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Notch Sensitivity Testing and Failure Analysis of Sandwich Composites

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University of Utah

JAMS 2016 Technical Review

March 22-23, 2016

THE UNIVERSITY OF UTAH

FAA Sponsored Project Information

- Principal Investigators: **Dr. Dan Adams**
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  Boeing
  Oregon State University
  ASTM Committee D30

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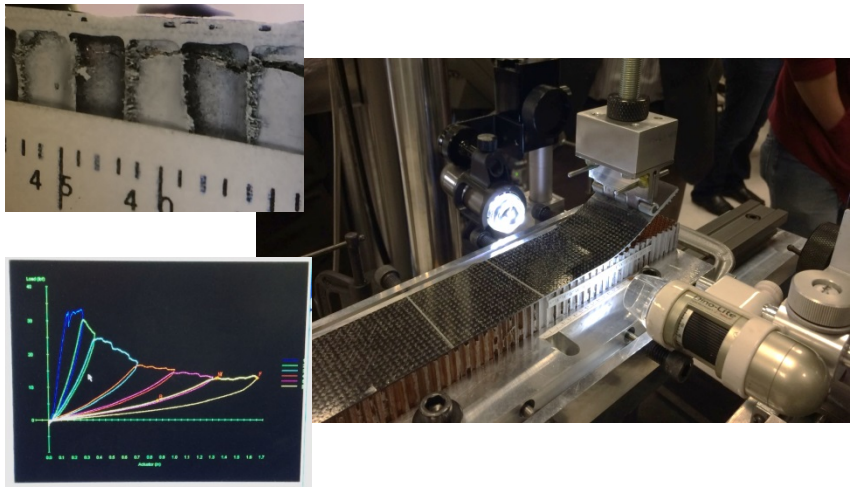
Outline

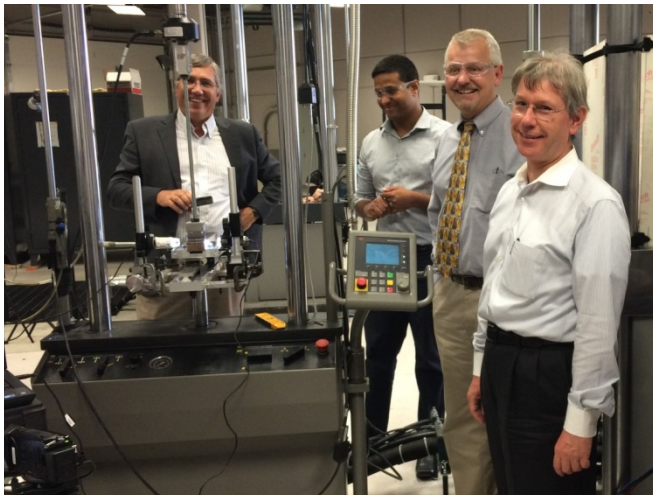
- **Brief updates: Previous research**
  - **Sandwich fracture mechanics**
  - **Sandwich damage tolerance**

- **Sandwich notch sensitivity investigation**
  - **Test method development**
  - **Numerical modeling – progressive damage analysis**

Status Update:
Mode I Sandwich Fracture Mechanics Test Method

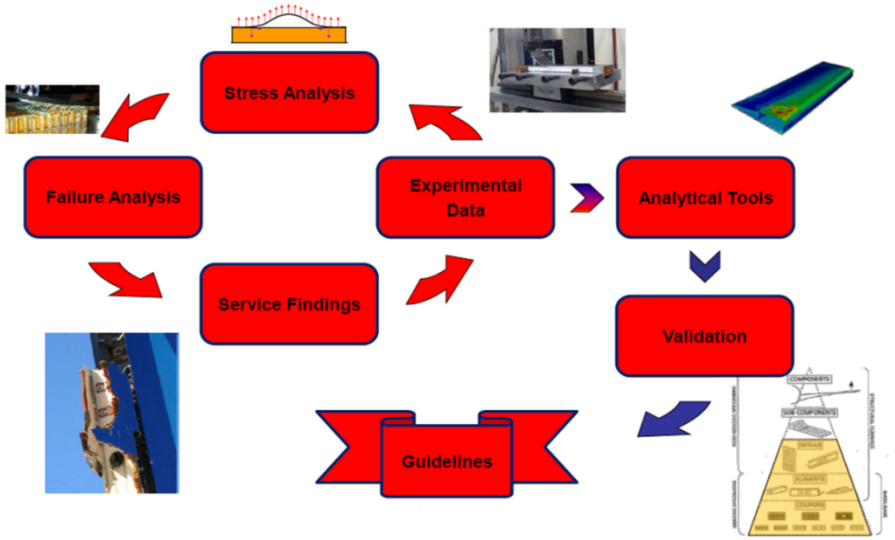
- **Single Cantilever Beam (SCB) Test Method**
  - **Draft ASTM standard completed**
  - **International round-robin test program initiated**
    - **7 test labs with previous SCB testing experience**
    - **Sandwich specimens fabricated, testing initiated**





Status Update:
Sandwich Disbond Assessment Initiative

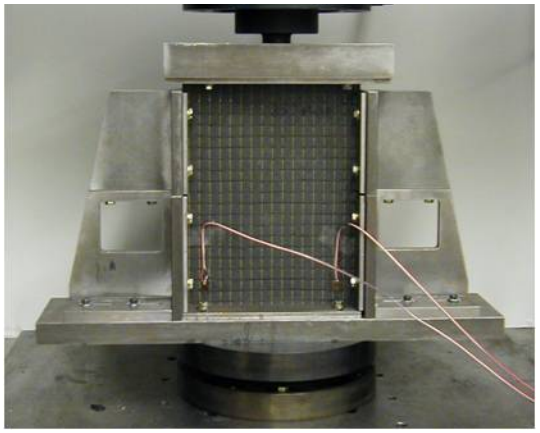
- **Identify, describe and address the phenomenon associated with facesheet/core disbonding and core fracture**
- **Develop a methodology to assess facesheet/core disbonding in sandwich components**
  - **Coupon**
  - **Sub-element**
- **New sections in CHM-17 (Volume 6)**



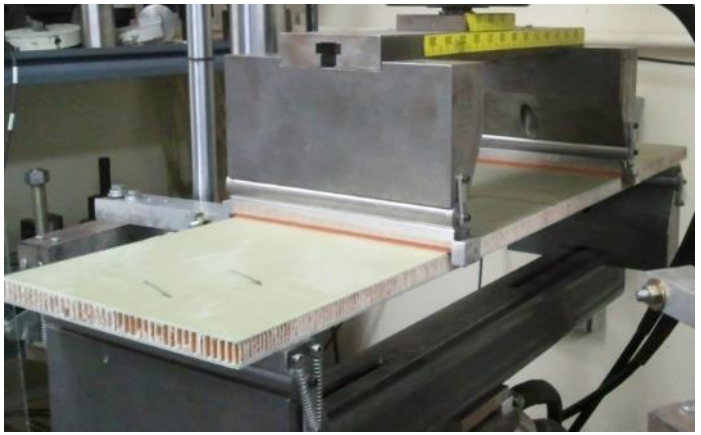
Seneviratne, W., "Fatigue Damage Growth Rate of Sandwich Structures using Single Cantilever Beam (SCB) Test," 2014 JAMS Technical Review

