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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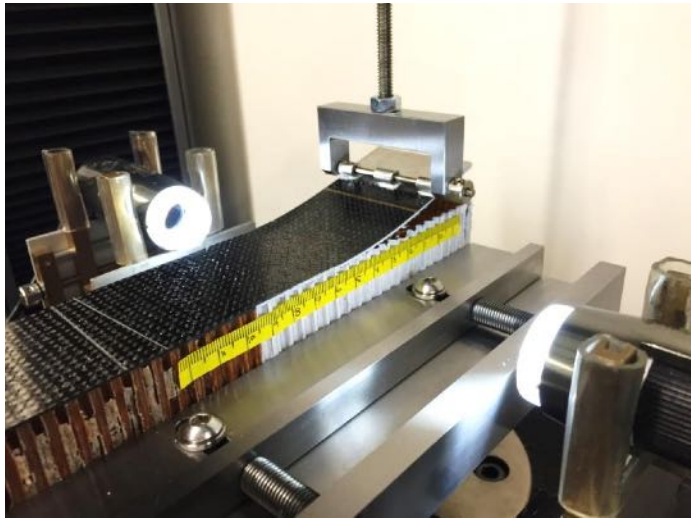
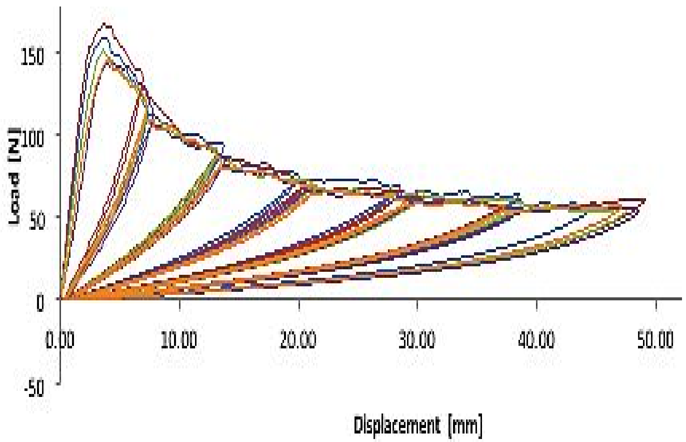
FAA Sponsored Project Information

- 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

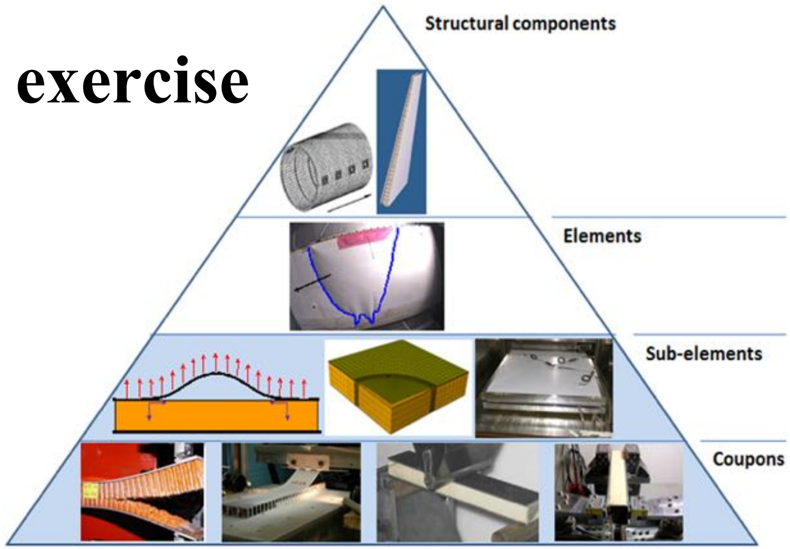
- **Initial subcommittee ballot by ASTM subcommittee D30.09**
- **Negative votes discussed at recent ASTM D30 meeting**
- **Follow-on testing underway to address concerns**
  - **Disbond initiation toughness procedure**
  - **Suitable loading rates, data acquisition rates**
- **Reballoting scheduled for Spring 2018**





Status Update:
Further Sandwich Disbond Related Activities

- SCB fatigue test method development
- Further Mixed-Mode & Mode II test method development and evaluation
- Follow-on U.S. Led Building Block exercise
  - Same sandwich configurations as previous coupon-level testing
  - Sub-element level testing
  - Analysis round-robin



- New content for upcoming revision of CMH-17 Handbook

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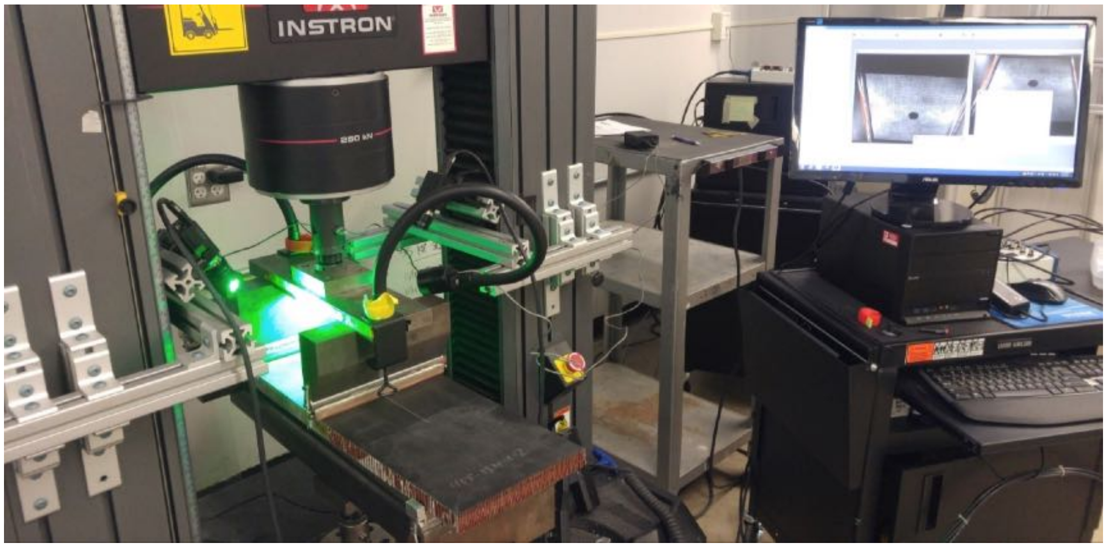
Status Update:
Sandwich Damage Tolerance

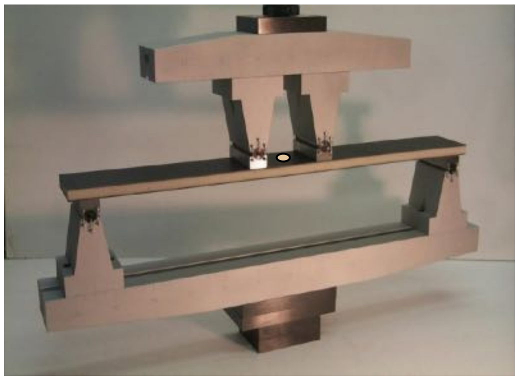
- **Draft standard of Sandwich composite Compression After Impact (SCAI) competed**
  - Balloting before next Spring ASTM D30 meeting
- **Draft practice of 4-Point Flexure After Impact (4-FAI) in progress**



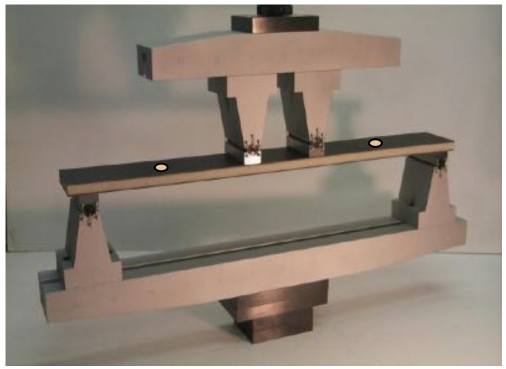
Research Objectives: Notch Sensitivity of Sandwich Composites

