods & associated analysis methodologies for composite sandwich panels**
- **Documentation of 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



Notched Core Shear Beam Flexure

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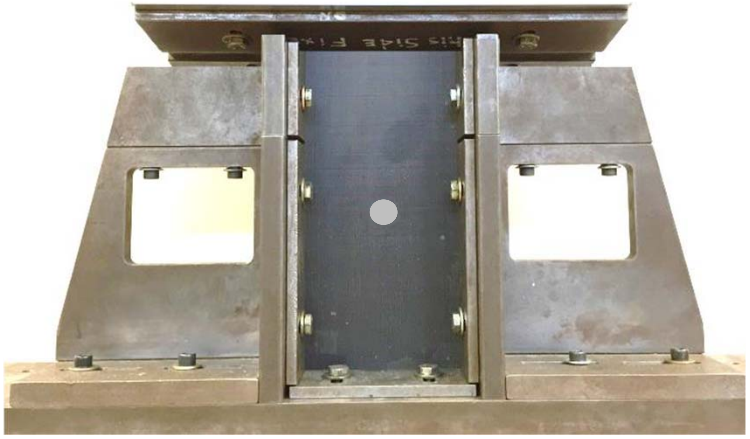
Testing Considerations: Sandwich Open-Hole Compression

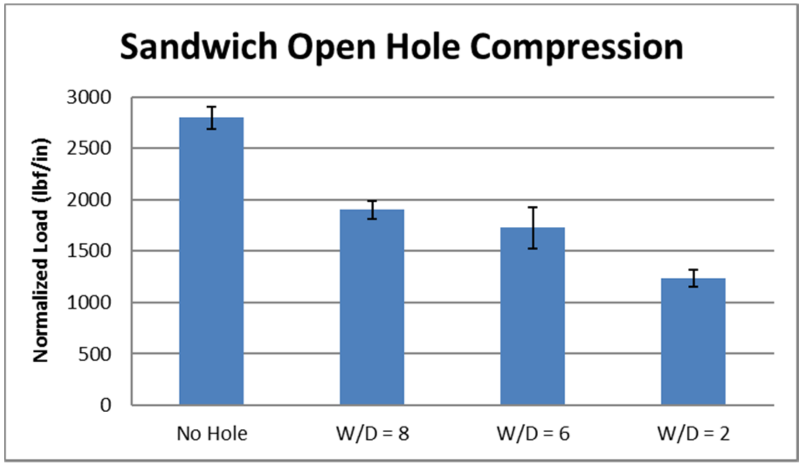
- Test fixture/Specimen support
  - End supports
    - Clamping top and bottom
    - Potting
  - Side supports
    - Knife edge
- Specimen size
  - Separation of central hole and boundary effects
  - Production of acceptable strength reductions
- Strain measurement
- Specimen alignment

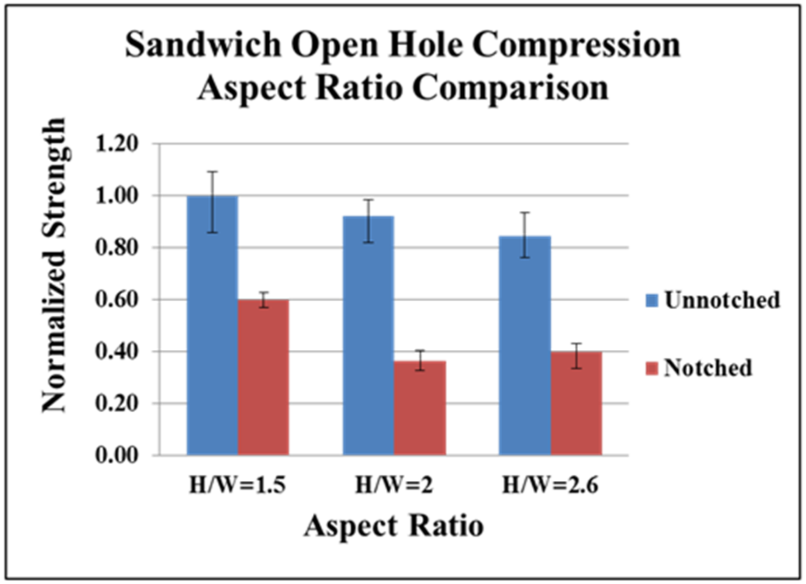


Open hole compression fixture for monolithic composites

Sandwich Open-Hole Compression: Determination of Sizing Guidelines

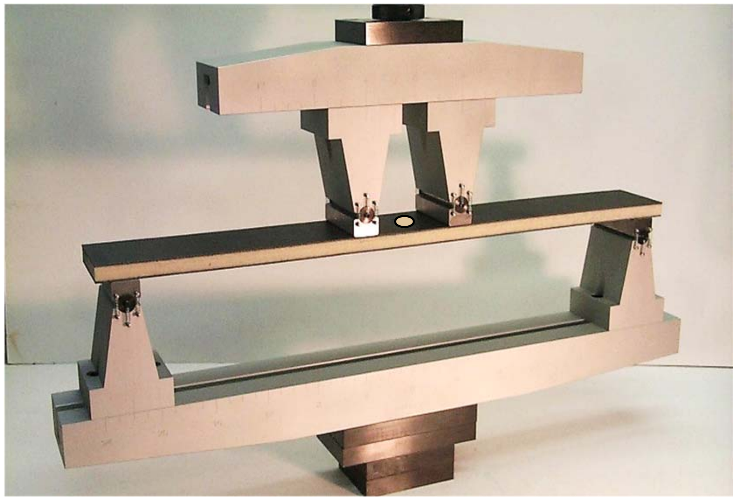
- **Hole diameter (W/D)**
  - **Legacy: W/D = 6**
  - **Acceptable strength reduction**
  - **Minimal finite width effects**
- **Aspect ratio (H/W)**
  - **H/W = 2**
  - **Acceptable strength reduction**
- **Standard configuration**
  - **Width: 4 in.**
  - **Height: 8 in.**
  - **Hole Diameter: 0.67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

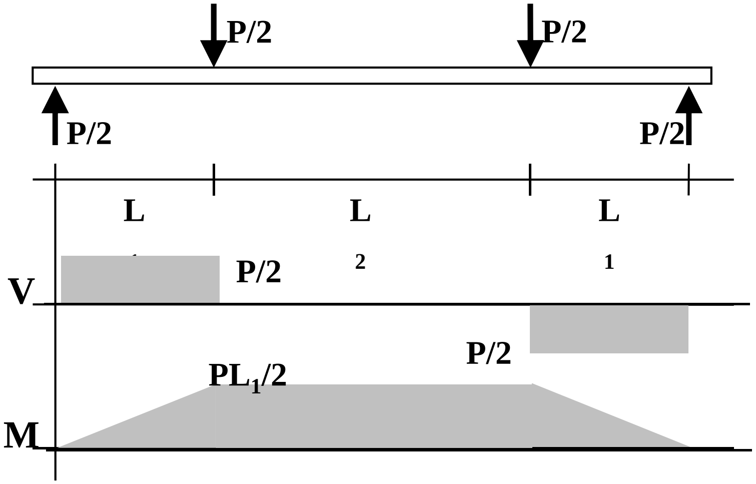




Testing Considerations: Sandwich Open-Hole Flexure Test

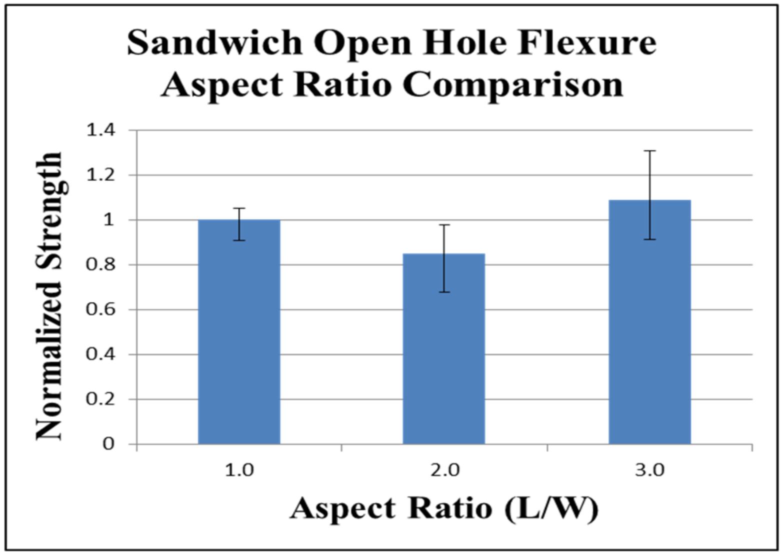
- **Test fixture/Specimen support**
  - Inner span
    - Separation of notch and loading boundary effects
  - Outer span
    - Develop sufficient bending moment
    - Ensure failure in inner span
- **Required specimen width**
  - Separation of central hole and specimen edges
  - Production of acceptable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

