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Evaluation of Notch Sensitivity in Composite Sandwich Structures

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University of Utah

2015 Technical Review

THE UNIVERSITY OF UTAH

FAA Sponsored Project Information

- Principal Investigators:
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  - **Dr. Mike Czabaj**
- Graduate Student Researchers:
  - **Marcus Stanfield**
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- FAA Technical Monitor:
  - **Lynn Pham**
- Primary Collaborators:
  - **Materials Sciences Corporation**
  - **Oregon State University**
  - **ASTM Committee D30**

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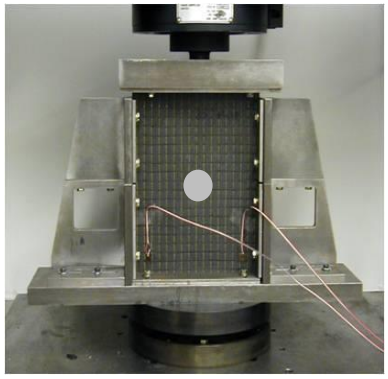
The University of Utah

Outline

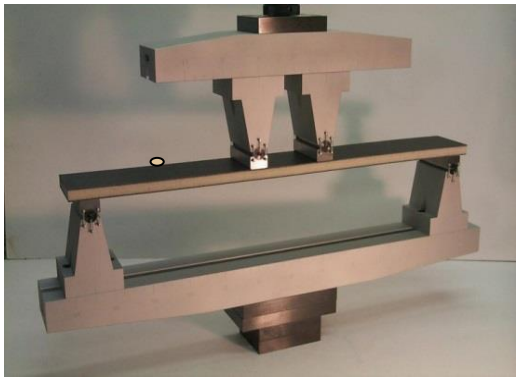
- **Introduction: Notch sensitivity of sandwich composites**
- **Sandwich Open Hole Compression test**
  - **Test method development**
  - **Numerical modeling: progressive damage analysis**
  - **Current status and future plans**
- **Sandwich Open Hole Flexure test**
- **Brief updates from previous sandwich composites research**
  - **Sandwich fracture mechanics**
  - **Sandwich damage tolerance**

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) with Parmigiani group (OSU)**
- **Explore development of new ASTM standards for notch sensitivity of sandwich composites**