- **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



Notched Core Shear Beam Flexure

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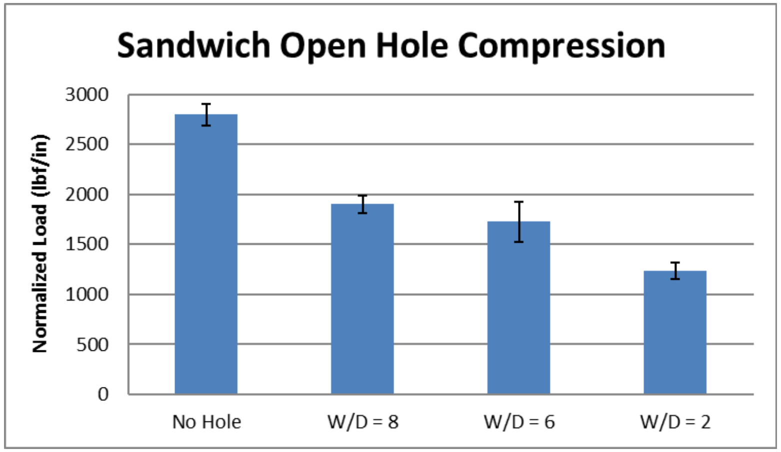
Testing Considerations: Sandwich Open Hole Compression

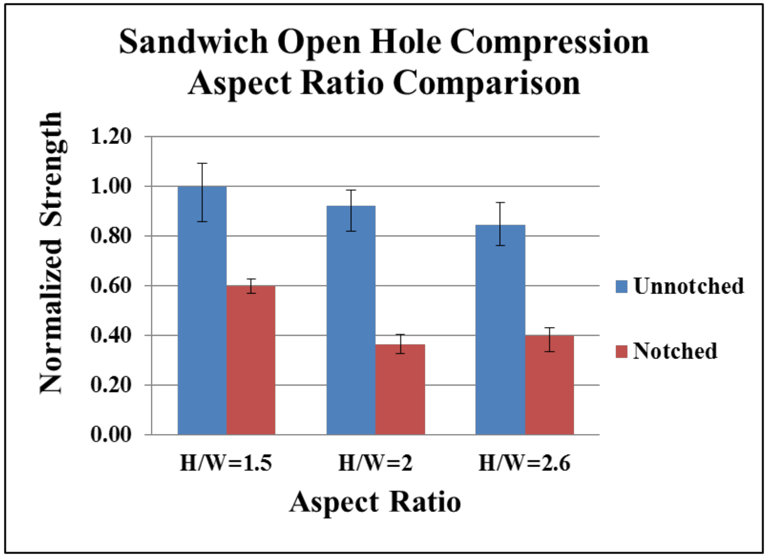
- **Test fixture/Specimen support**
  - End supports
    - Clamping top and bottom
    - Potting
  - Side supports
    - Knife edge
- **Specimen size**
  - Separation of central hole and boundary effects
  - Production of acceptable strength reductions
- **Strain measurement**
- **Specimen alignment**

Open hole compression fixture for monolithic composites

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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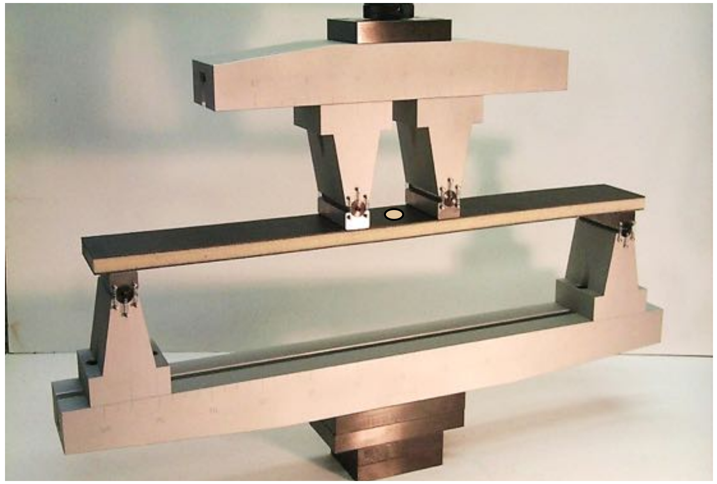
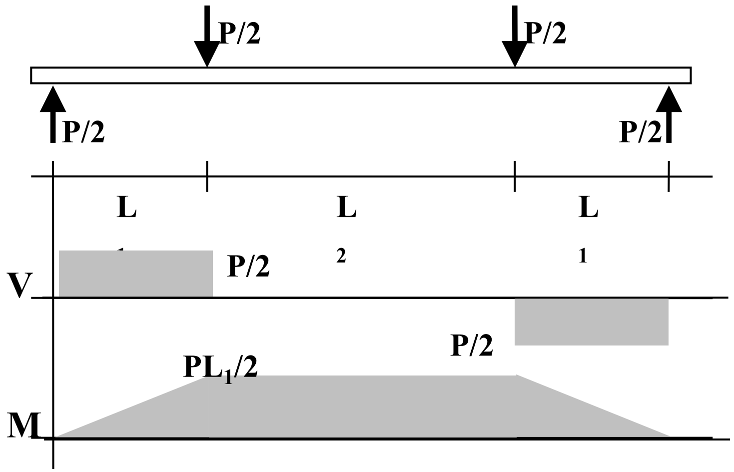
Testing Considerations: Sandwich Open Hole Flexure

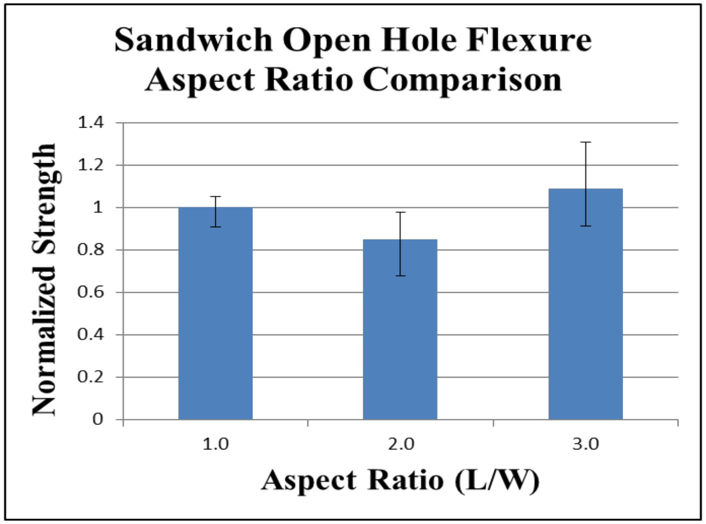
- Test fixture/specimen support
  - Inner span
    - Separation of notch and loading boundary effects
  - Outer span
    - Develop sufficient bending moment
    - Ensure failure in inner span
- Required specimen width
  - Separation of central hole and specimen edges
  - Production of acceptable strength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