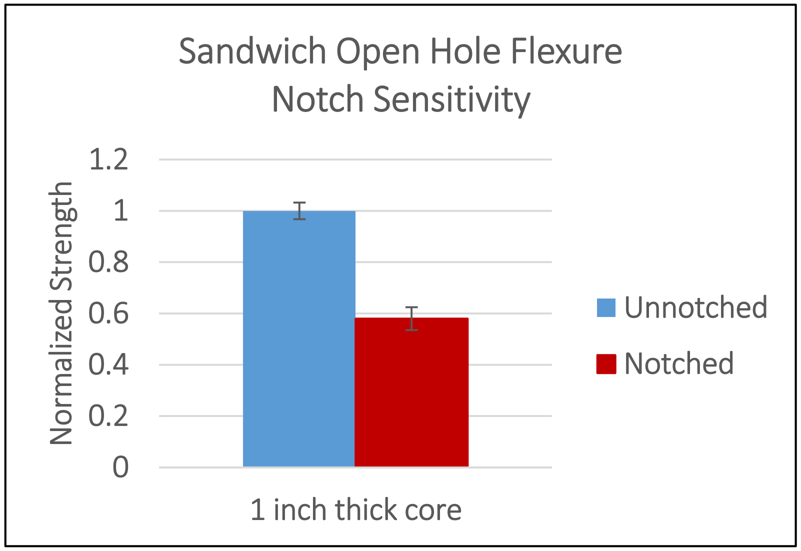




Sandwich Open-Hole Flexure Test: Determination of Sizing Guidelines

- **Current 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





Third Loading Configuration: Core Damage and Notch Effects

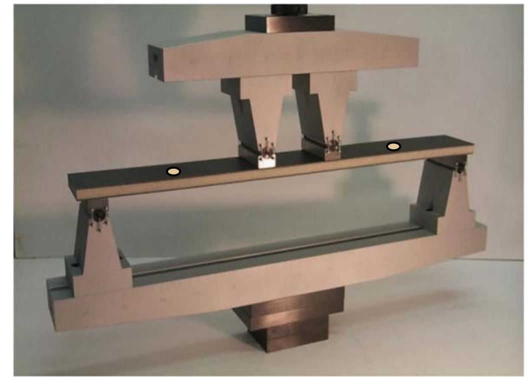
- **Effects of core notch or core damaged on material response**
  - **Notched core shear**
    - **Circular centered thru holes**
    - **Beam flexure**
  - **Sandwich disbond after core crush**
    - **Quasi-static indentation**
    - **Multiple crush geometries**
    - **SCB Mode I fracture testing**

Notched Core Shear by Beam Flexure

Disbond after Core Crush

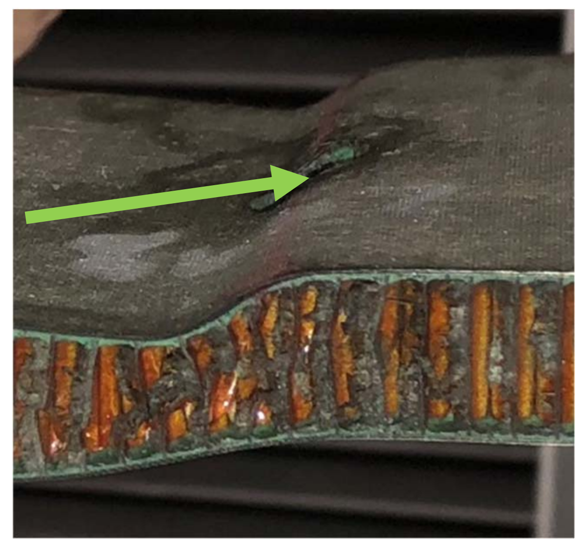
Testing Considerations:
Notched Core Shear by Beam Flexure

- Investigating notch effects in Nomex honeycomb core
- Three-point flexure loading
- Sandwich configurations:
  - W = 3 in. L = 8 in. C = 0.5 in.
  - 3 pcf 1/8 in. cell Nomex
  - Notched & Unnotched
- Through hole, 0.5 in. dia (W/D=6)
- Sized to ensure core shear failure (ASTM C393)
- L and W core directions tested



Notched Core Shear Beam Flexure

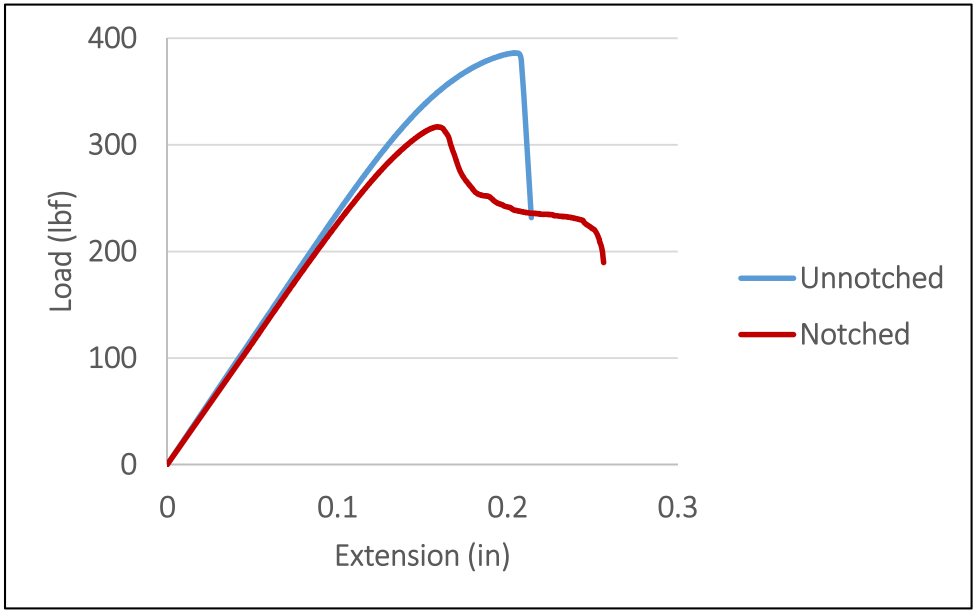
Notch

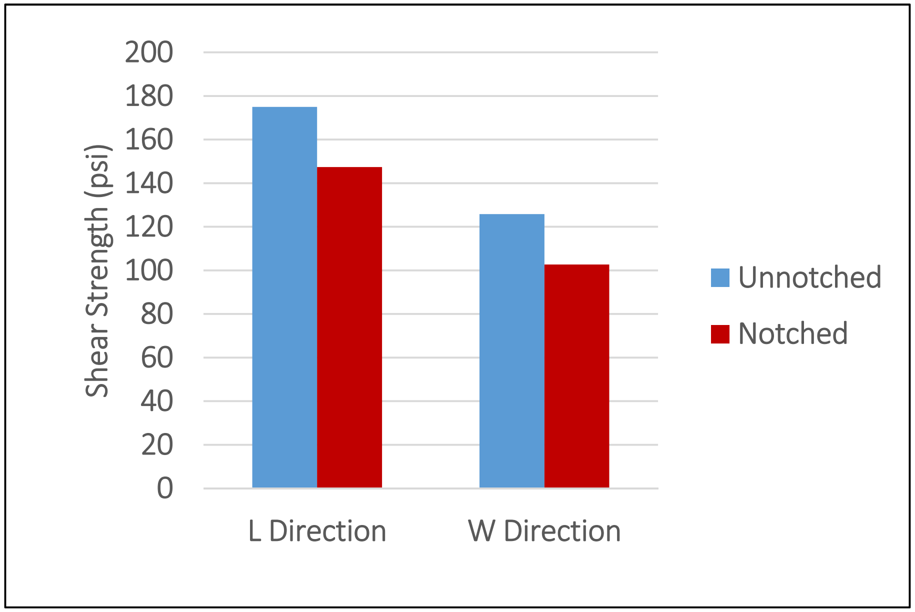


Current Focus:
Notched Core Shear Results

- **Similar behavior between L and W core orientations**
- **Net section shear failure**
- **No significant notch effect observed**