Status Update:
Development of Sandwich Damage Tolerance Test Methods

- Draft standards of CAI completed
- Draft standard for 4-Point Flexure After Impact under development
- Follow-on "scaling" effort underway through Air Force SBIR program



Compression After Impact (CAI)

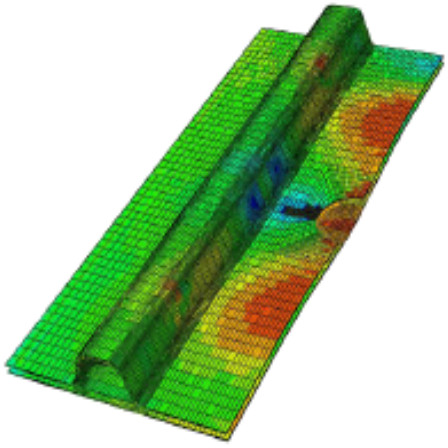


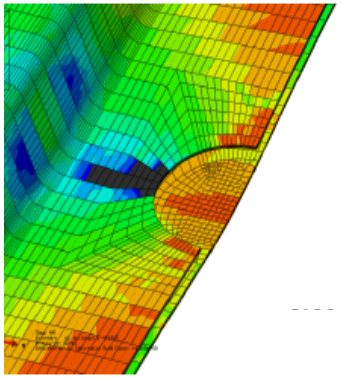
4-Point Flexure After Impact (4-FAI)

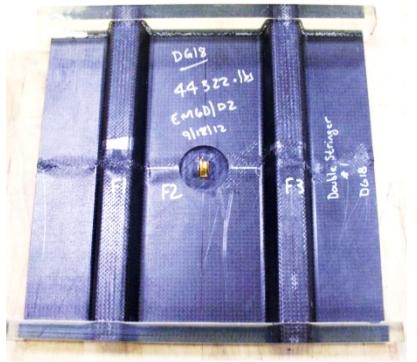
Follow-On Sandwich Damage Tolerance Effort:

Scale-Up of Sandwich Damage Tolerance Test Results

- **Collaborative research with Materials Sciences Corp. & Boeing St. Louis**
- **Univ. of Utah focus on sandwich damage tolerance**







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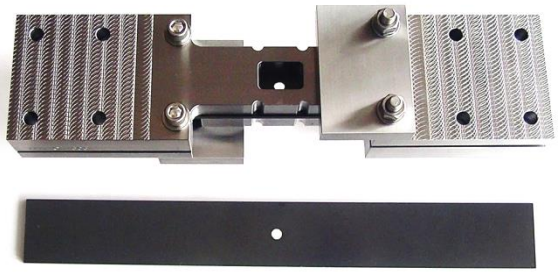
Background:
Notch Sensitivity of Sandwich Composites

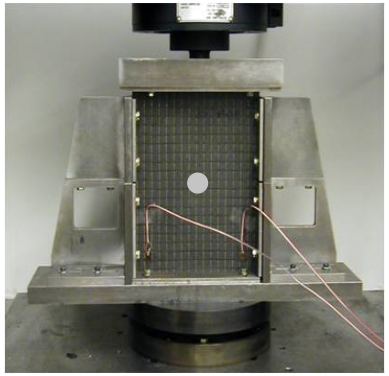
- Relatively high level of maturity for monolithic composite test methods
  - ASTM D 5766 – Open Hole Tension
  - ASTM D 6484 – Open Hole Compression
  - Out-of-plane shear (Parmigiani)



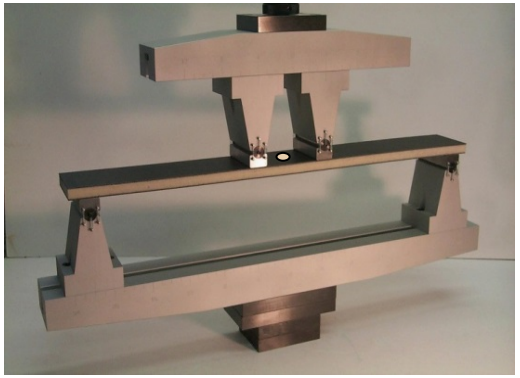
- Less attention to sandwich composites
  - Currently no standardized tests for notch sensitivity
- Failure prediction of notched monolithic composites is receiving considerable attention
  - Reduced focus on analysis of notched sandwich composites

Research Objectives:
Notch Sensitivity of Sandwich Composites

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



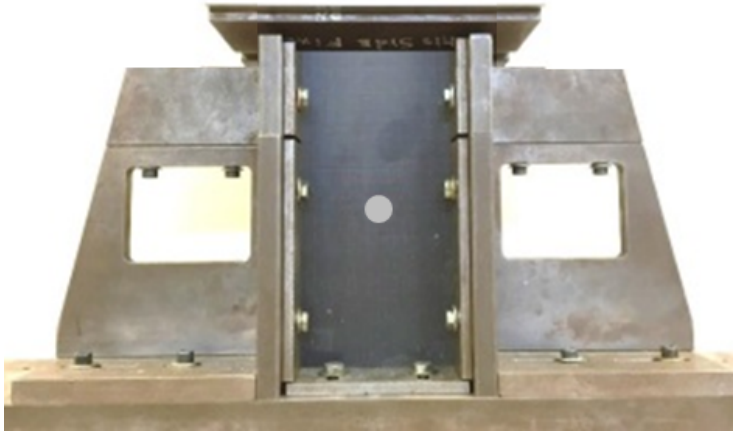
Sandwich Open Hole Compression



Sandwich Open Hole Flexure

Test Considerations:
Sandwich Open-Hole Compression

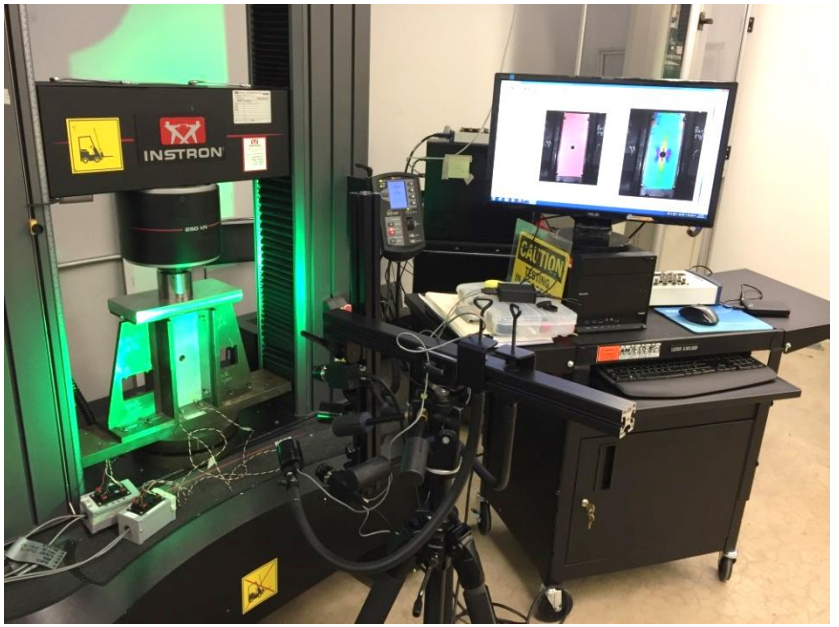
- **Test fixture/Specimen support**
  - **End supports**
    - **Clamping top and bottom**
    - **Potting**
  - **Side supports**
    - **Knife edge**
- **Specimen size**
  - **Separation of central hole and boundary effects**
  - **Production of acceptable strength reductions**
- **Specimen alignment**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