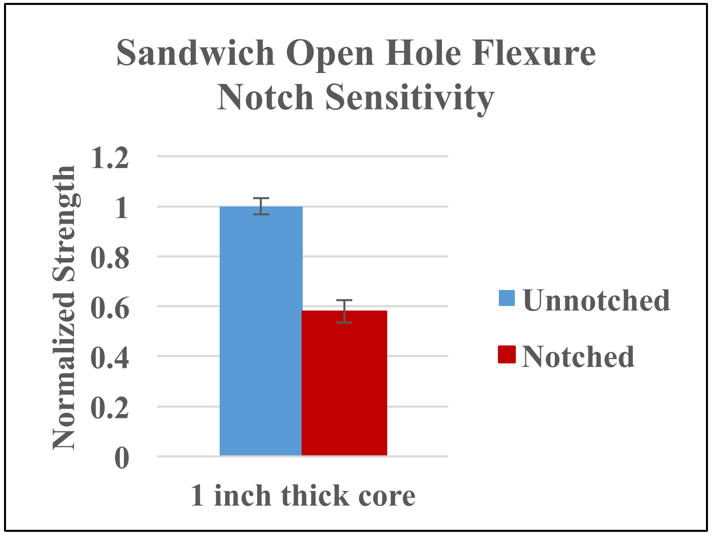




Previous Work: Specimen Size

- **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





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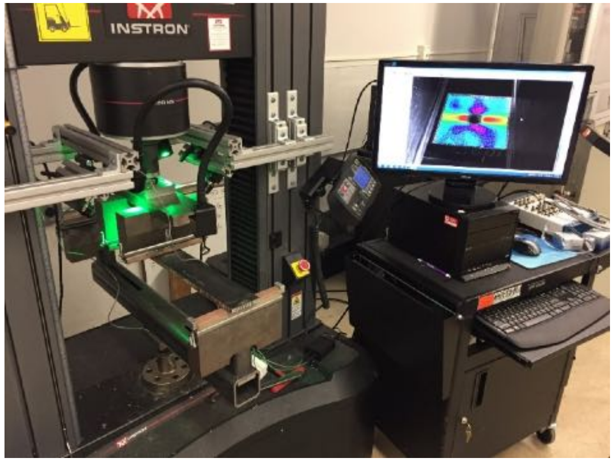
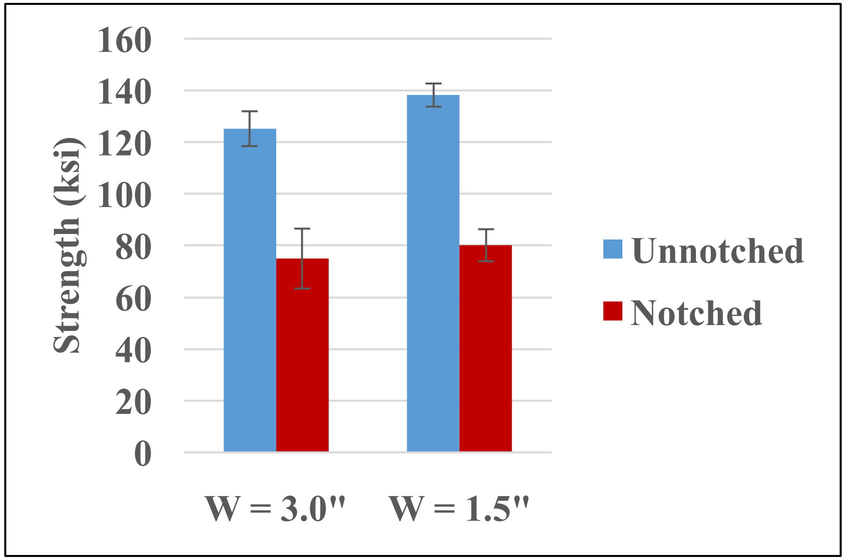
Current Focus: Minimum Width

- **Investigating width to thickness (W/C)**
- **Sandwich configurations:**
  - **W = 3 in. D = 0.5 in. C = 1 in. (W/D=6, W/C=3)**
  - **W=1.5 in. D = 0.25 in. C = 1 in. (W/D=6, W/C=1.5)**
- **Similar strengths and notch reductions produced**



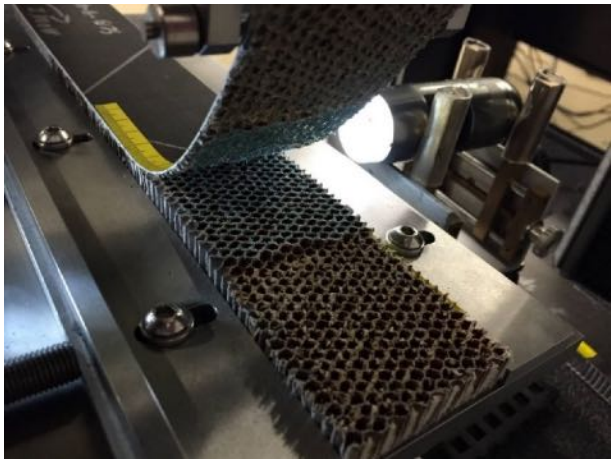
Notch Reduction Factors	
W = 3 in.	0.60
W = 1.5 in.	0.58



Third Loading Configuration: Core Damage and Notch Effects

- **Effects of core notch or core damage 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

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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)
- L and W core directions tested

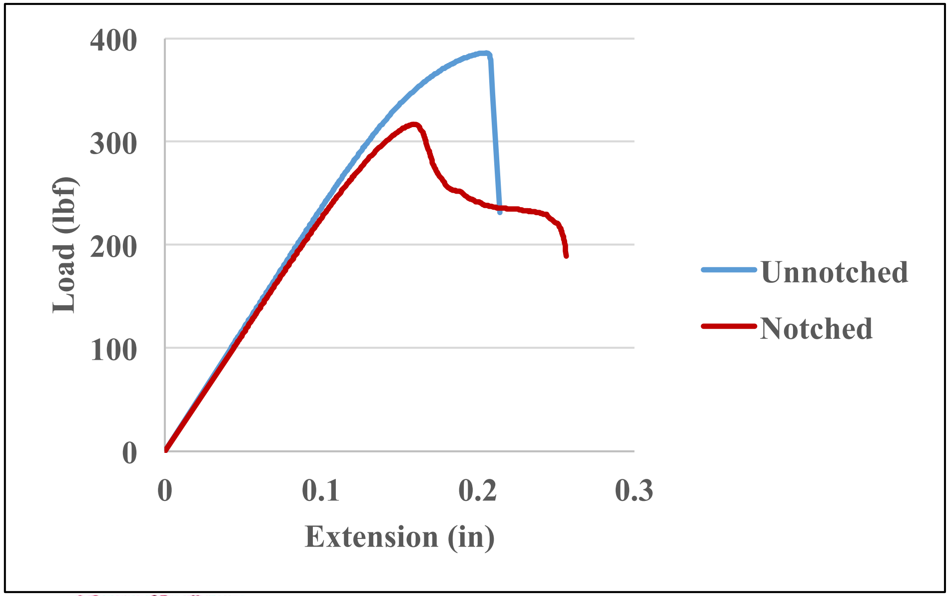
Notch

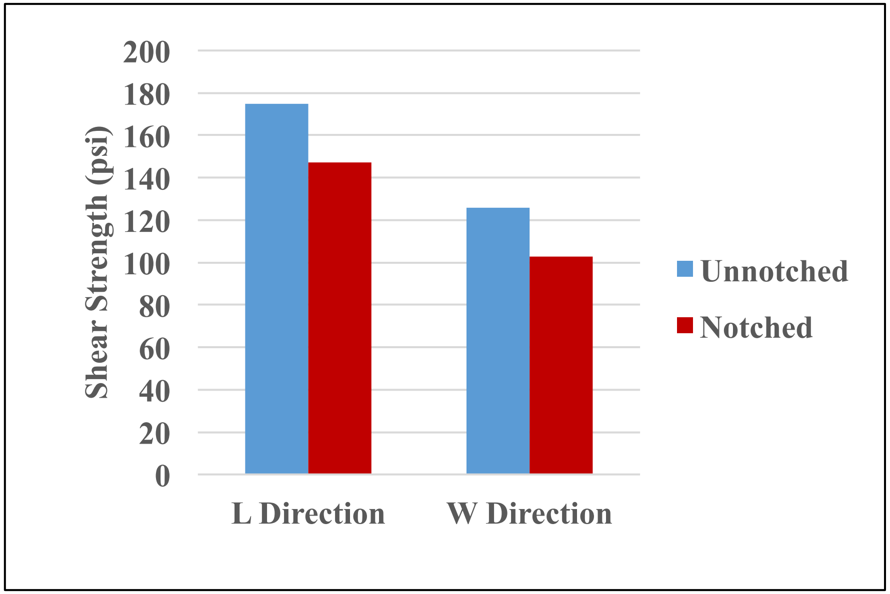
Sized to ensure core shear failure (ASTM C393)

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	





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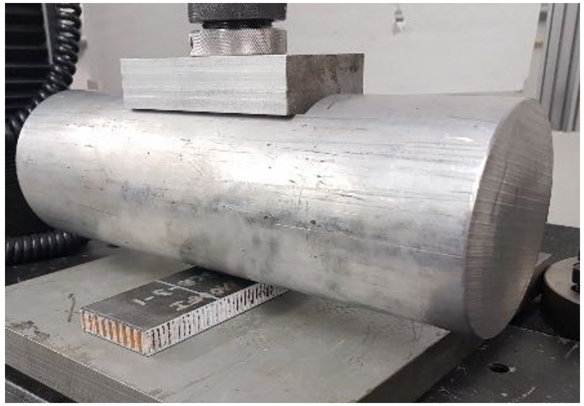
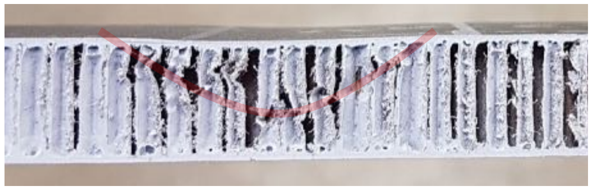
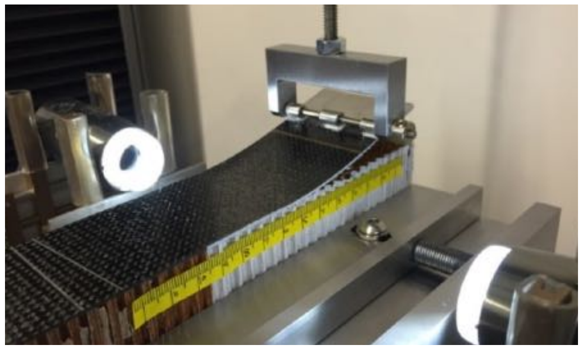
Testing Considerations: Disbond after Core Crush