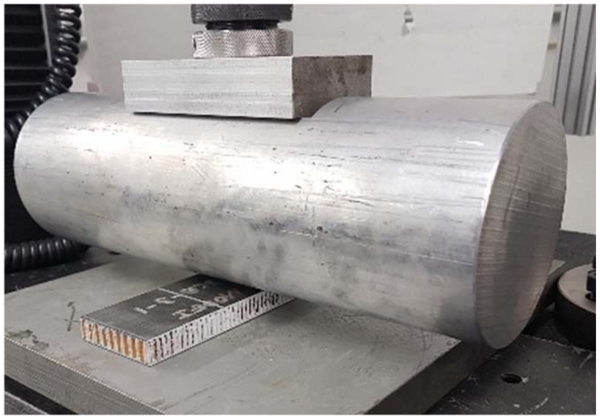
Direction	L	W
Notched Shear Strength Ratio	0.84	0.82
Notched Area Ratio (W-D)/W	0.83	

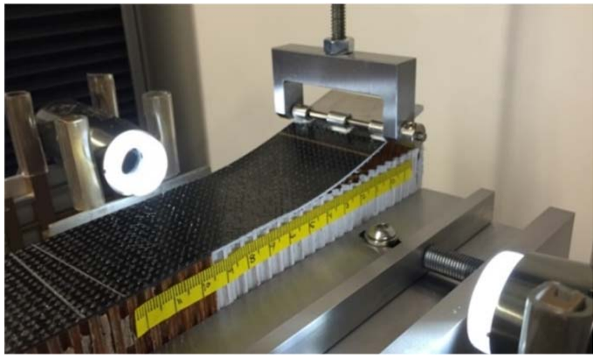




Testing Considerations:
Disbond After Indentation

- **Quasi-static indentation**
  - Minimize facesheet damage
  - Produce region of crushed core
- **Indenter geometries**
  - Flat plate (uniform crush)
  - Wedge (tapered crush)
  - Cylinder (discreet crush region)
- **Mode I facesheet disbond testing following indentation**
  - Single Cantilever Beam (SCB) test
  - Fracture toughness reductions due to core crush
  - Thru-thickness failure locations and fracture surfaces





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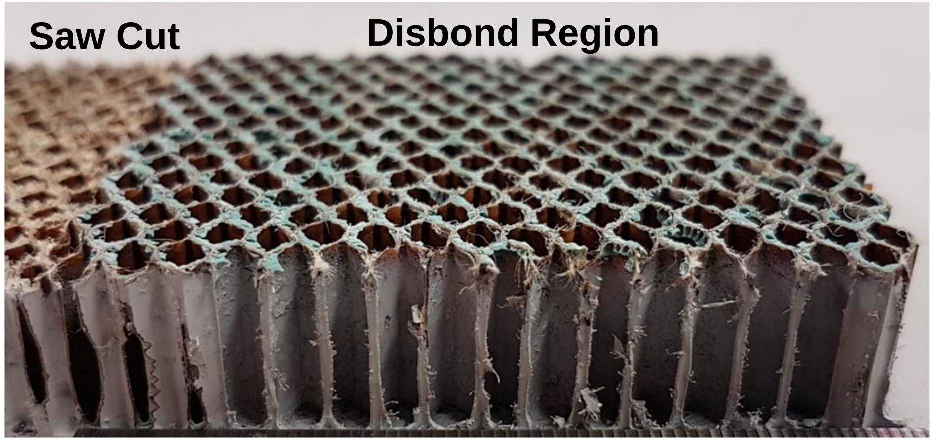
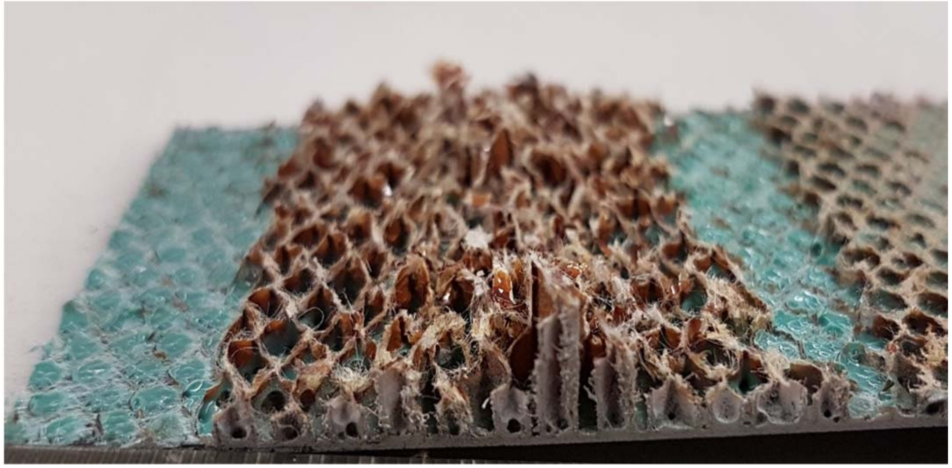
Disbond After Indentation Testing:
Fracture Path Through Core Crush Region

- **Fracture at core/facesheet interface for undamaged core**
- **Fracture propagates along crushed core boundary in region of indentation**

Undamaged 8 pcf Nomex core



Indentation Region, 8 pcf Nomex core



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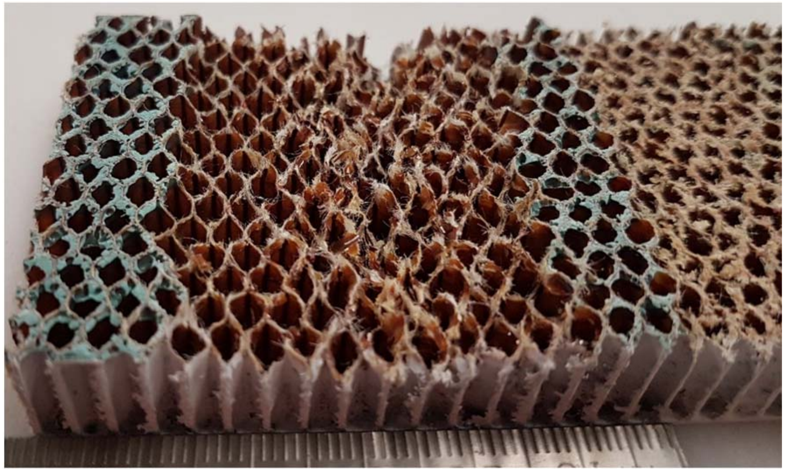
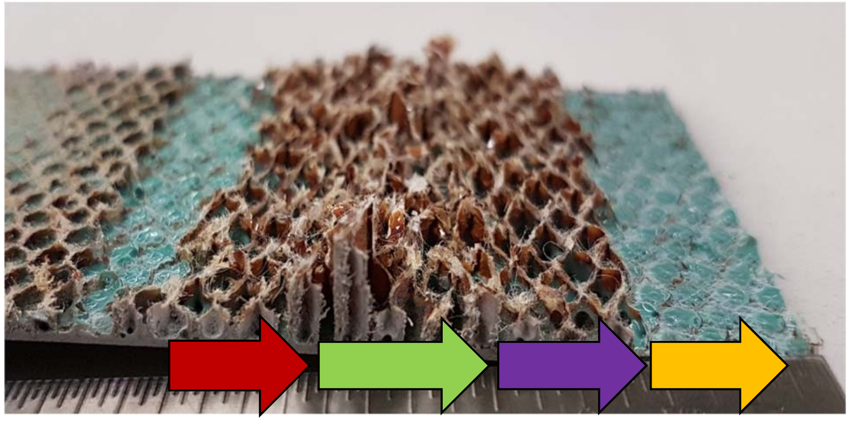
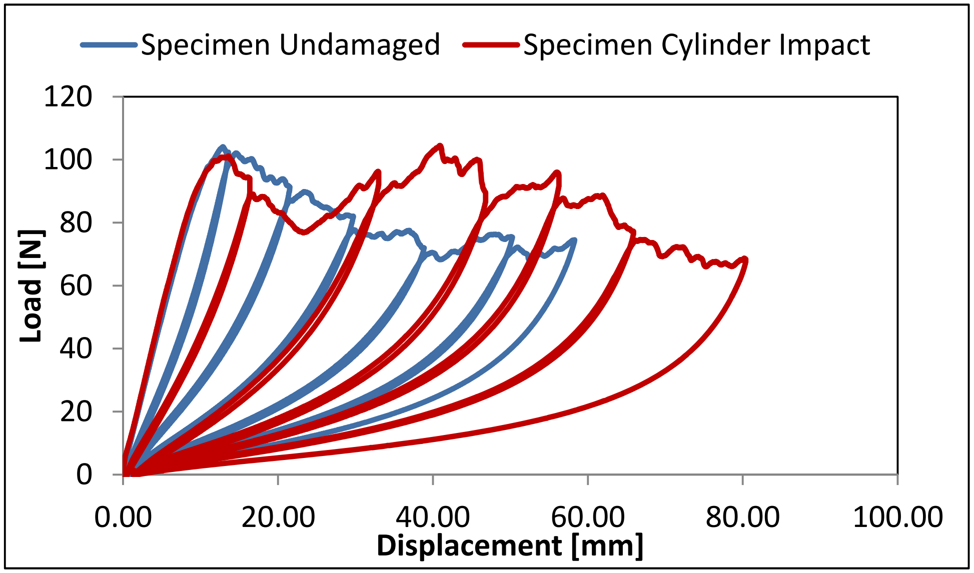