Open-hole compression fixture for monolithic composites

Sandwich Open Hole Compression: Specimen Geometry Investigation

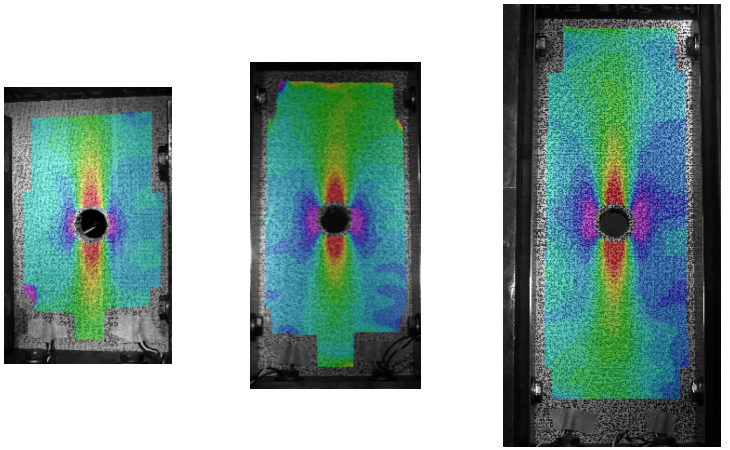
- **Desire width to hole diameter (W/D) ratio to produce suitable strength reduction**
  - Monolithic laminates: 6:1 ratio
- **Require height to width (H/W) ratio to separate effects of hole and loaded ends**
- **Requirements for load introduction at specimen ends**
- **Experimental and numerical investigation**

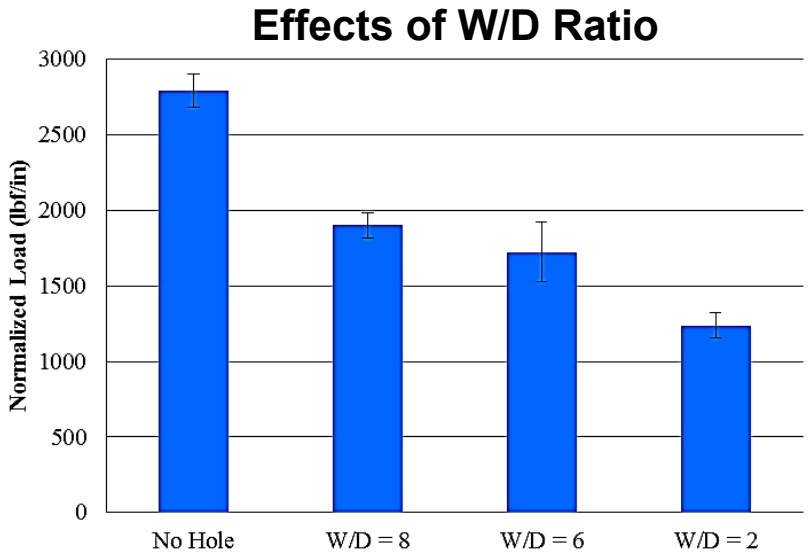


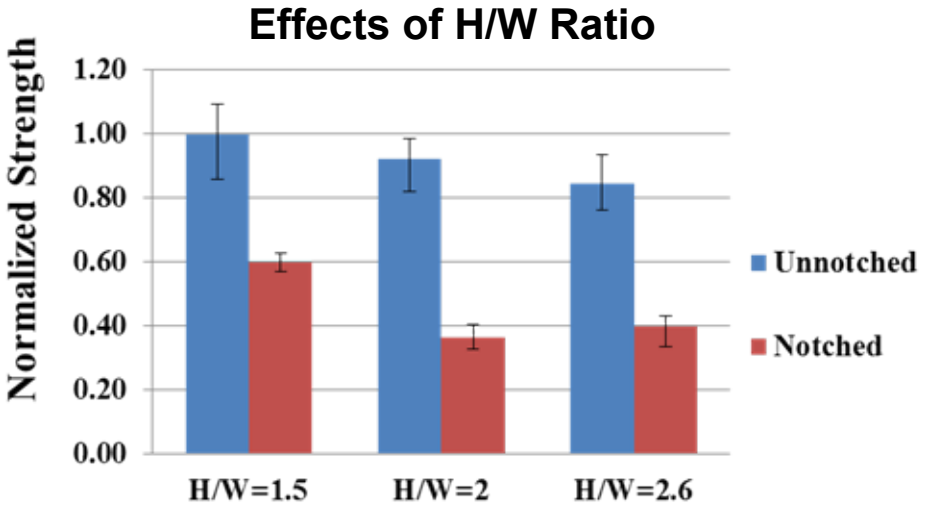
Results:
Sandwich OHC Specimen Geometry Investigation

Preliminary Recommendations

- Width to hole diameter: W/D = 6
- Specimen aspect ratio: H/W = 2
- Specimen size: 4 in x 8 in.,
- Hole diameter: 0.67 in.