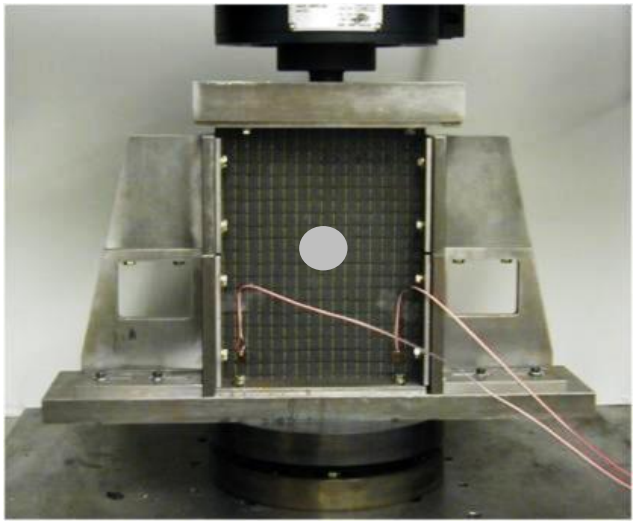
Sandwich Open Hole Compression



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**

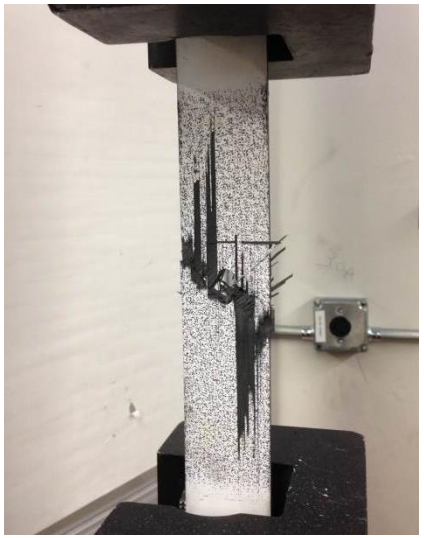


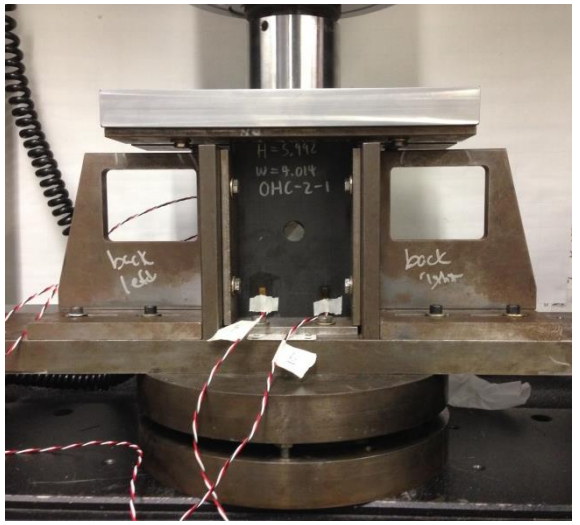
- **Specimen size**
  - **Separation of central hole and boundary effects**
  - **Production of acceptable strength reductions**
- **Specimen alignment**
- **Strain measurement**

Open hole compression fixture for monolithic composites

Failure Analysis of Notched Sandwich Specimens
Development of Modeling Approach

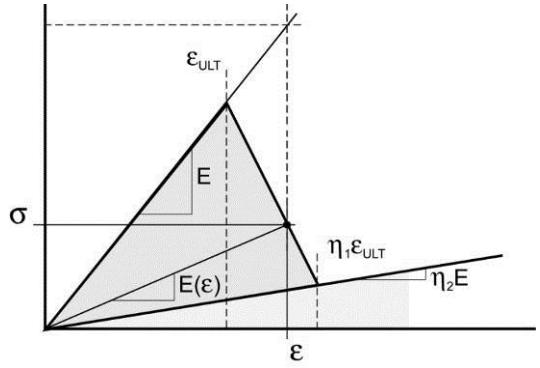
- **Modeling of damage progression in carbon/epoxy facesheet material**
  - **Open-hole tension test**
  - **Open-hole compression test**
- **Modeling of damage progression in sandwich composites**
  - **Sandwich open-hole compression**

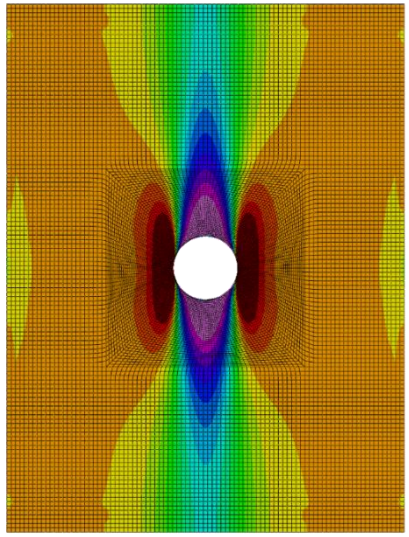




Analysis of Notched Sandwich Specimens
ABAQUS with NDBILIN:

- 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

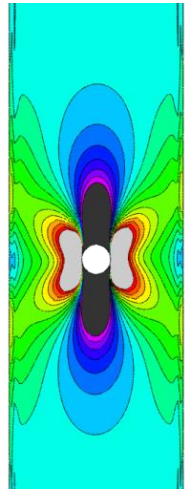
Damage Progression in Facesheets: Analysis of Open Hole Tests

- Simulation of open-hole tension (ASTM D5766) and compression (ASTM D6484) testing of IM7/8552 carbon/epoxy laminates