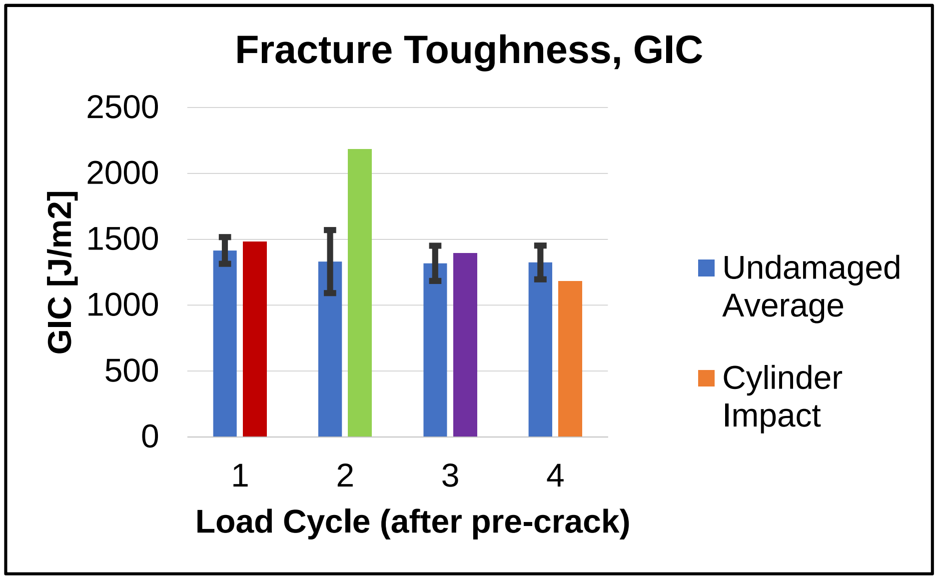
Bottom

Initial Test Results: Disbond After Indentation Testing

- **Increased fracture toughness in regions of crushed core**
- **Highest G_{IC} obtained in central region of core crushing**
- **Further testing underway**

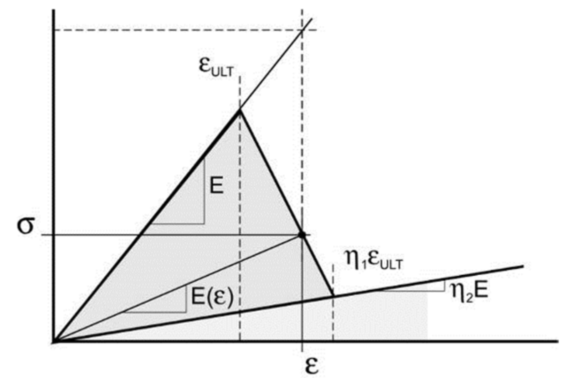


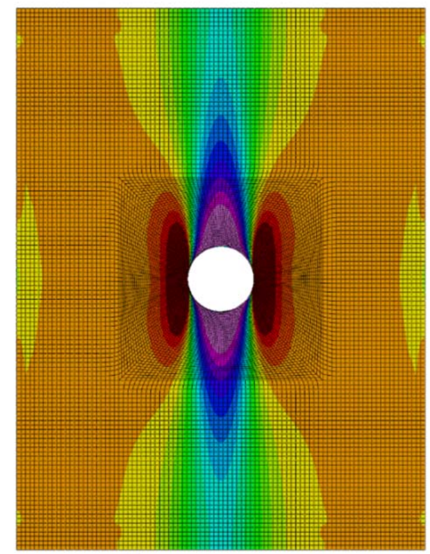




Analysis of Notched Sandwich Specimens
ABAQUS with NDBILIN:

- 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

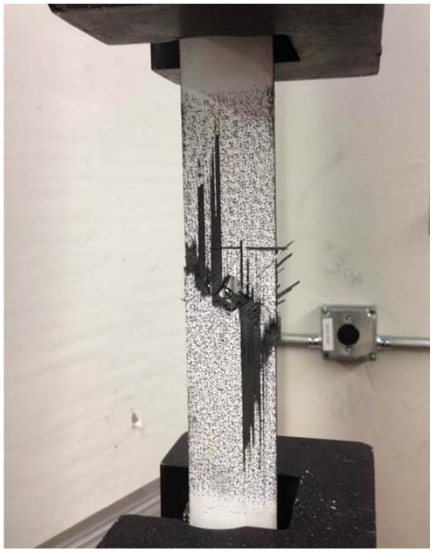


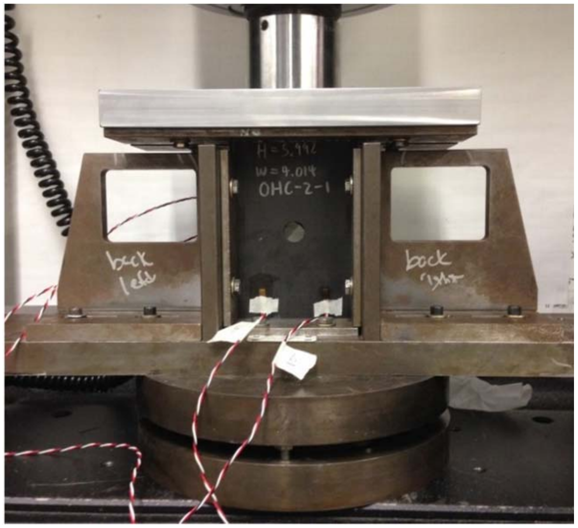


Materials Sciences Corporation

Analysis of Notched Sandwich Specimens
Validation of Modeling Approach

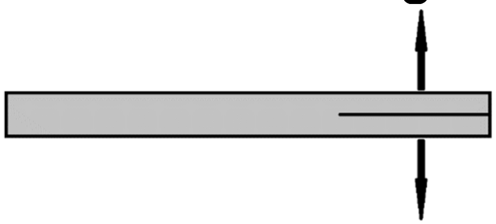
- **Modeling of damage progression in facesheets**
  - **Interlaminar disbond (Mode I and II)**
    - **Cohesive Surfaces**
  - **Laminate tension (+/-45 layup)**
  - **Open-hole tension test**
  - **Open-hole compression test**
- **Modeling of damage progression in sandwich composites**
  - **Sandwich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