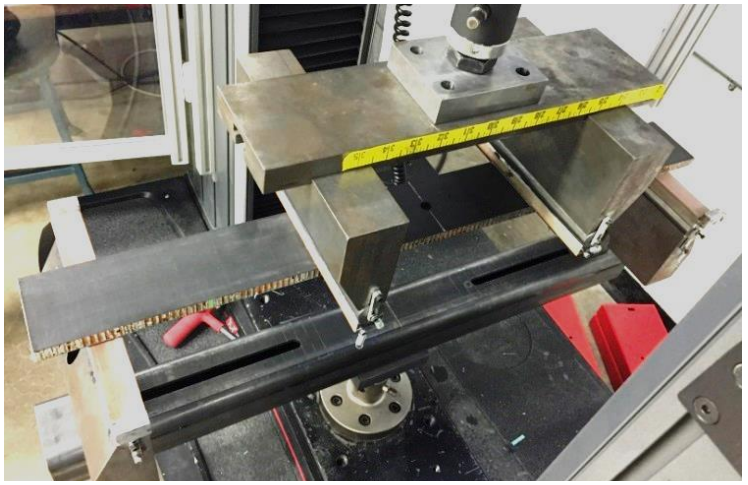


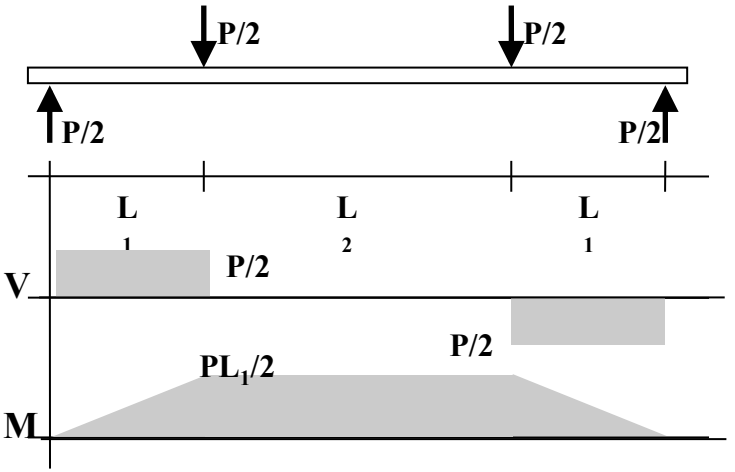




Test Considerations:
Sandwich Open-Hole Flexure Test

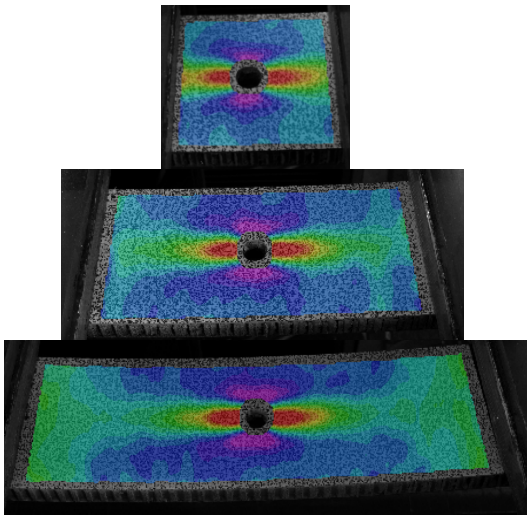
- Desire width to hole diameter (W/D) ratio to produce suitable strength reduction
- Require inner span length to width (L_i/W) ratio to separate effects of hole and load points
- Require outer span length to prevent core shear failures
- Experimental and numerical investigation

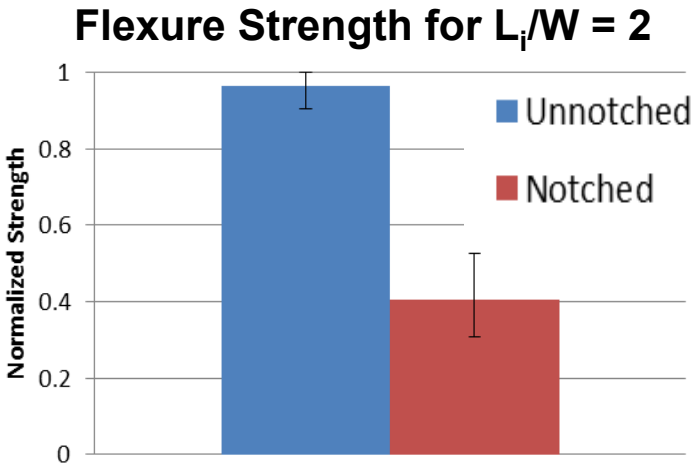




Sandwich Open Hole Flexure: Specimen Geometry Investigation

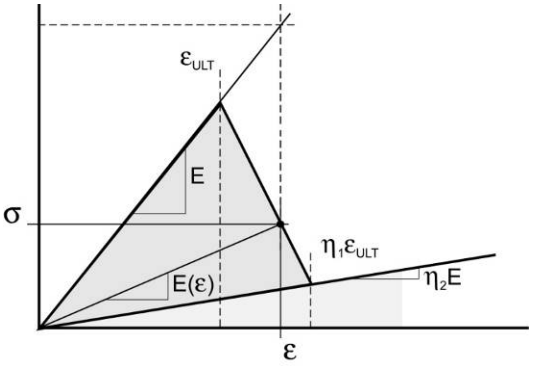
- **Sandwich configuration:**
  - **Carbon/epoxy facesheets**
  - **1 in. thick 8 lb/ft^3 Nomex core**
- **Specimen geometry:**
  - **Width to hole diameter: W/D = 6**
    - Specimen width: 3 in.
    - Hole diameter: 0.5 in.
- **Effects of inner span, L_i**
  - **3 in., 6 in., and 9 in.**
  - **Constant applied moment**
    - **Outer span – Inner span = 20 in.**
    - Inner span to width : $L_i/W = 2$

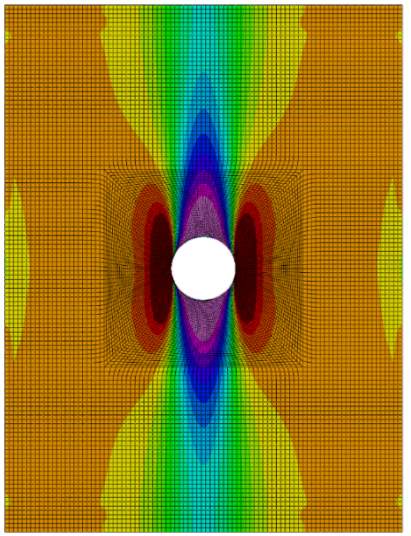




Analysis of Notched Sandwich Specimens ABAQUS with NDBILIN:

- User-defined nonlinear material model (UMAT) for ABAQUS Standard
- 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