  $[0/90/\pm45]_{2S}$ $[45/0/-45/90]_{2S}$ $[90/45/0/-45]_{2S}$

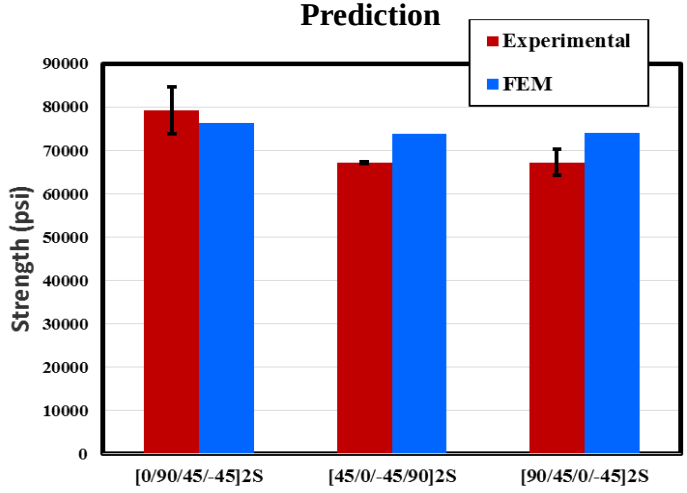
- Comparison with results from mechanical testing
  - Ultimate strength
  - Stress vs. strain plots
  - Strain fields from Digital Image Correlation

- Sandwich facesheet layup $[0/90/0]_T$ currently under investigation



Finite Element Prediction

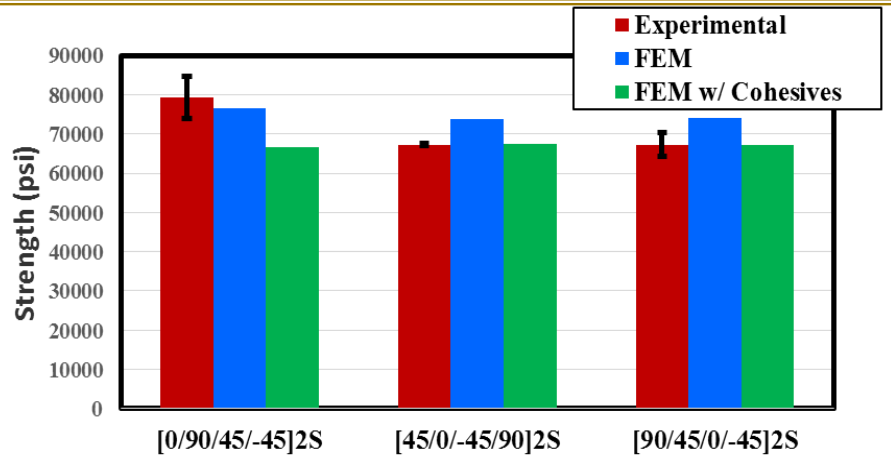
Experimental Result



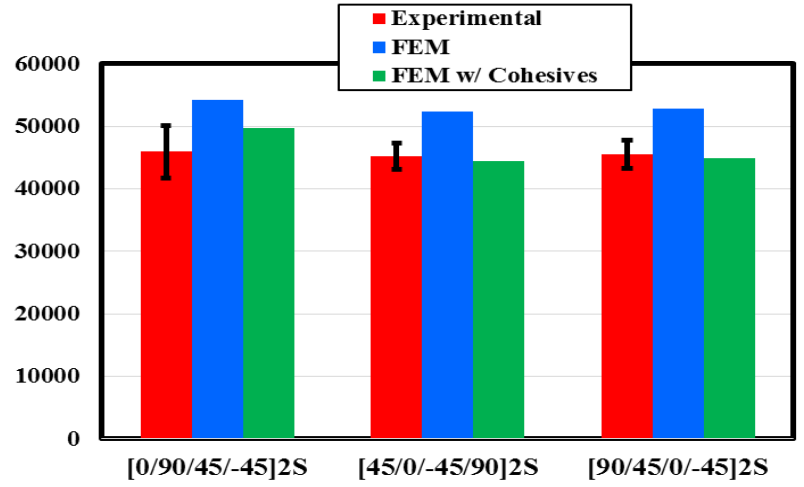
Open-Hole Tension Results

Damage Progression in Facesheets: Incorporation of ABAQUS Cohesive Elements

- Over prediction of strength without cohesive elements
- Cohesive elements calibrated using Mode I & II fracture toughness testing
- Decrease in strength prediction with cohesive elements inserted between plies
- Investigation continuing