- **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**

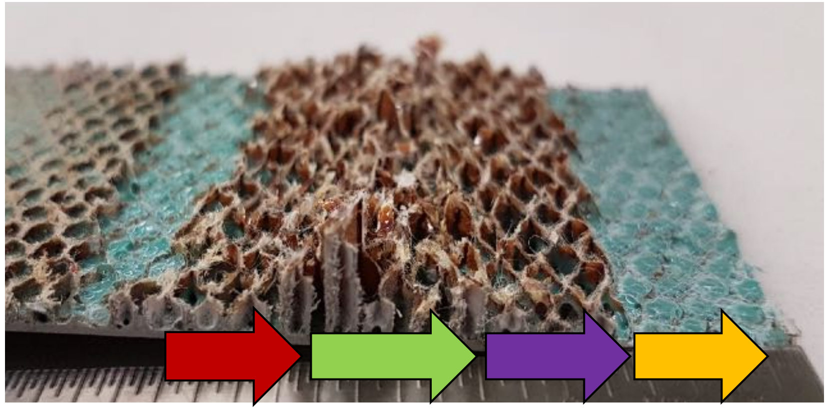


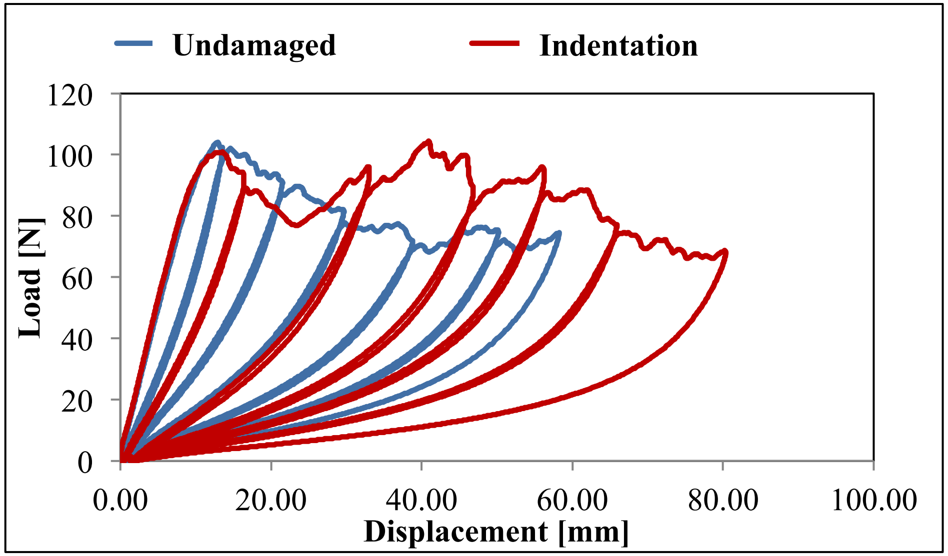


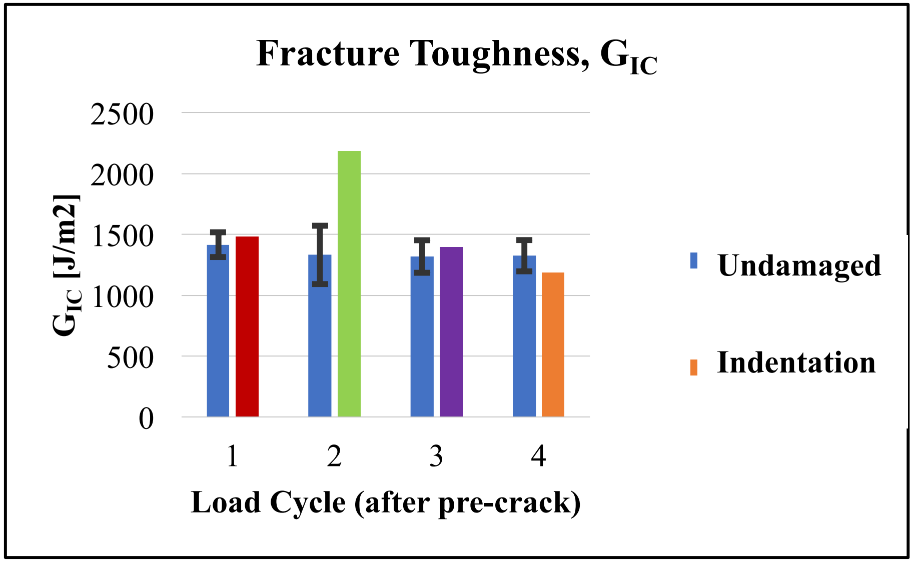


Initial Test Results: Disbond After Indentation Testing

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



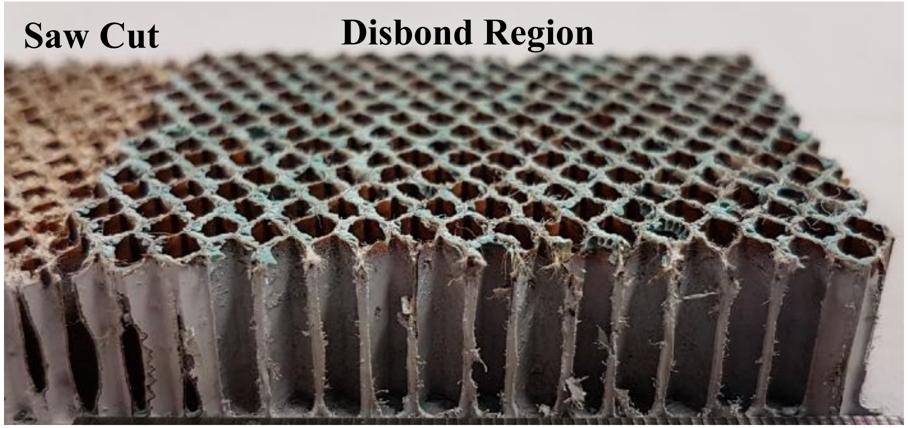




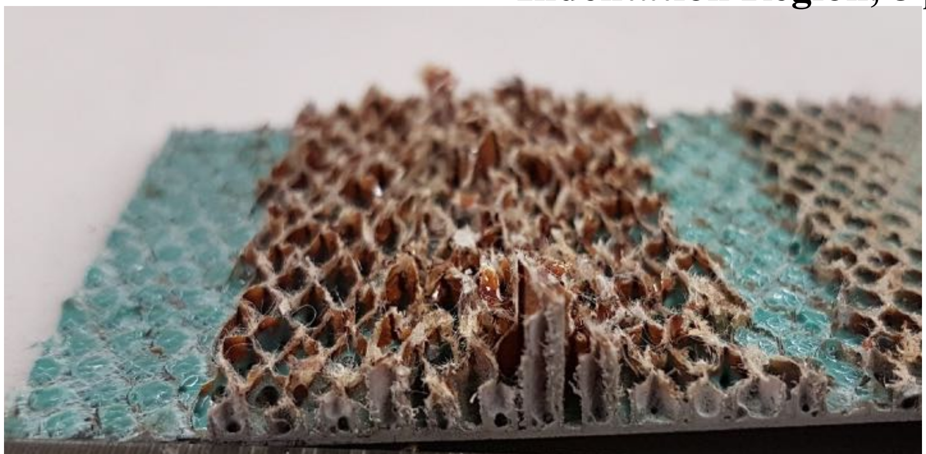
Disbond After Indentation Testing: Fracture Path Through Core Crush Region