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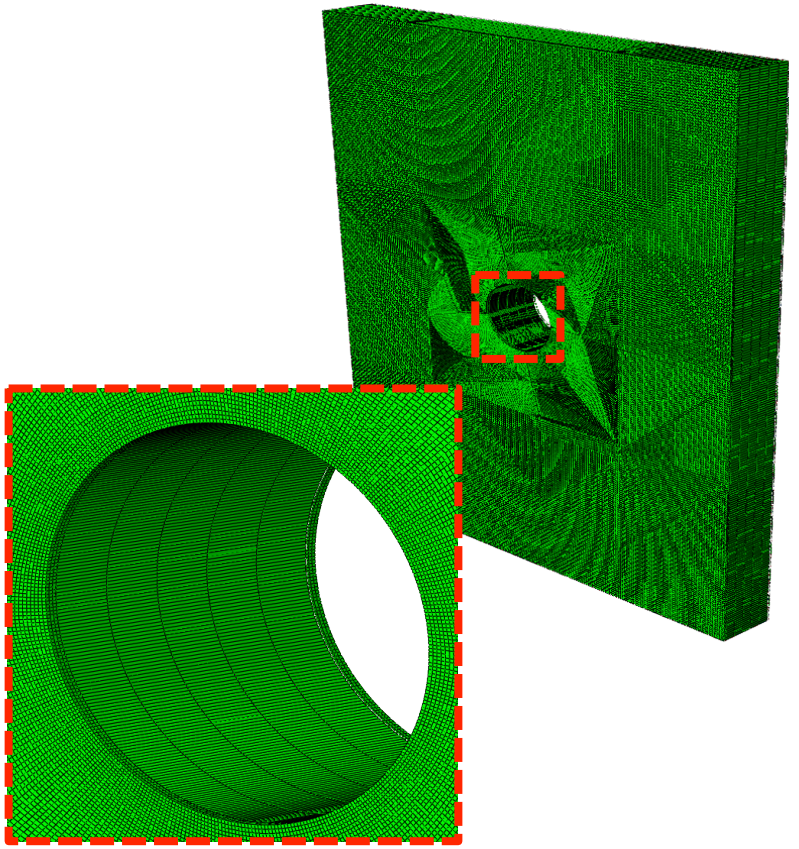
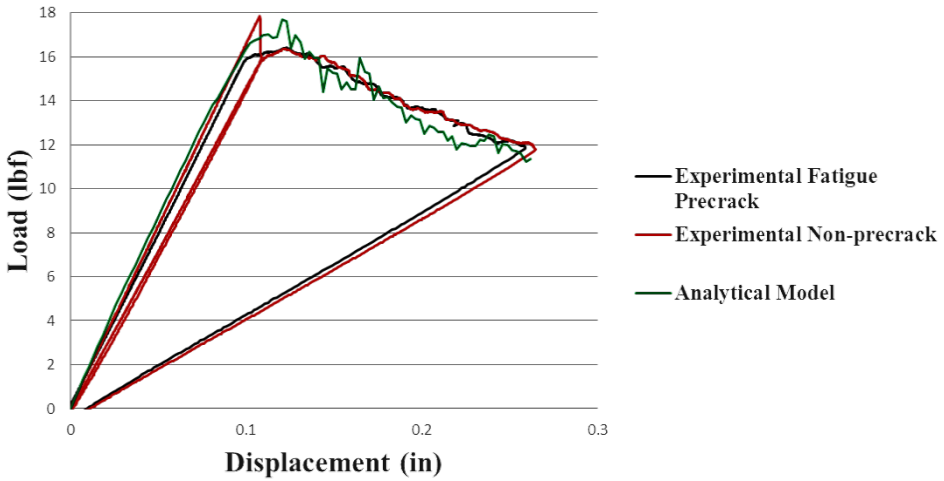
Analysis of Notched Sandwich Specimens
Numerical Modeling Approach:

- **Composite laminate facesheets:**
  - One element per ply thickness
- **Core material:**
  - Currently linear elastic elements
- **Cohesive elements:**
  - Between plies in facesheets
  - Between facesheets and core
- **Refined mesh in notch region**
- **Progressive damage analysis via NDBILIN material model**

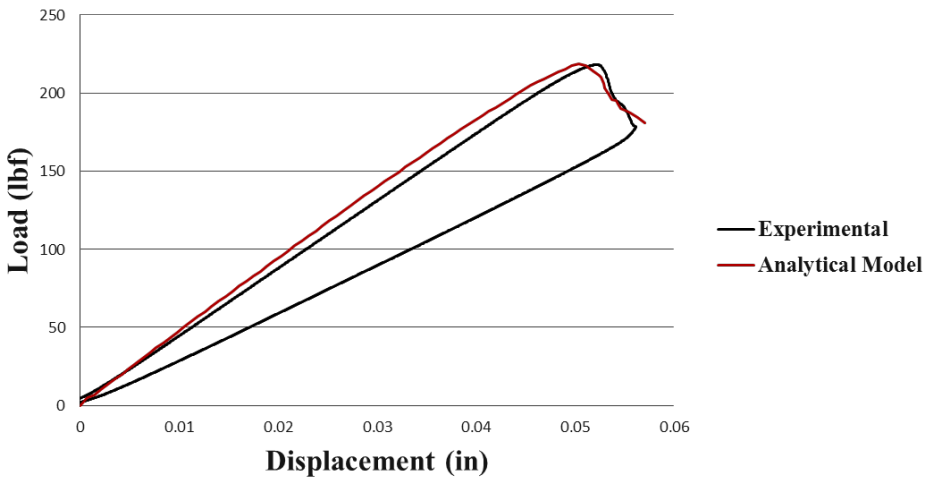


Calibration of Cohesive Elements: Carbon/Epoxy Facesheets

Mode I
Double Cantilever Beam (ASTM D5528)

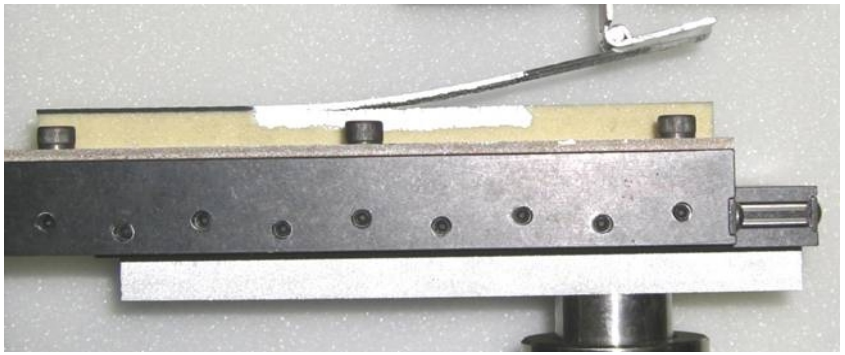


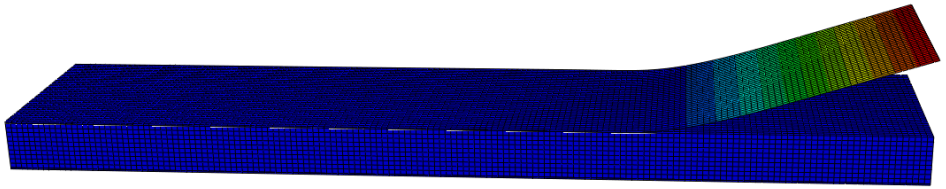
Mode II
End Notched Flexure (ASTM D7905)



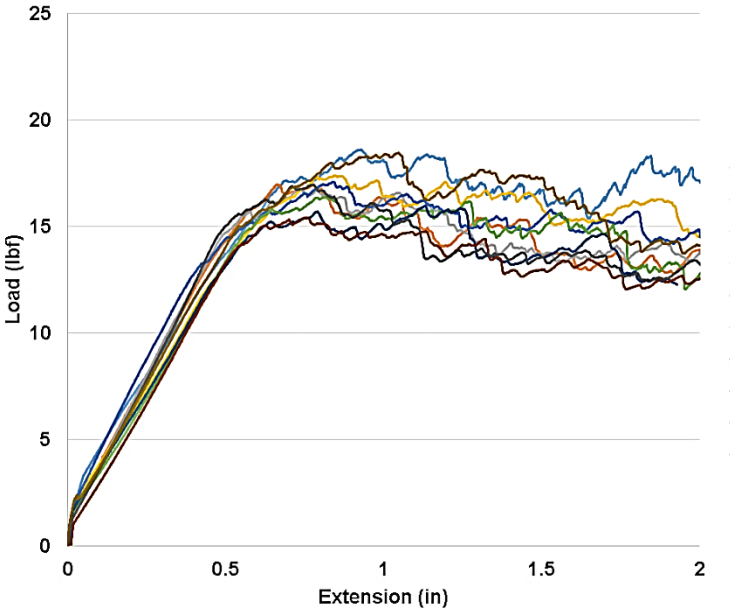
Calibration of Cohesive Elements: Facesheet/Core Interface