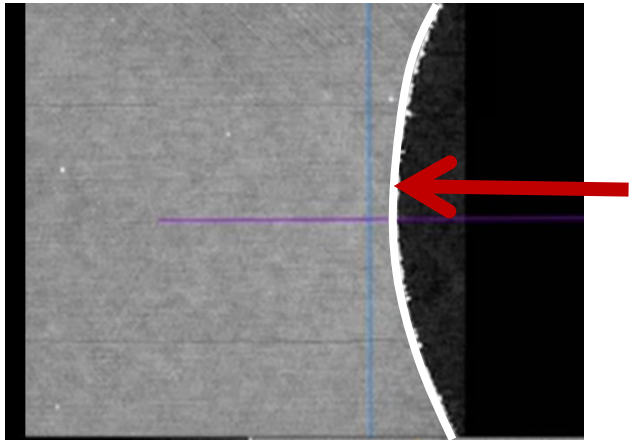
Open-Hole Tension



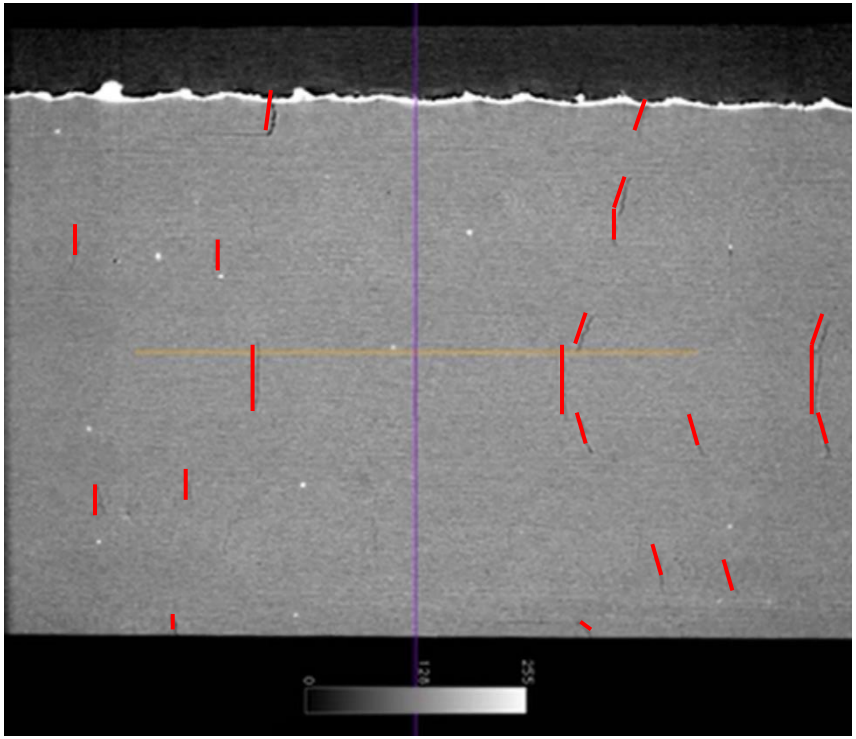
Open-Hole Compression

Damage Progression in Facesheets:
Experimental Determination of Damage Accumulation

X-ray Micro-CT scan results: Open hole tension testing of $[45/0/-45/90]_{2S}$ laminate (~80% of ultimate load)