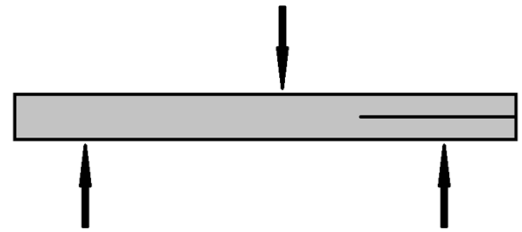


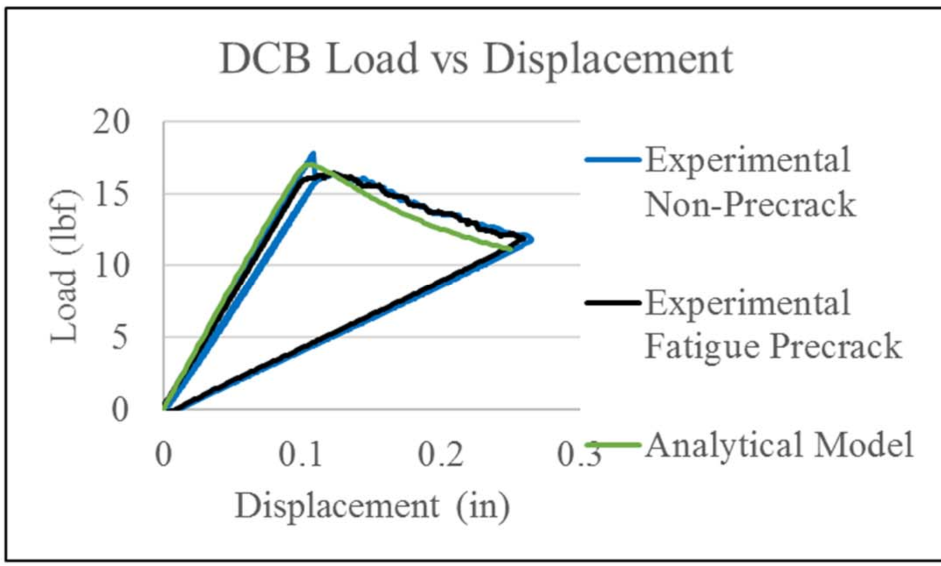


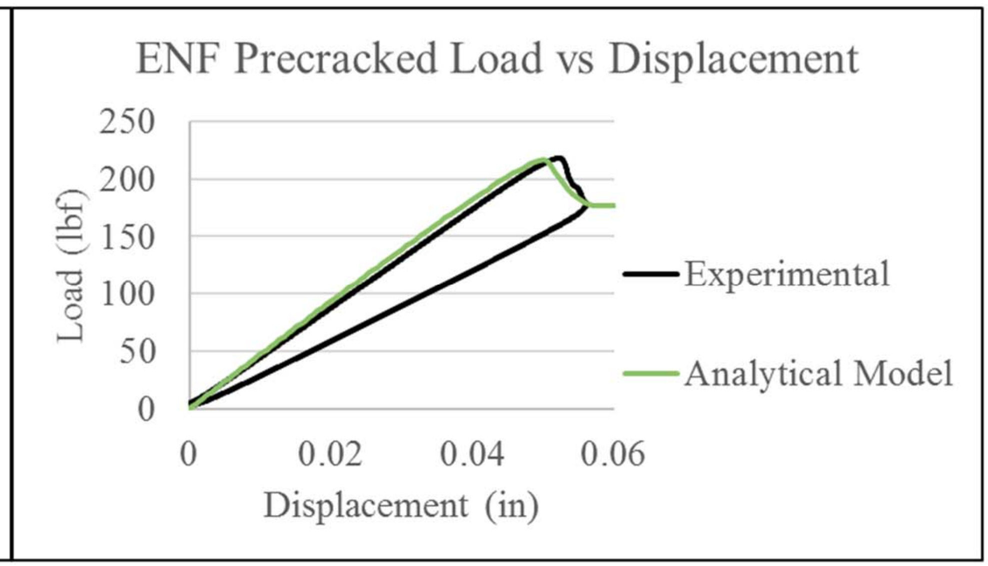
Damage Progression in Facesheets: Interlaminar Disbond

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



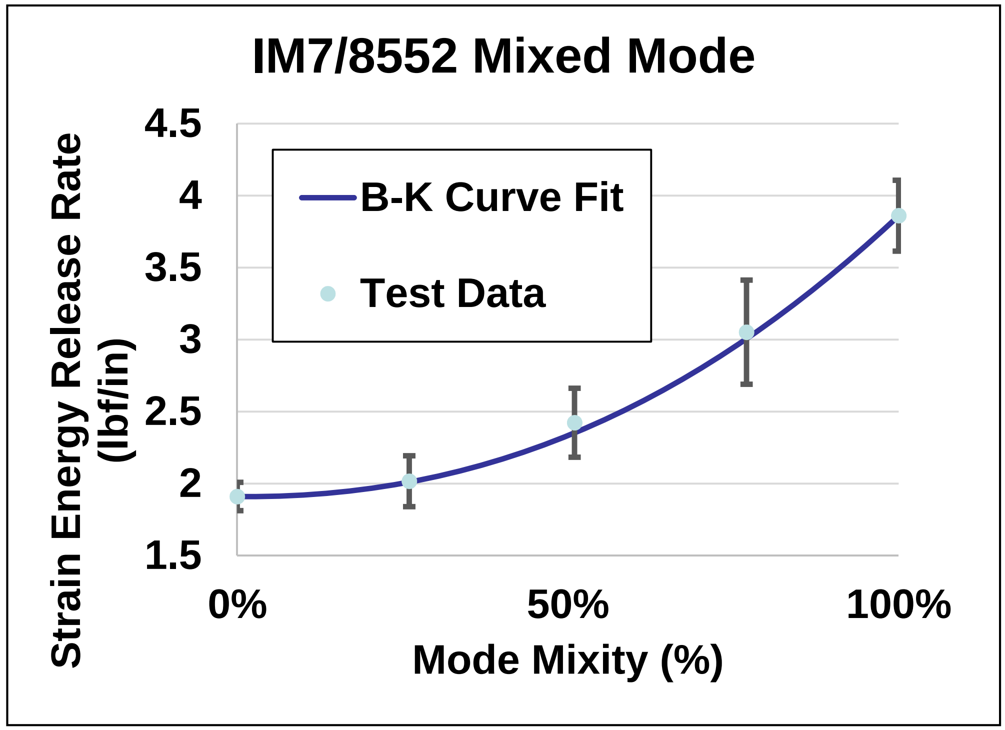






Damage Progression in Facesheets: Mixed-Mode Interlaminar Disbond

- **Calibration of interlaminar cohesive surfaces**
  - Mixed-Mode Bend (MMB) using ASTM D6671
  - Fit using Benzeggagh-Kenane (B-K) criterion

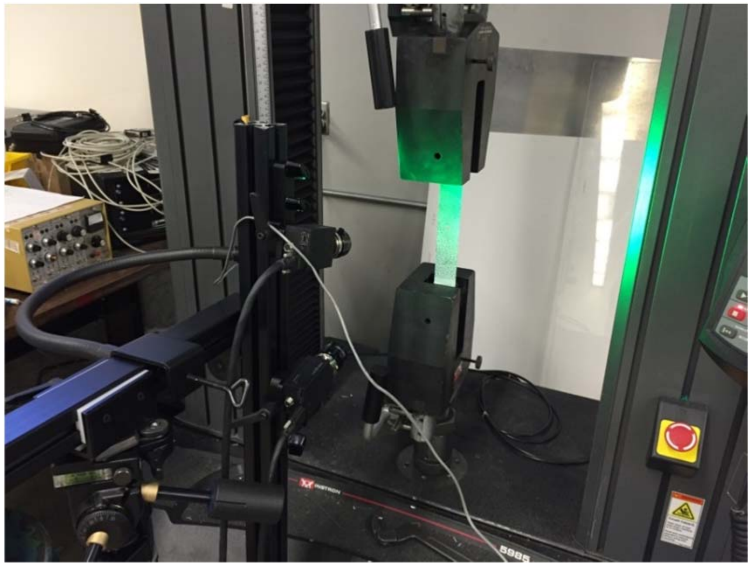


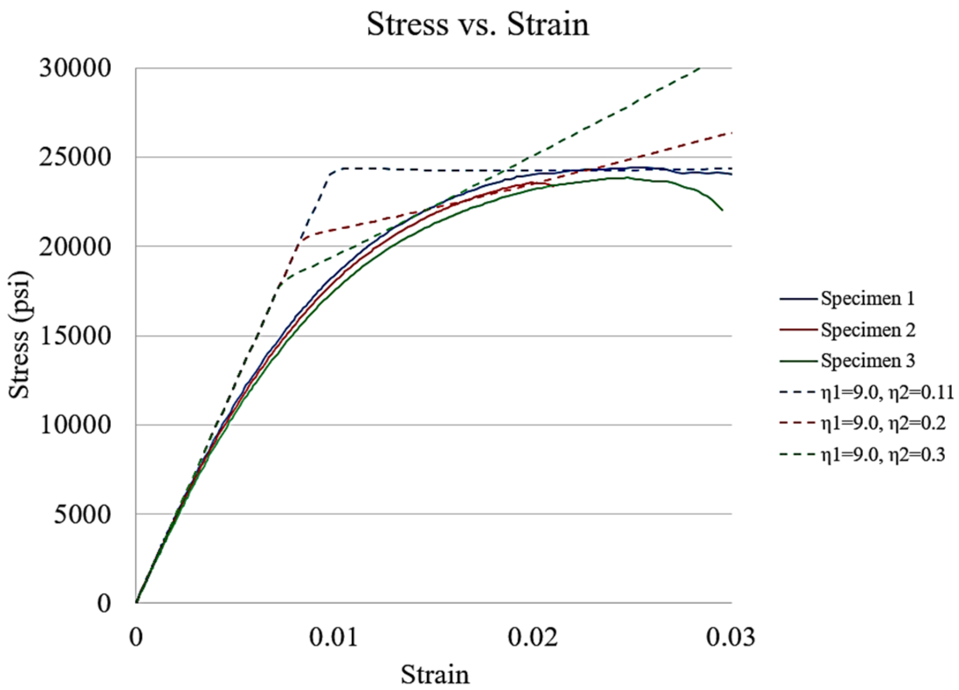
Damage Progression in Facesheets: Analysis of +/-45 Laminates