Mode I: Sandwich Single Cantilever Beam (SCB) Test





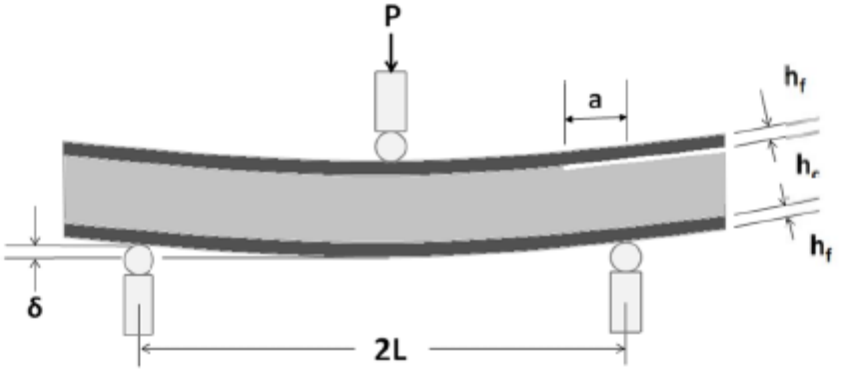
SCB Model Displacements

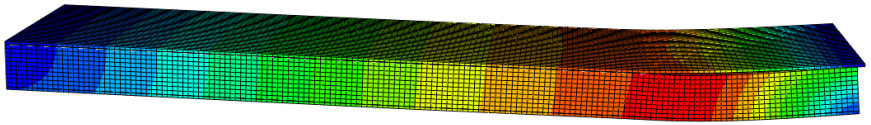


Load vs Extension Data

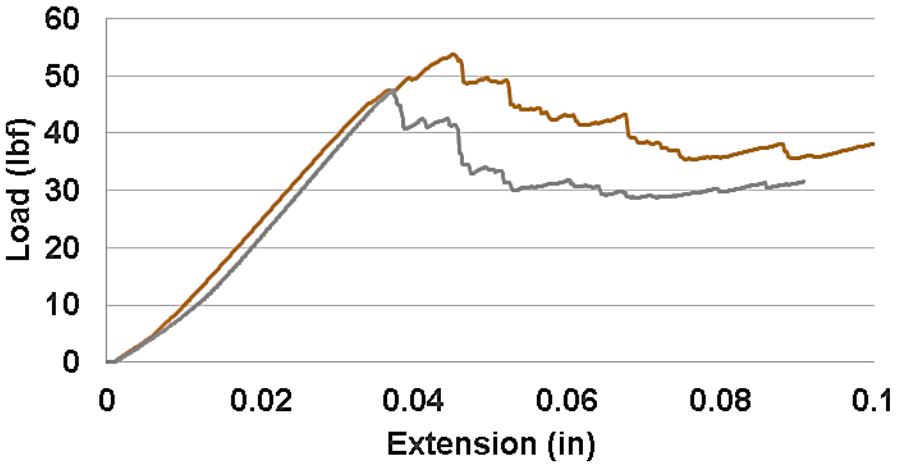
Calibration of Cohesive Elements: Facesheet/Core Interface

Mode II: Separated End Notched Flexure





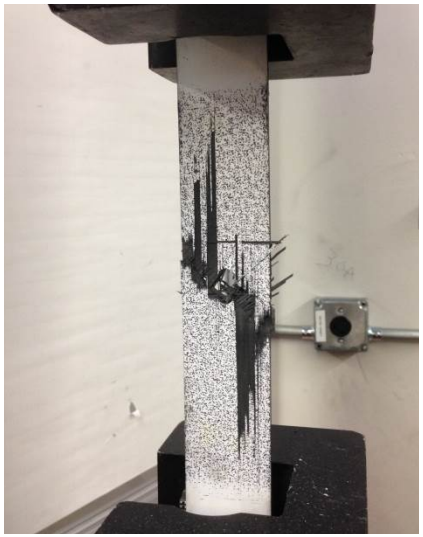
Sandwich Model Displacements

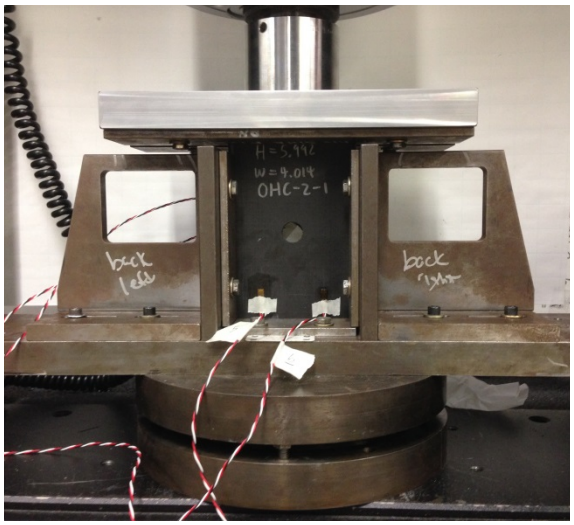


Load vs Extension Data

Analysis of Notched Sandwich Specimens
Validation of Modeling Approach

- **Modeling of damage progression in carbon/epoxy facesheet material**
  - **Open-hole tension test**
  - **Open-hole compression test**
- **Modeling of damage progression in sandwich composites**
  - **Sandwich open-hole compression**
  - **Sandwich open-hole flexure**



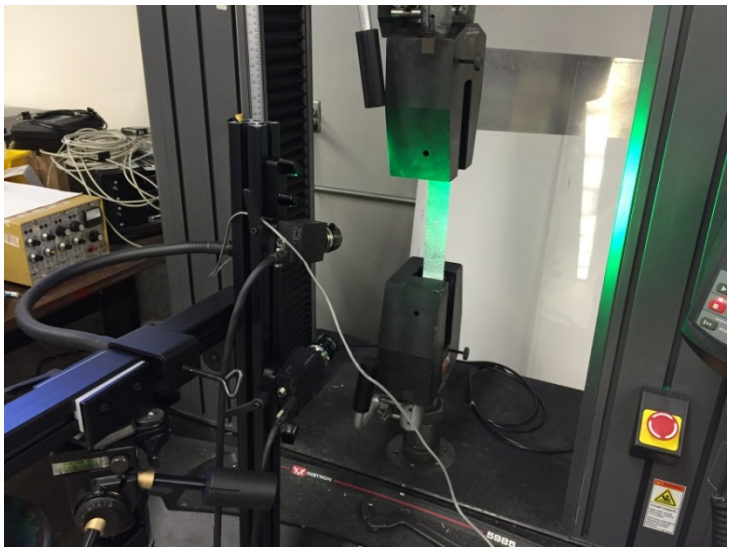


Damage Progression in Facesheets: Analysis of Open Hole Tests

- Simulation of open-hole testing of IM7/8552 carbon/epoxy laminates
- Open-hole tension (ASTM D5766)