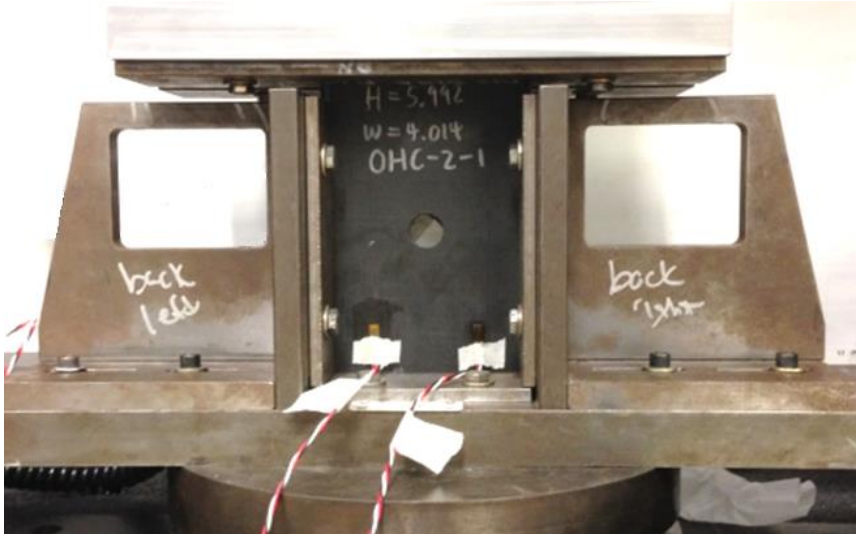


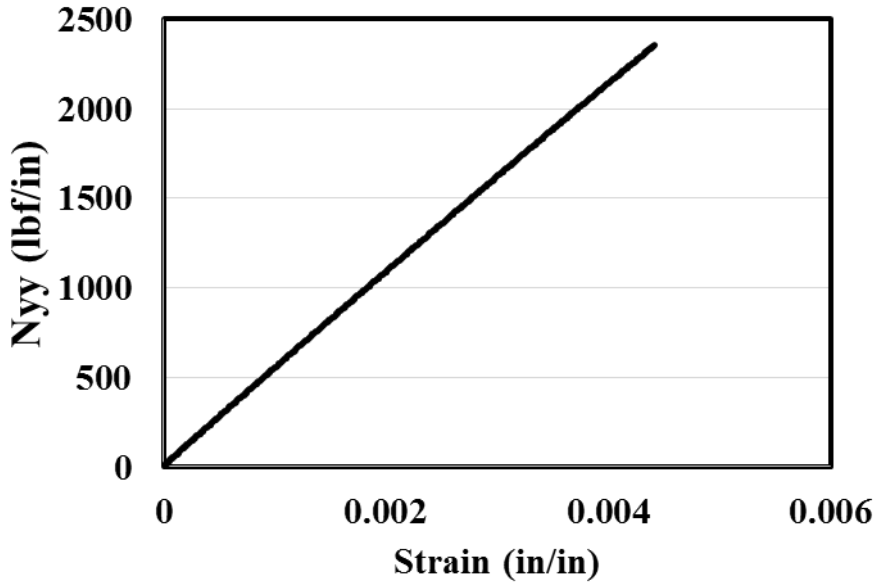
Edge of hole



Damage Progression in Sandwich Composites:
Sandwich Open Hole Compression Test

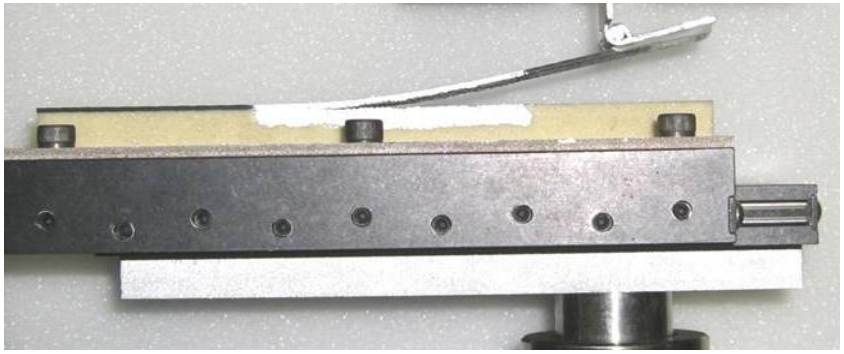
- IM7/8552 carbon/epoxy $[0/90/0]_T$ facesheets
- 3 lb/ft^3 0.5 in. thick Nomex honeycomb core
- 4.5 in. wide x 6.0 in. tall specimens
- 0.75 in. central circular hole (W/D = 6)