- **Simulation of tension testing of IM7/8552 carbon/epoxy laminates**

  $[45/-45]_{2S}$

- **NDBILIN matrix shear strength and damage parameters were modified to model test behavior**

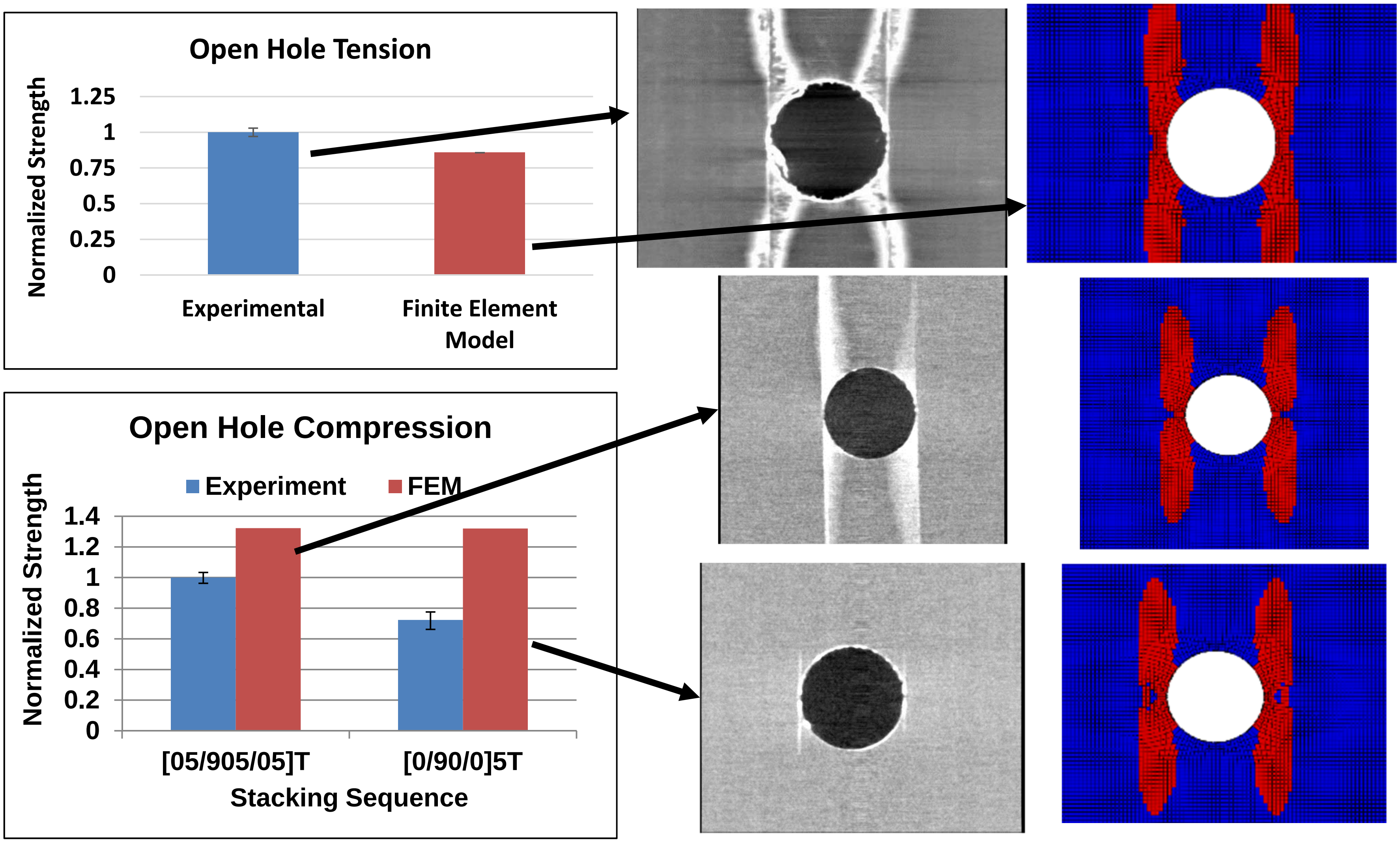




- **Infinite potential solutions exist**

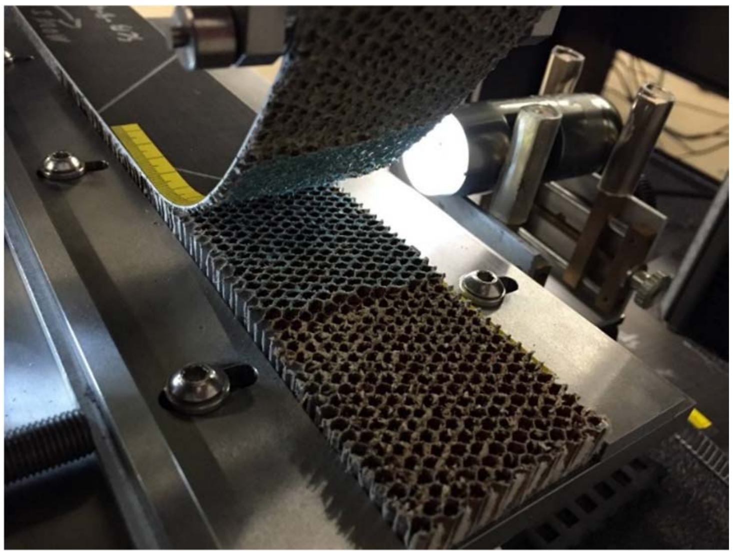
Current Focus:
Damage Progression in Facesheets

- **Revisit open hole results with updated cohesive surface parameters and matrix damage parameters**

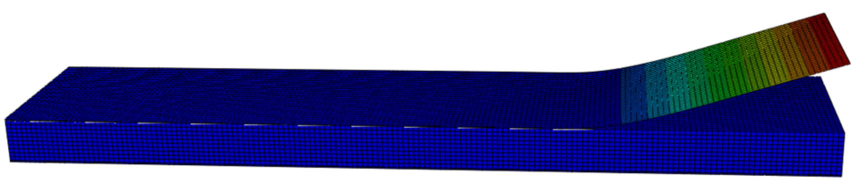


Damage Progression in Sandwich Composites: Interface Disbond

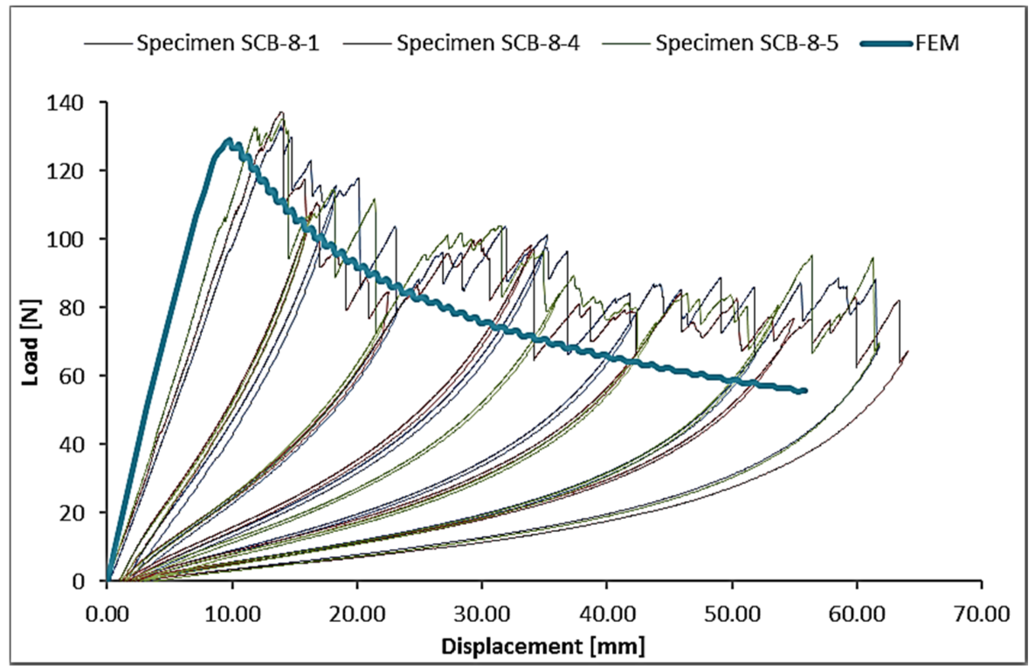
- **Calibration of interfacial cohesive elements**
  - **Mode I Sandwich SCB**