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

Undamaged 8 pcf Nomex core



Indentation Region, 8 pcf Nomex core



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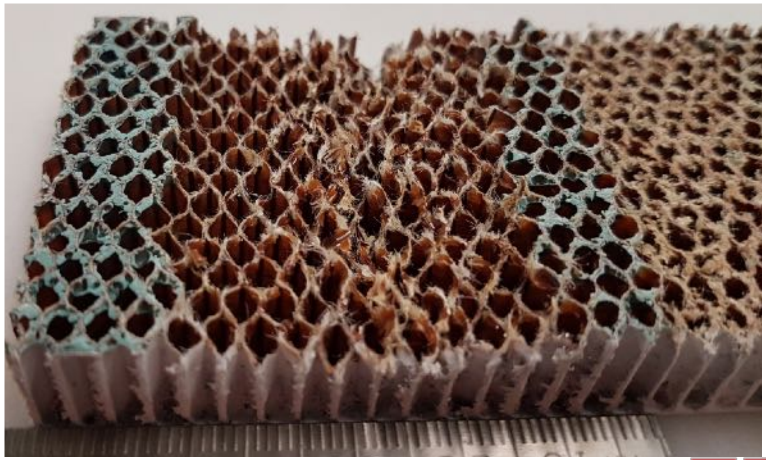
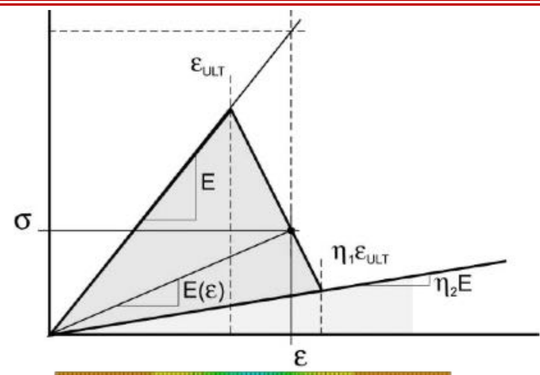
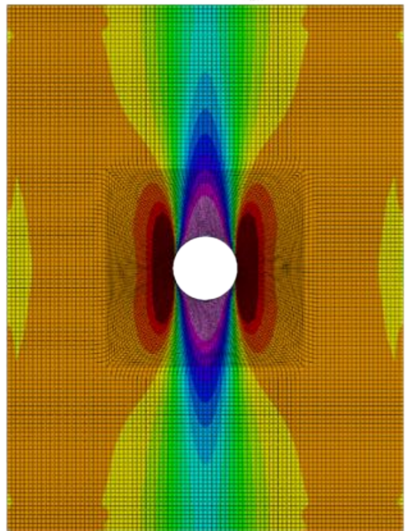


Bottom

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





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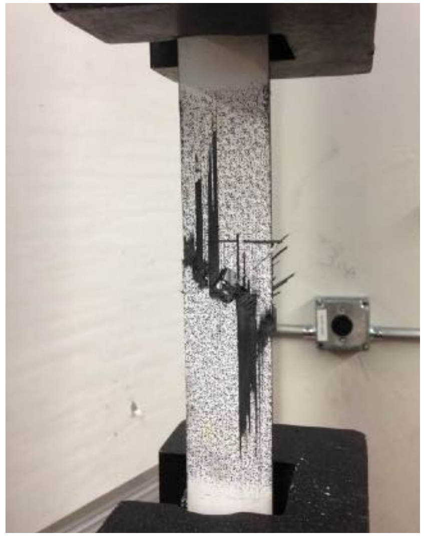
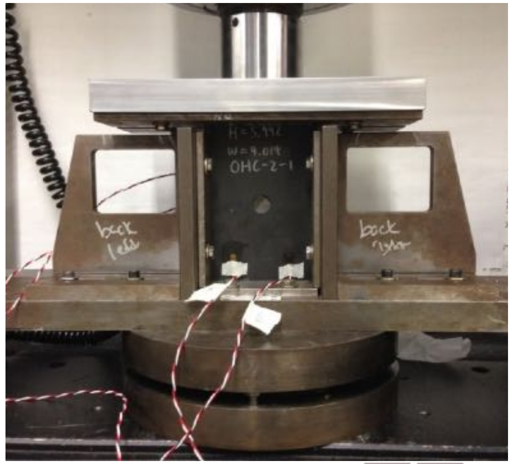
Failure Analysis of Notched Sandwich Specimens

Development of Modeling Approach

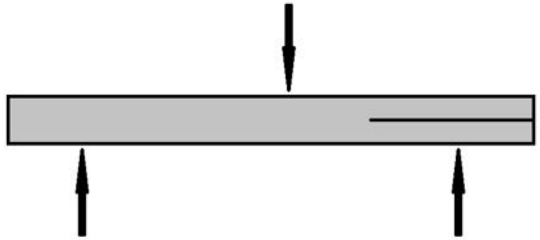
- **Modeling of damage progression in facesheets**
  - **Analysis of delamination (Mode I and Mode II)**
    - **Cohesive Surfaces**
  - **Analysis of +/-45 laminate tension test**
  - **Analysis of laminate open-hole <u>tension</u> test**
  - **Analysis of laminate open-hole <u>compression</u> test**
- **Modeling of damage progression in sandwich composites**
  - **Sandwich interface disbond (Mode I and II)**
    - **Cohesive Elements**
  - **Sandwich flexure test**
  - **Sandwich open hole compression test**