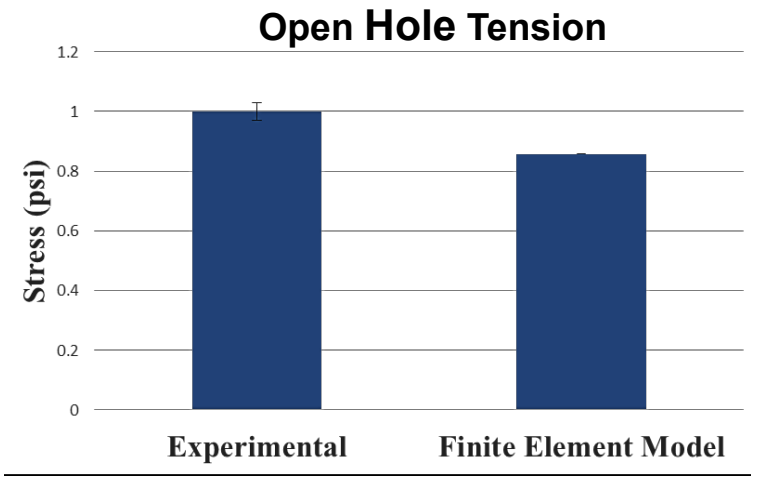
  $[0/90/0]_T$
- Open-hole compression (ASTM D6484)

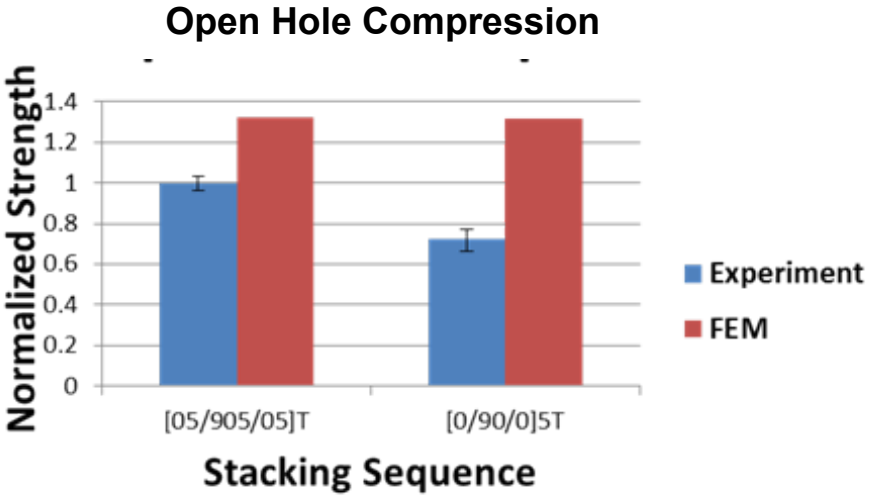
  $[0_5/90_5/0_5]_T$ $[0/90/0]_{5T}$
- Comparison with results from mechanical testing
  - Ultimate strength
  - Stress vs. strain plots
  - Strain fields from Digital Image Correlation
  - Damage Progression using X-ray CT



Damage Progression in Facesheets: Analysis of Open Hole Tests

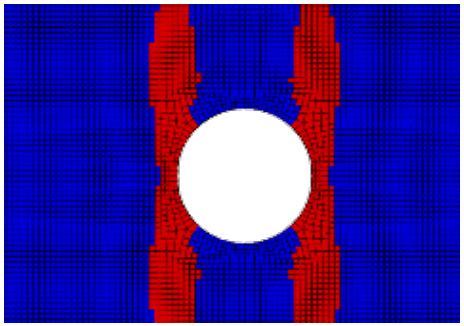
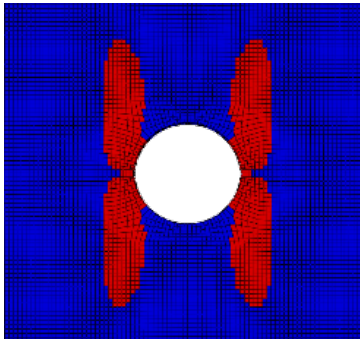
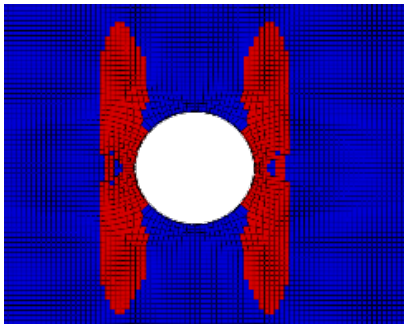
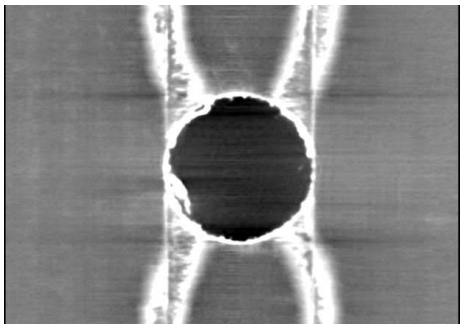
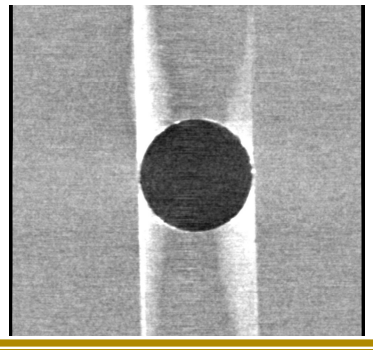
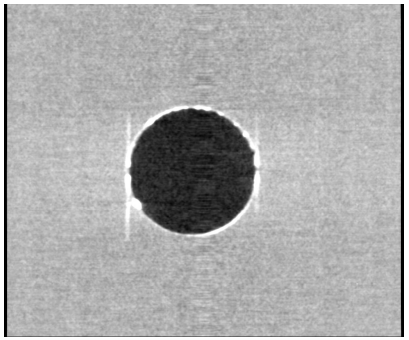
- **Better correlation on failure stress in tension than in compression**
- **Compression strength over-predicted in finite element simulation**
  - **Investigating ABAQUS Riks buckling analysis**





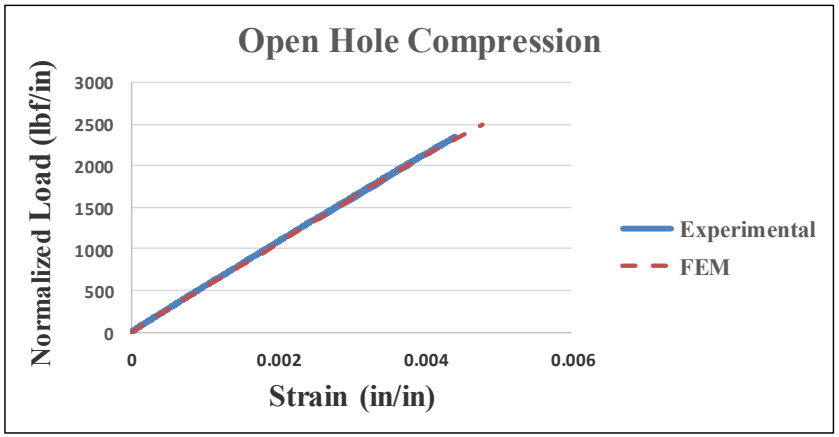
Damage Progression in Facesheets: Analysis of Open Hole Tests