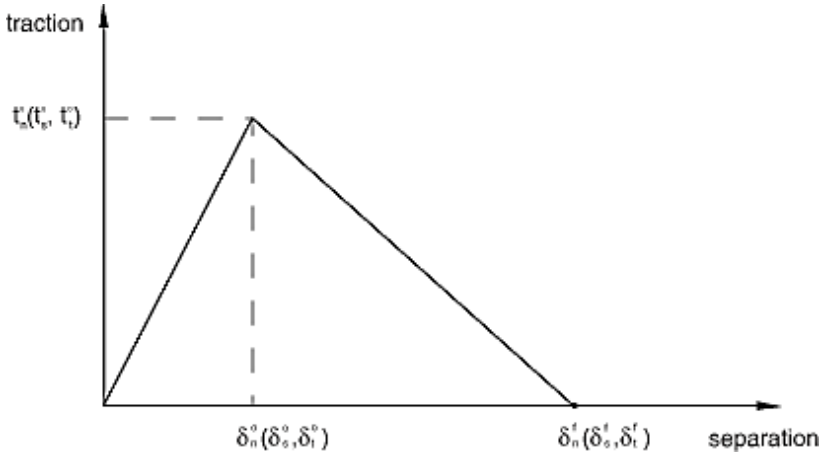


Damage Progression in Facesheets: Incorporation of ABAQUS Cohesive Elements

- **Use of Mode I Single Cantilever Beam (SCB) and Mode II Sandwich Flexure test methods for facesheet/core disbonding**
- **Incorporation of ABAQUS cohesive elements between facesheets and core**