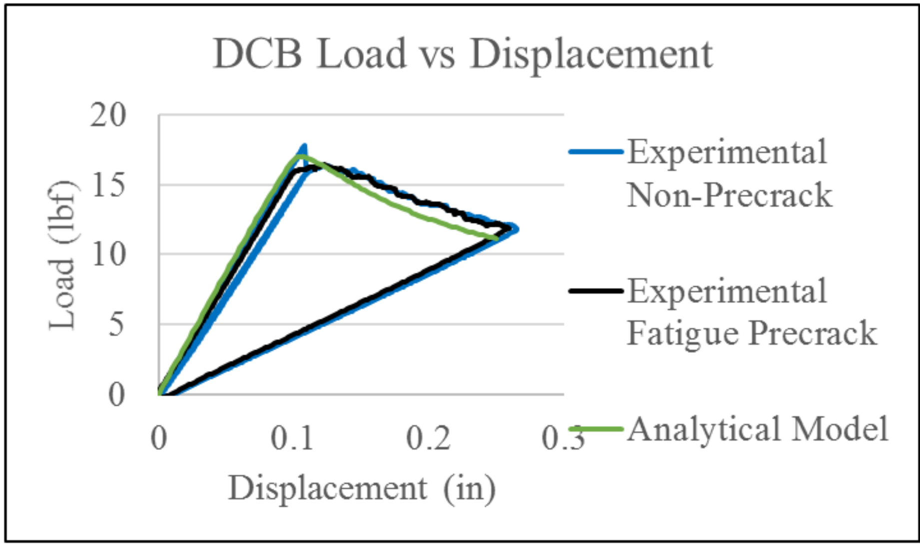


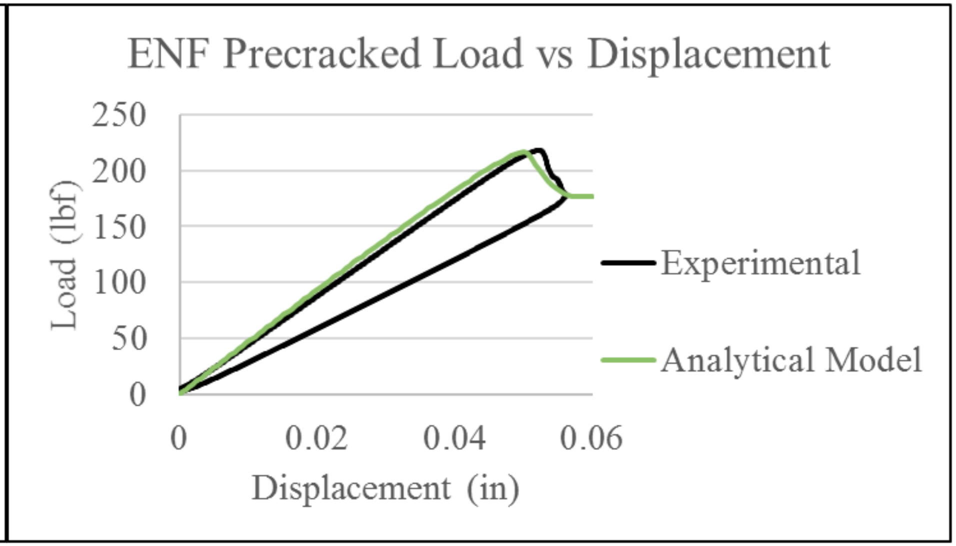


Damage Progression in Facesheets: Analysis of Delamination

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

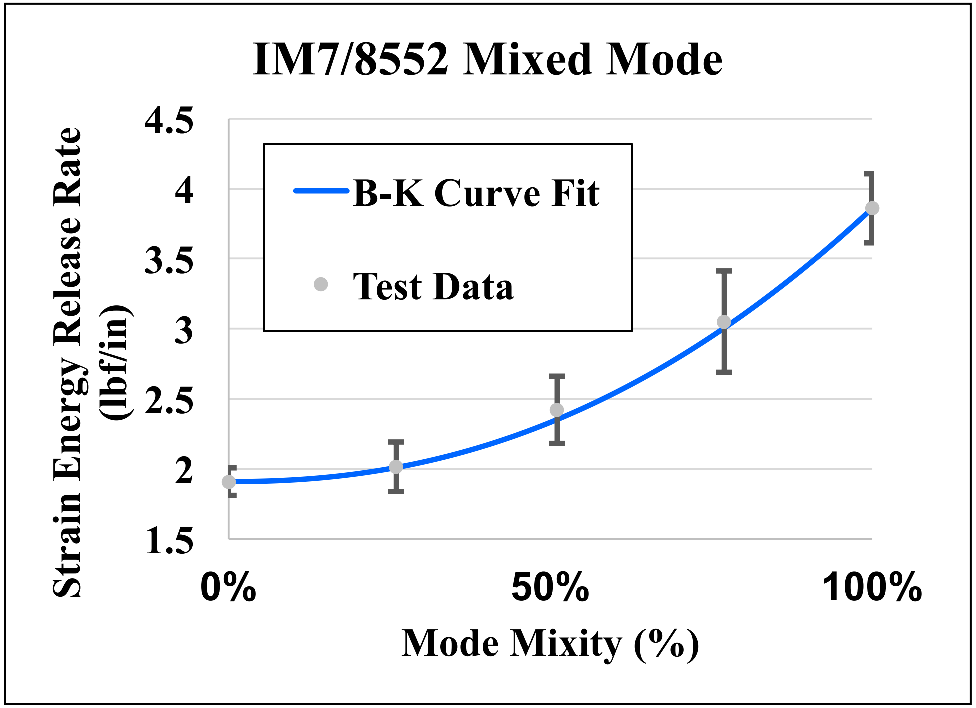






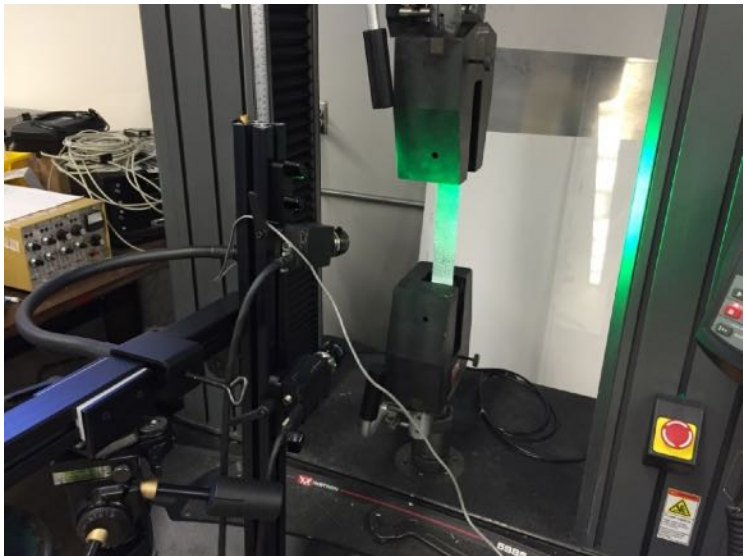
Analysis of Facesheet Delaminations: Mixed-Mode Delamination Growth

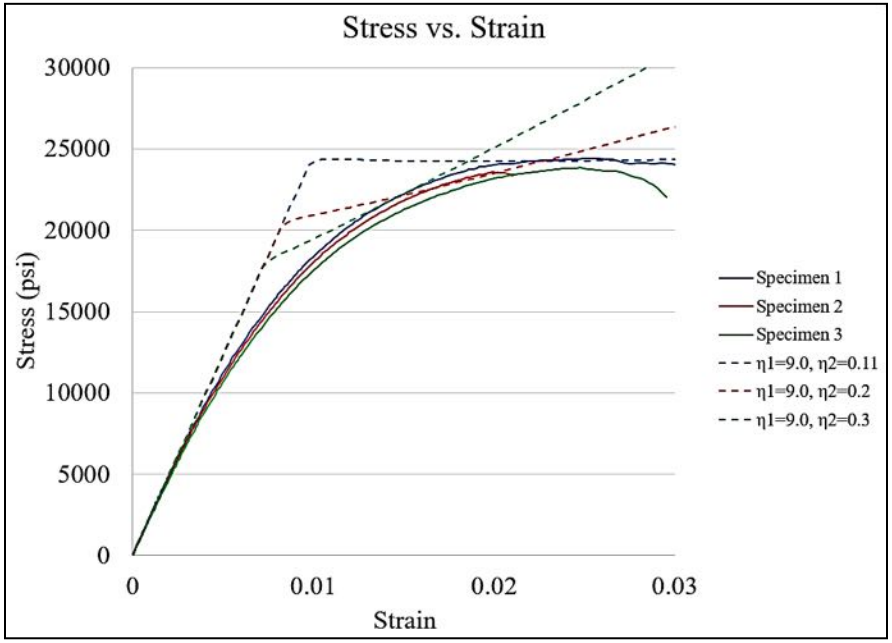
- **Calibration of cohesive surfaces**
  - Mixed Mode Bend (MMB) using ASTM D6671
  - Fit using Benzeggagh-Kenane (B-K) criterion



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

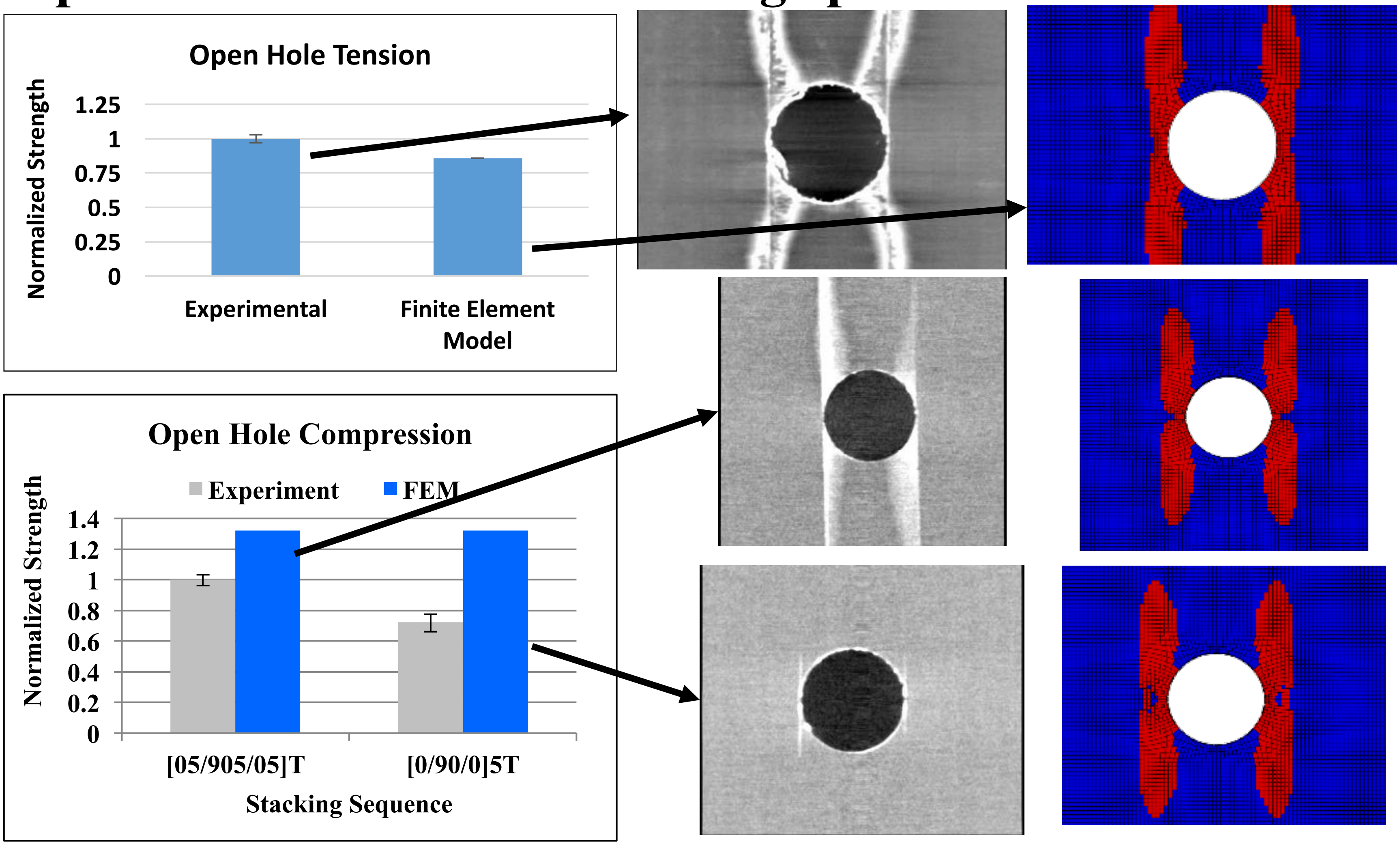
- **Simulation of un-notched and open-hole tension testing**
- **IM7/8552 carbon/epoxy, $[45/-45]_{2S}$ laminates**
- **Matrix shear strength and damage parameters calibrated using measured stress-strain behavior**