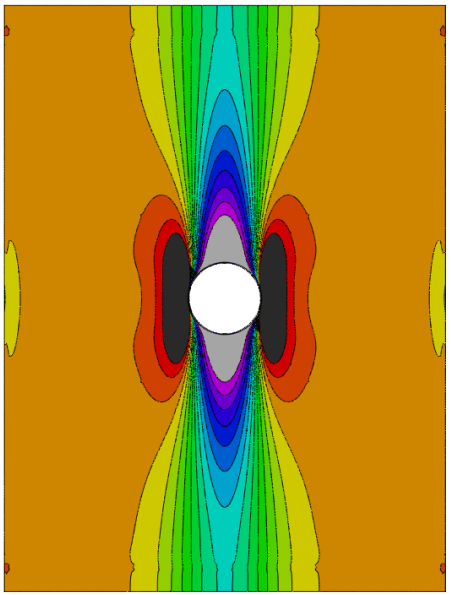
- Better correlation of damage propagation in tension than in compression
- Compressive failure modes not predicted in model

	Tension $[0/90/0]_T$	Compression $[0/90/0]_{5T}$	Compression $[0_5/90_5/0_5]_T$
ABAQUS/ NDBILIN			
X-ray CT			

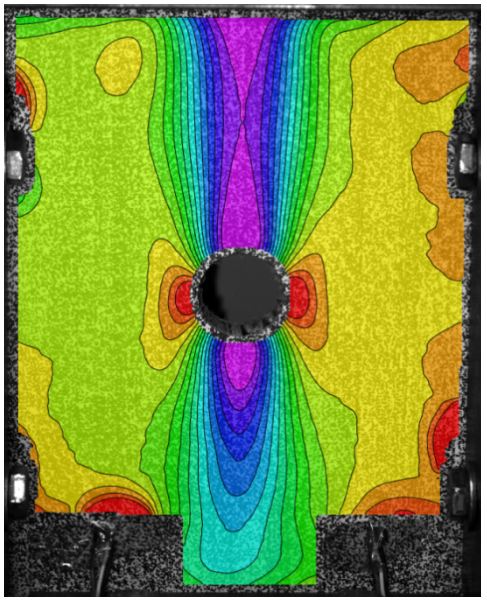
Damage Progression in Sandwich Composites: Sandwich Open-Hole Compression Test

- Good agreement with measured stiffness
- Over-prediction of notched compression strength
- Incorporating cohesive elements between facesheet and core





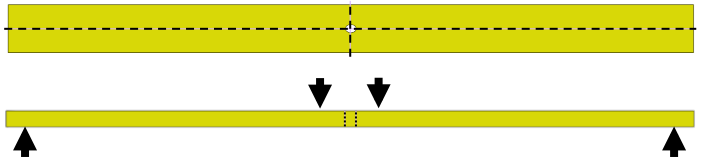
ABAQUS/NDBILIN Prediction

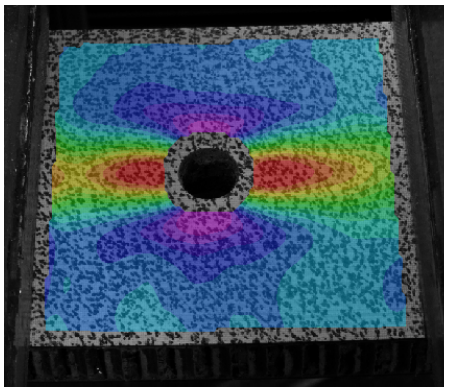


DIC Results

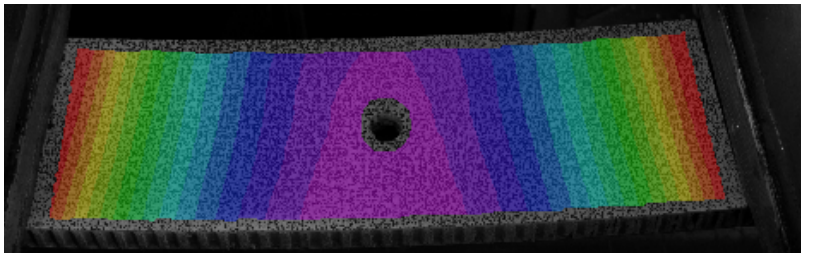
Current Focus:
Sandwich Open-Hole Flexure Test

- No observed out-of-plane buckling from DIC results
- Use of quarter-symmetry model with symmetry boundary conditions
- Exploring modeling of central span with applied bending moments





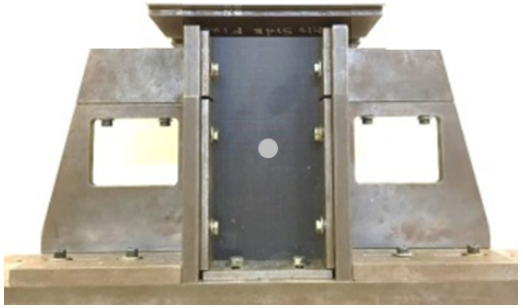
DIC: Compression Strains

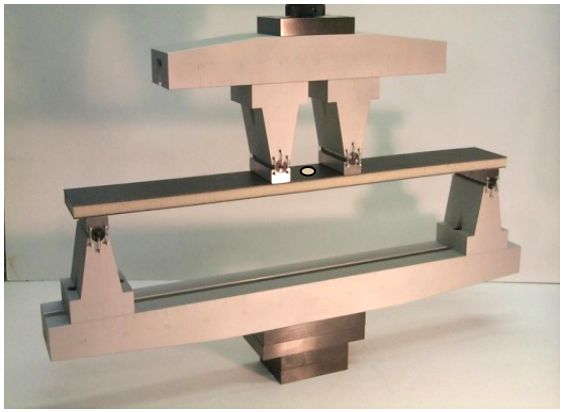


DIC: Out-of-plane deformation

Upcoming Work:
Notch Sensitivity of Sandwich Composites

- Development of sizing guidelines for sandwich open hole compression and flexure tests
- Incorporate Riks Buckling analysis in laminate and sandwich compression models
- Modeling damage progression in sandwich open-hole flexure
- Selection next loading configuration for investigation





Summary:
Benefits to Aviation

- **Standardized test methods for sandwich composites:**
  - **Fracture mechanics**
  - **Damage tolerance**
  - **Notch sensitivity**
- **Development of notch sensitivity analysis methods for sandwich composites**
- **Scaling of test results for application on composite sandwich structures**

Thank you for your attention!

Questions?

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