Single Cantilever Beam Test



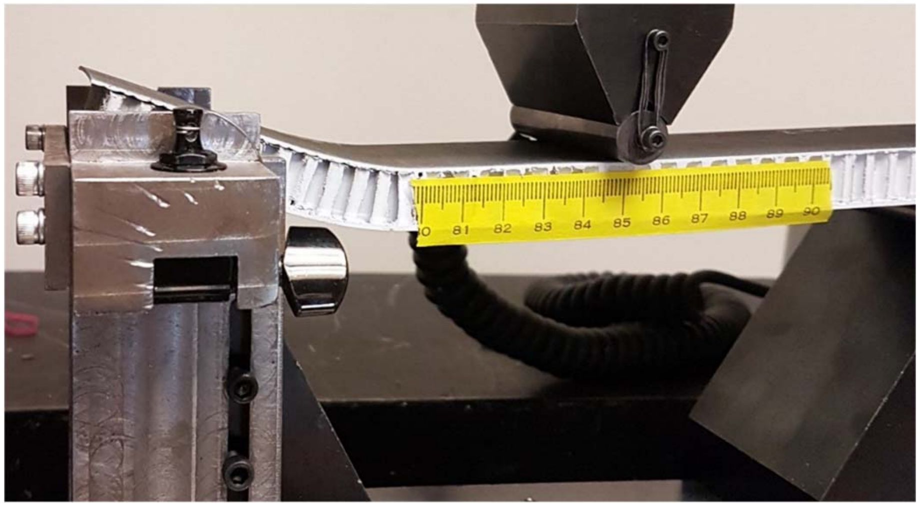
Single Cantilever Model Displacements



Load vs Extension Data

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

- **Calibration of interfacial cohesive elements**
  - **Mode II and MMB**
  - **Cell buckling at crack tip, no crack growth**
  - **Analytical and numerical models do not account for constraint effect on honeycomb core**

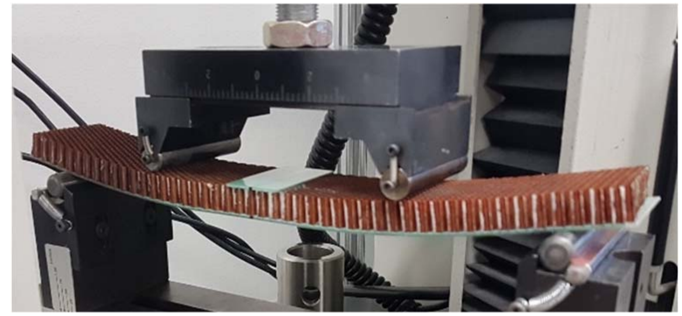


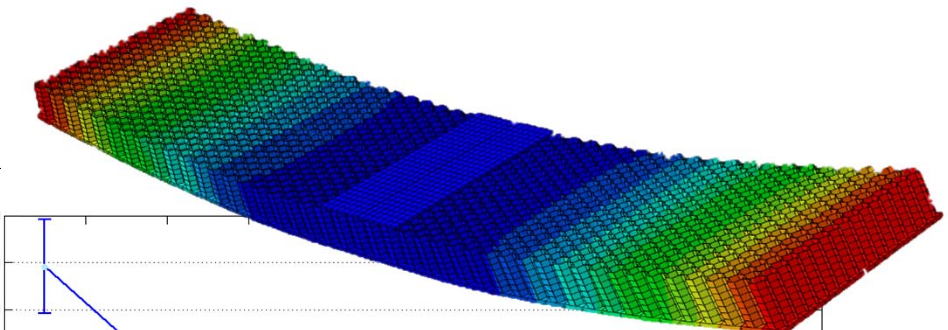
Mode II Sandwich ENF Test

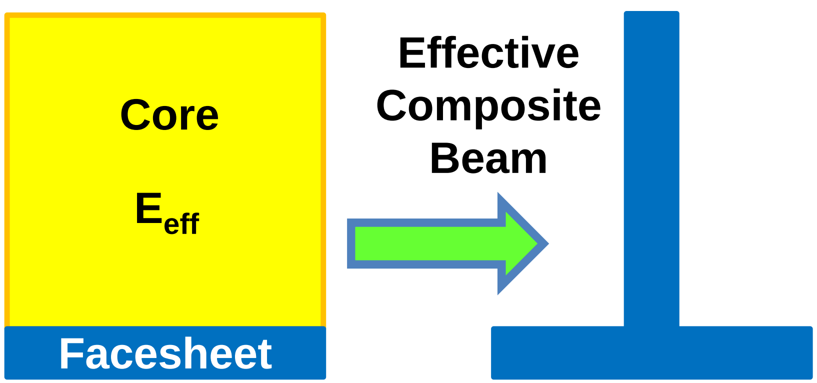
Sandwich Mixed Mode Bend Test

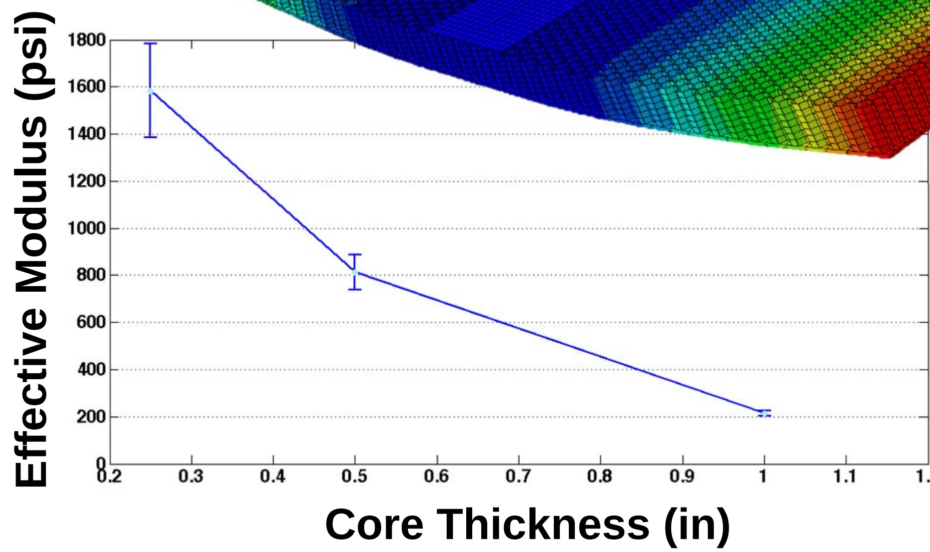
Current Focus:
Core Constraint Effect

- **Open Face Flexure Tests**
  - Nomex honeycomb core
  - Multiple core thicknesses
  - Core modeled explicitly
  - Homogeneous core in work



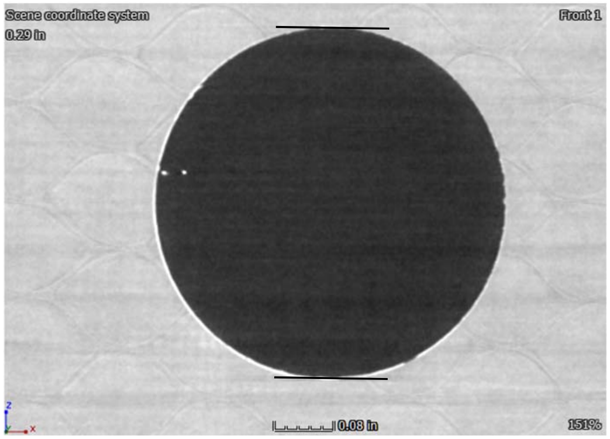






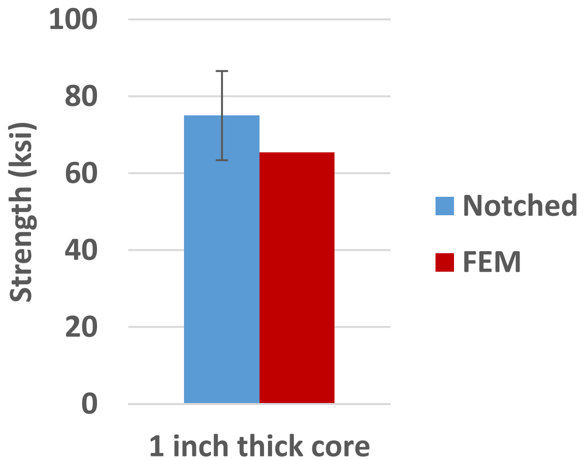
Damage Progression in Sandwich Composites: Sandwich Open-Hole Flexure Test