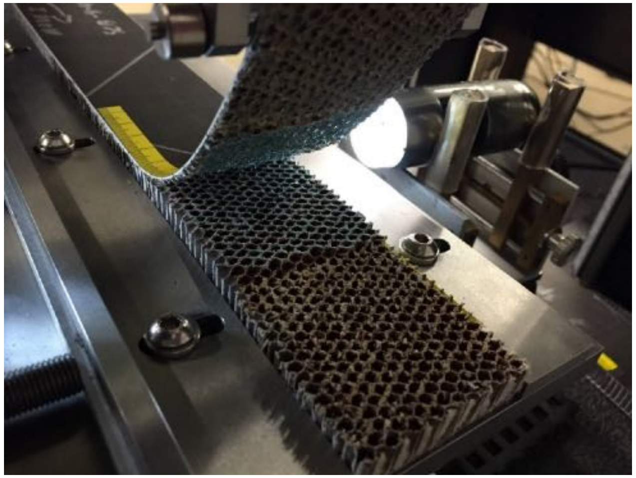
Damage Progression in Facesheets: Current Focus

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

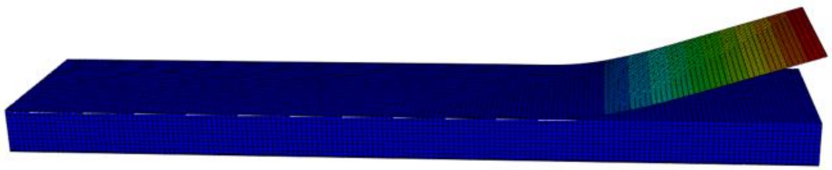


Damage Progression in Sandwich Composites: Analysis of Interfacial Disbond

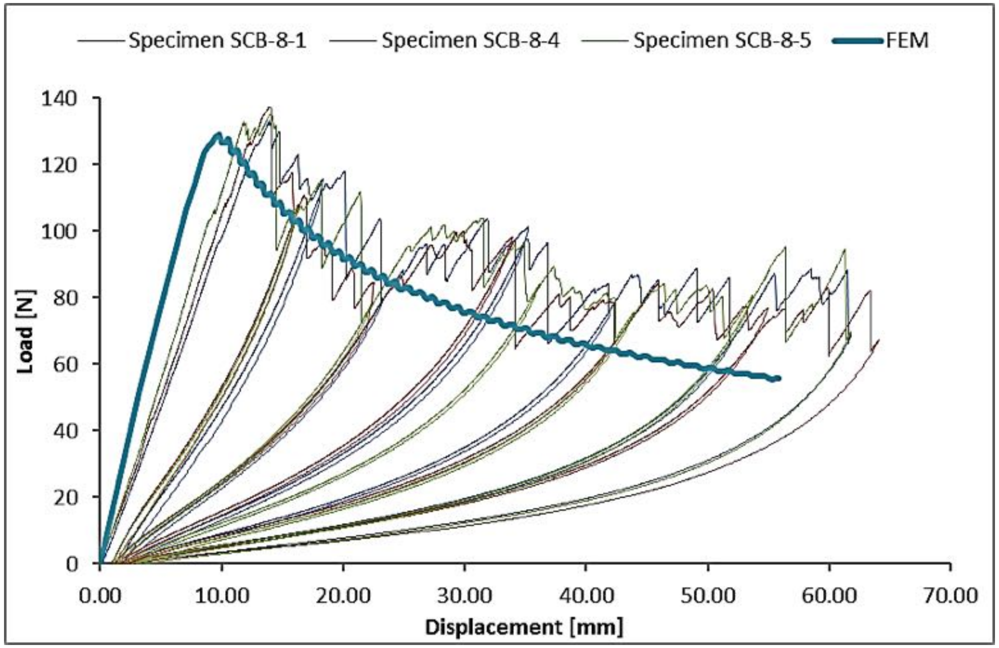
- **Calibration of interfacial cohesive elements**
  - **Mode I Sandwich SCB**



Single Cantilever Beam Test



Single Cantilever Model Displacements



Load vs Displacement Data

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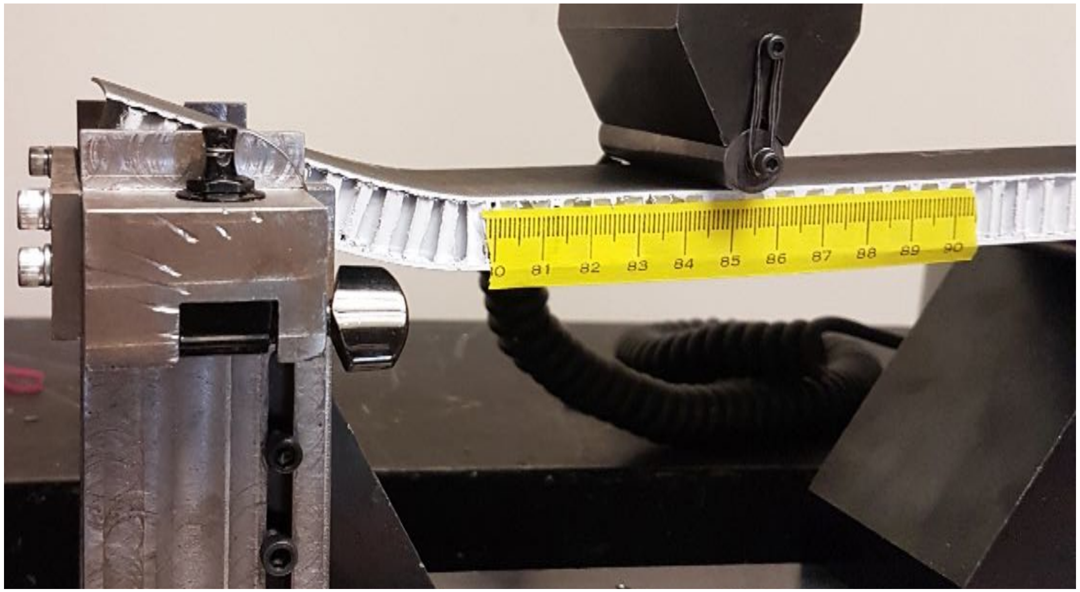
Damage Progression in Sandwich Composites: Current Focus

- Calibration of interfacial cohesive elements
  - Mode II and MMB
  - In progress

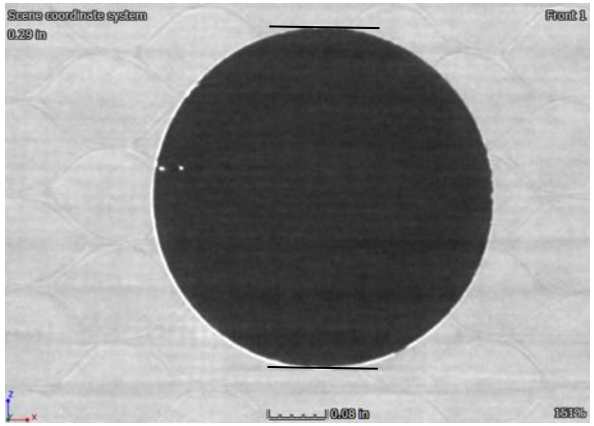


Mode II Sandwich ENF Test

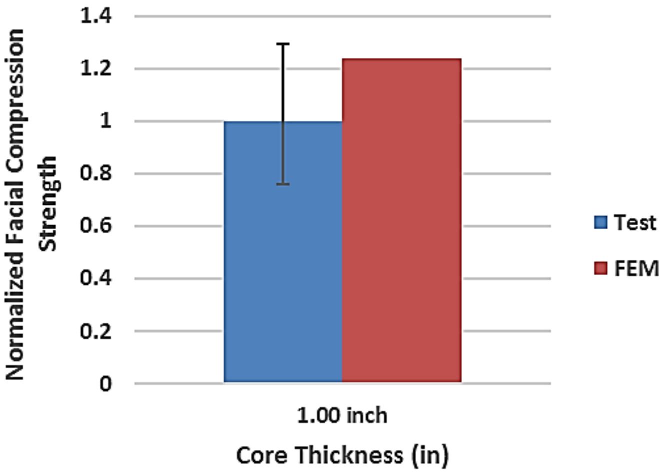
Sandwich Mixed Mode Bend Test

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

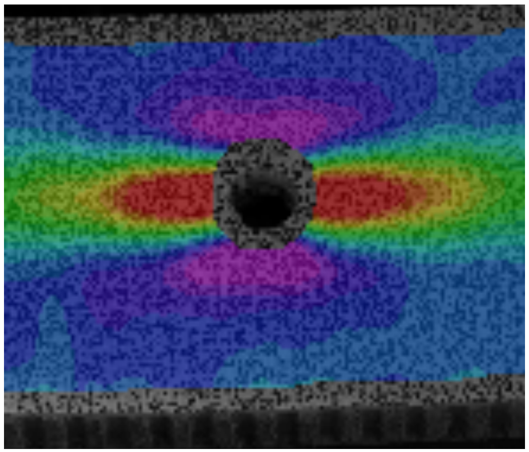
- **90% load X-ray CT shows minimal damage progression**
- **Model over predicting damage and failure load**