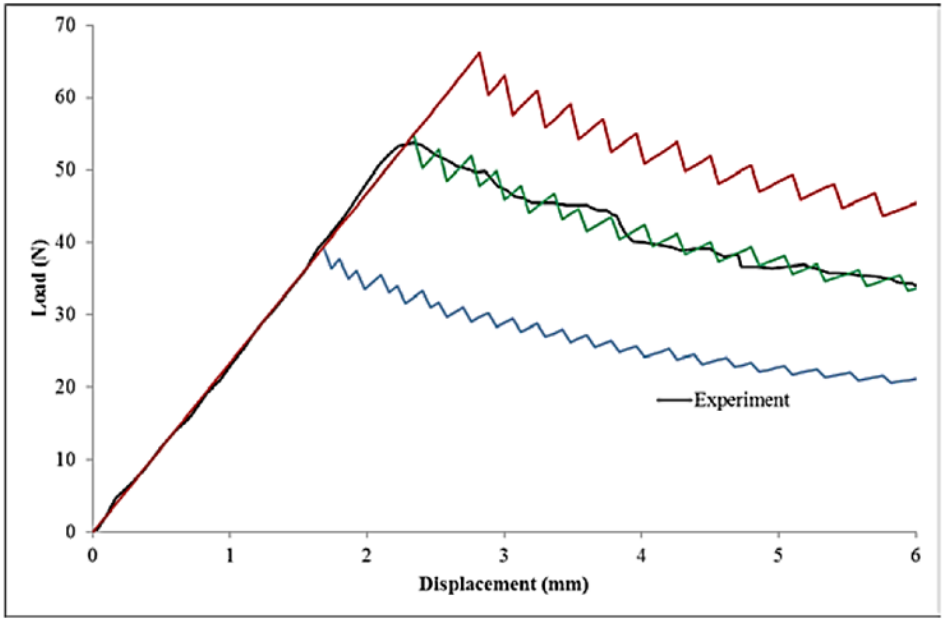
Single Cantilever Beam Test

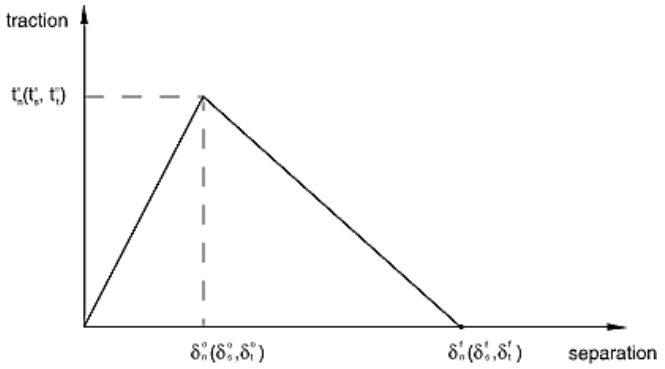


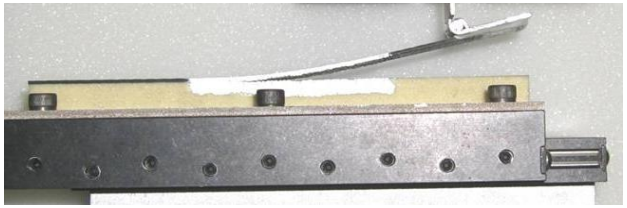
Traction Separation Constitutive Response

Damage Progression in Sandwich Composites: Cohesive Element Sensitivity Study

- **Simulation of SCB test**
- **Comparison of predicted and experimental load displacement curves**
- **Optimization of cohesive element parameters**

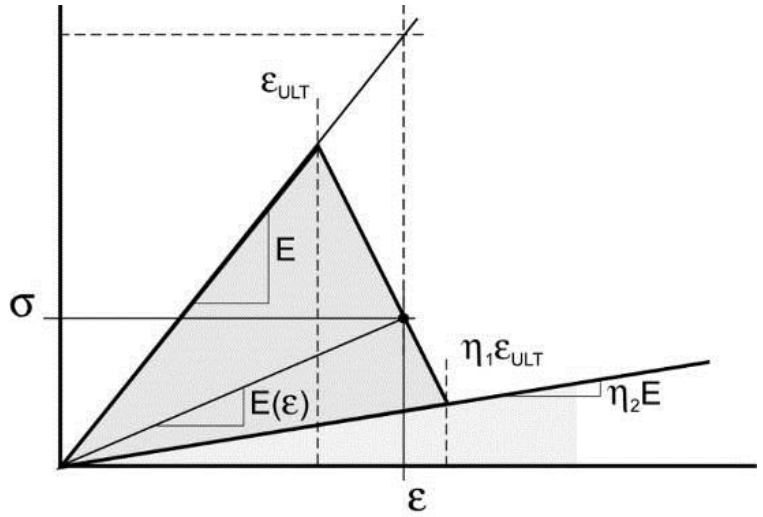




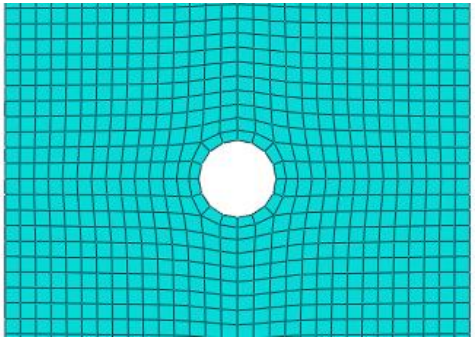


Damage Progression in Sandwich Composites: Sensitivity Study

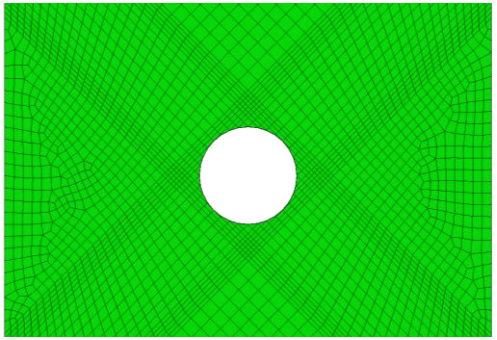
- **Material properties**
  - **Tension/compression**
- **Mesh density**
- **Mesh orientation**
  - **Random**
  - **Notch centric**
  - **Aligned with fiber direction**
- **Solution parameters**
  - **Viscous damping**
  - **Step size**