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

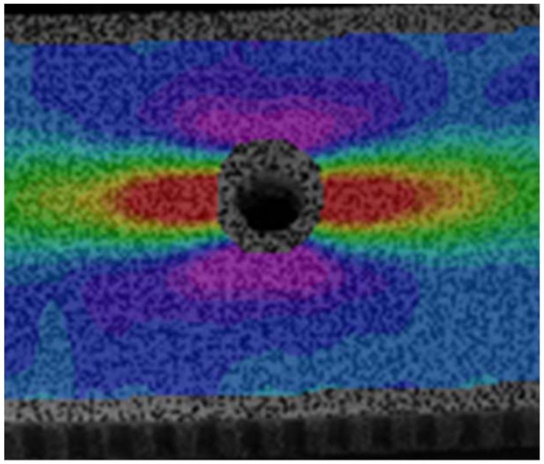


X-Ray CT

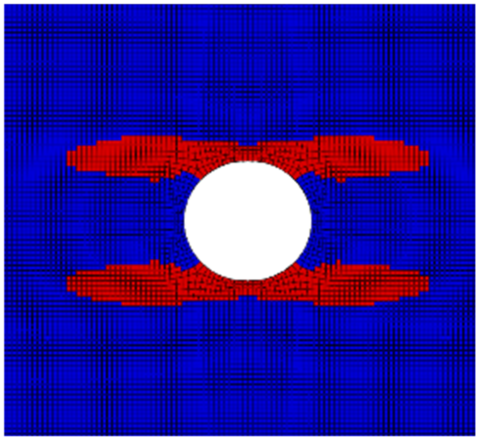
(Courtesy of Southwest Research Institute)



Compression Strength



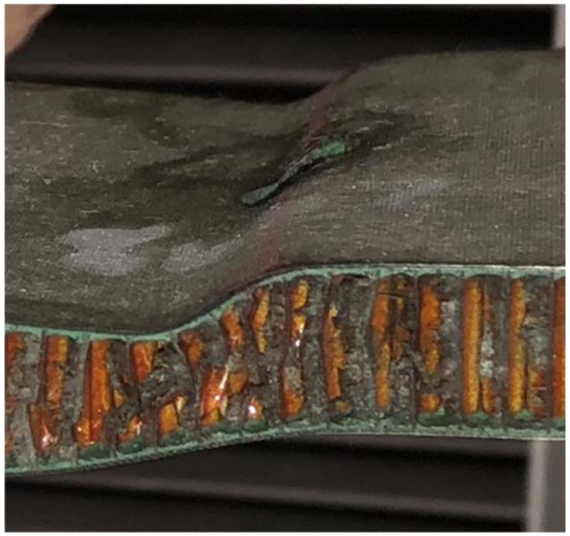
DIC Strain



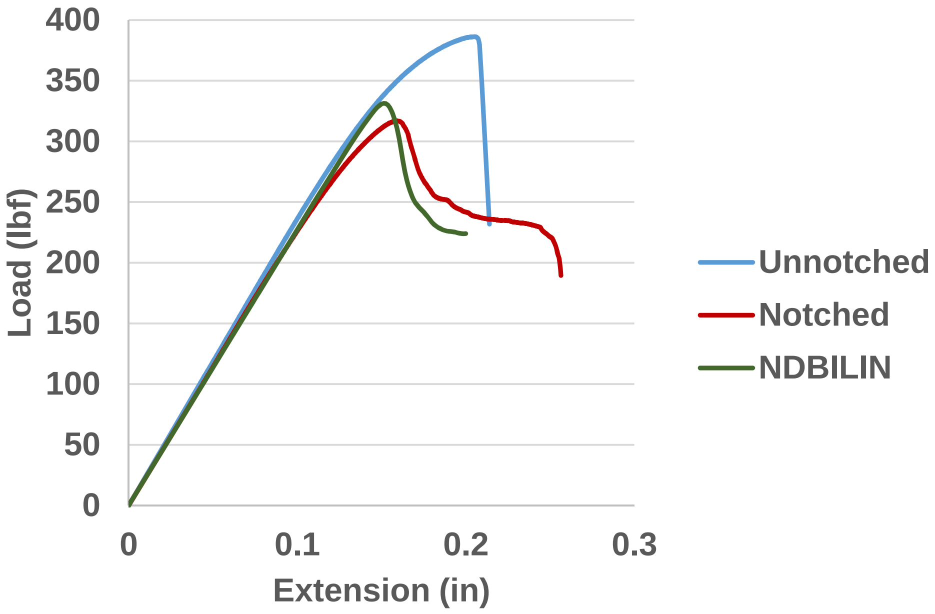
NDBILIN Damage Prediction

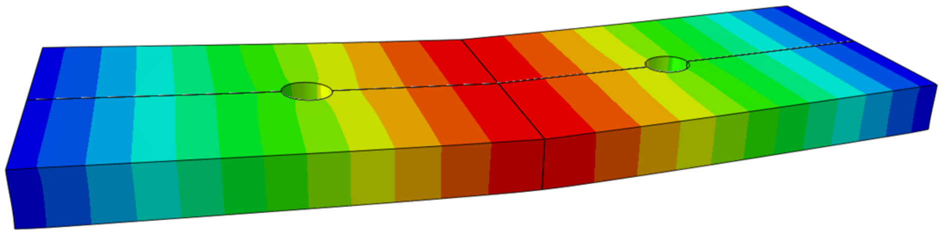
Damage Progression in Sandwich Composites: Sandwich Open-Hole Shear Test

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



Sandwich Open-Hole Shear Failure

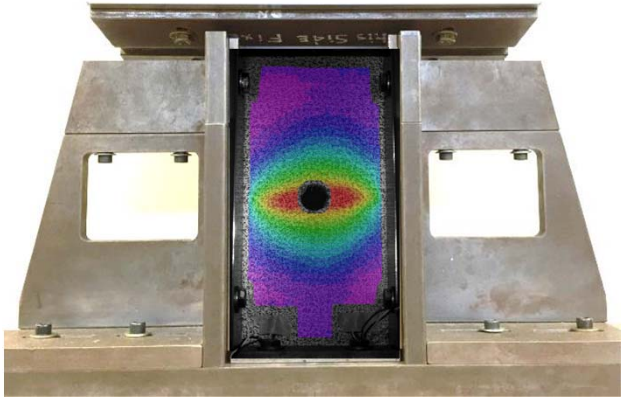




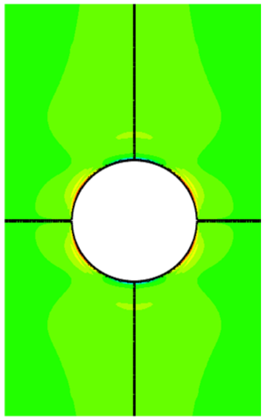
Model Displacements

Damage Progression in Sandwich Composites: Sandwich Open-Hole Compression Test

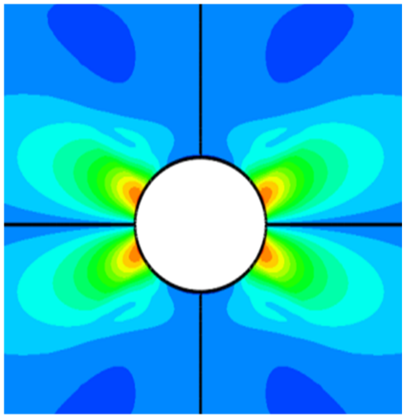
- Out-of-plane displacement observed in DIC measurements
- First mode facesheet buckling observed
- Investigating facesheet buckling using ABAQUS Riks
- Zero thickness cohesive elements caused numerical errors during perturbation step
- Cohesive surfaces implemeneted
- Non-linear vs Riks shows a large increase in cohesive stress



Out-of-plane deformation



Non-Linear



Riks

Future Work:
Notch Sensitivity of Composite Sandwich Structures

- Development of sizing guidelines for sandwich open hole compression and flexure tests
- Incorporate updated material/model parameters in laminate open hole tension/compression simulations
- Explore implementation of homogeneous core for Mode II and MMB
- Incorporate initial disbond with Teflon inserts to validate buckling model

Thank you for your attention!

Questions?