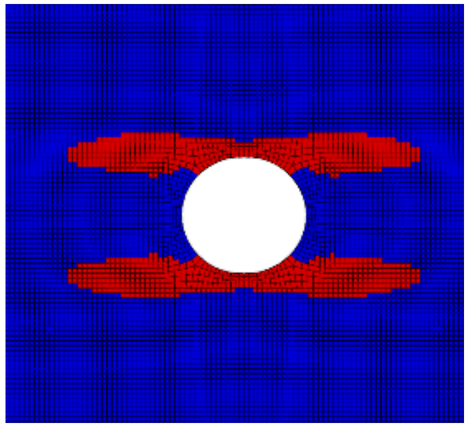
X-Ray CT
(Courtesy of Southwest Research Institute)



Compression Strength Comparison



DIC Strain



NDBILIN Damage Prediction

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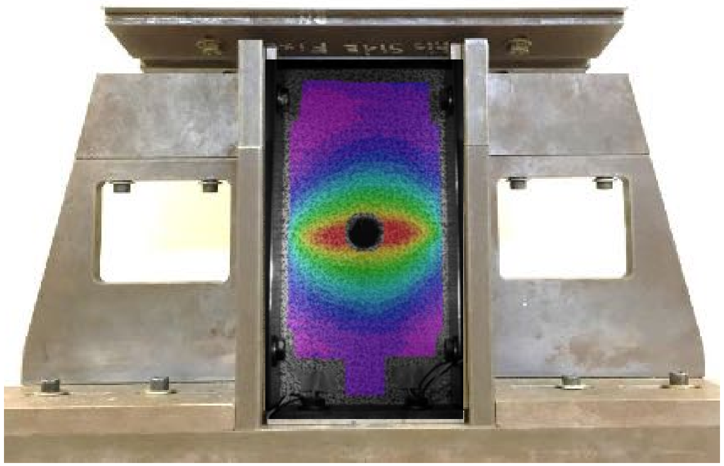
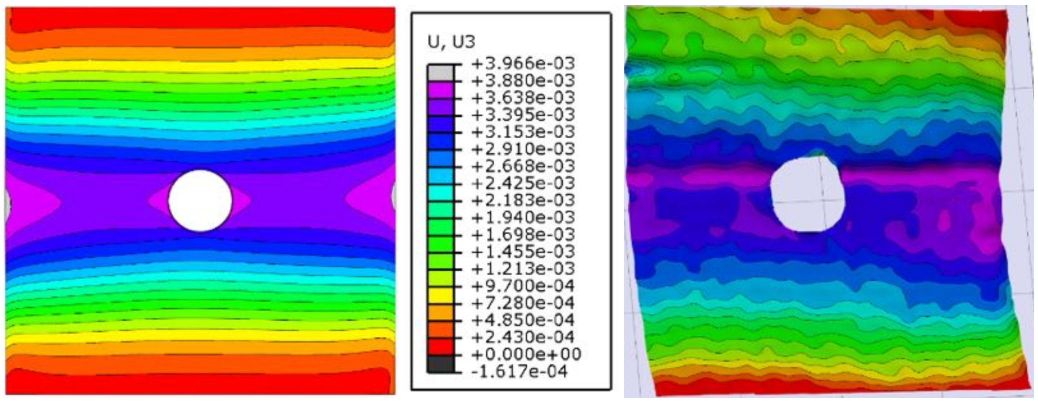
Damage Progression in Sandwich Composites: Analysis of Sandwich Open-Hole Compression Tests

- **Out-of-plane displacements observed in DIC measurements**
- **First mode facesheet buckling observed**
- **Investigating facesheet buckling using ABAQUS**
- **Starting with buckling observed in modified IITRI OHC tests**



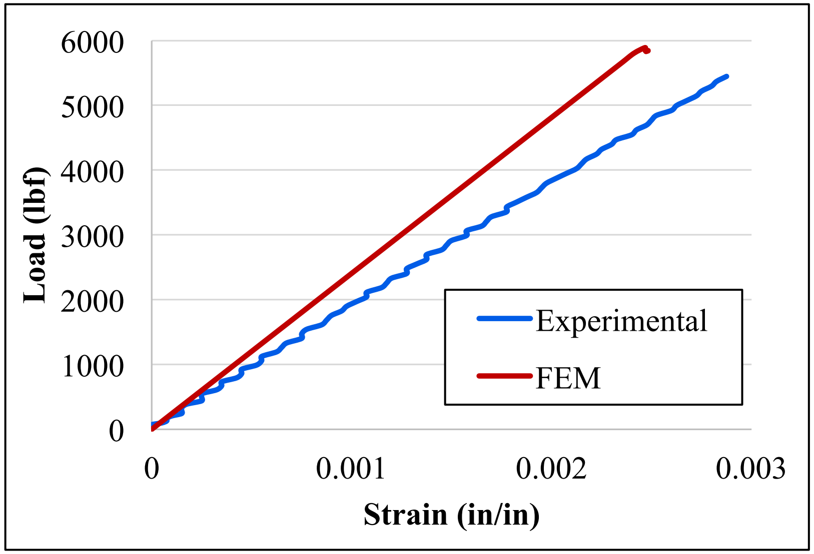
Sandwich OHC out-of-plane deformation

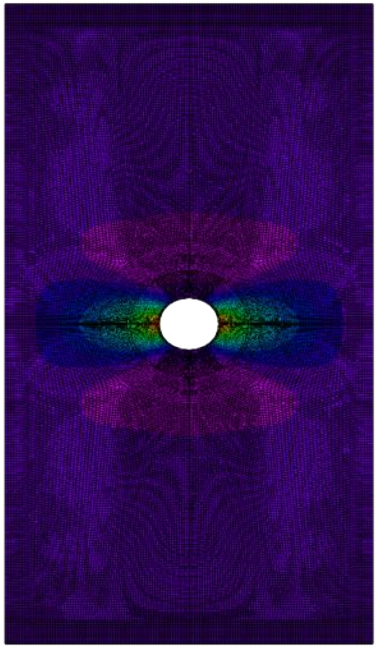


IITRI displacement results
FEM vs DIC

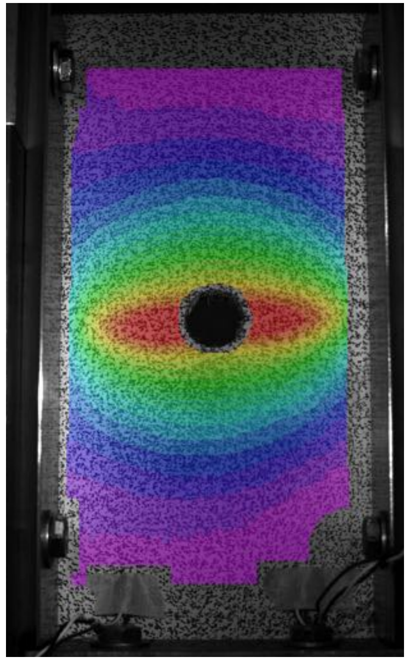
Damage Progression in Sandwich Composites: Facesheet Buckling

- Buckling behavior modeled using ABAQUS Riks
- Incorporating cohesive properties and NDBILIN
- Slightly over predicting stiffness and failure load
- Cohesive surfaces





ABAQUS Riks



DIC Out-of-Plane

Upcoming Work:
Notch Sensitivity of Composite Sandwich Structures

- **Development of sizing guidelines for sandwich open-hole compression and flexure tests**
- **Further investigate notched core shear and disbond-after-indentation test configurations**
- **Explore best practices for modeling core damage**
- **Incorporate updated material/model parameters in laminate open hole tension/compression simulations**
- **Investigate buckling solution for facesheet delamination compression tests**

Thank you for your attention!

Questions?