Damage parameters



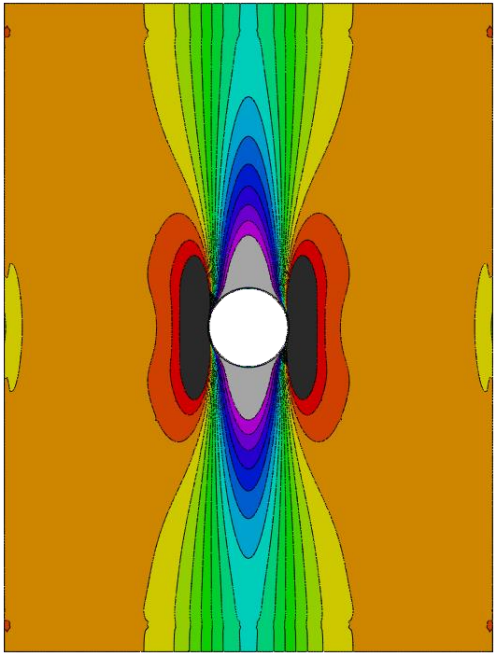
Notch-centric mesh



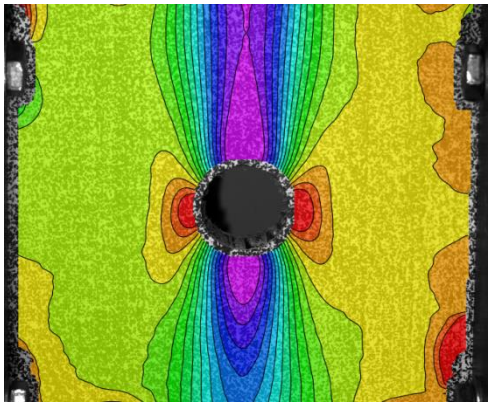
Fiber-aligned mesh

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

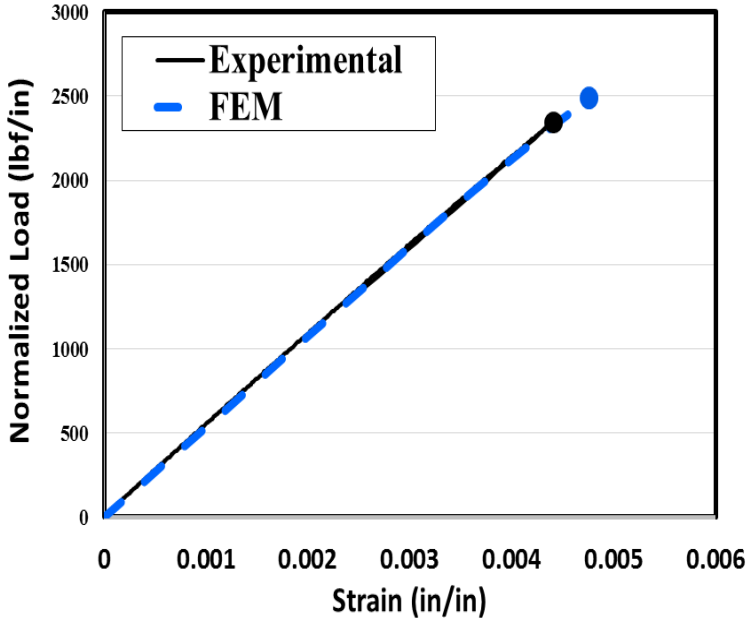
- Good agreement with measured stiffness
- Over-prediction of notched compression strength



ABAQUS/NDBILIN Prediction

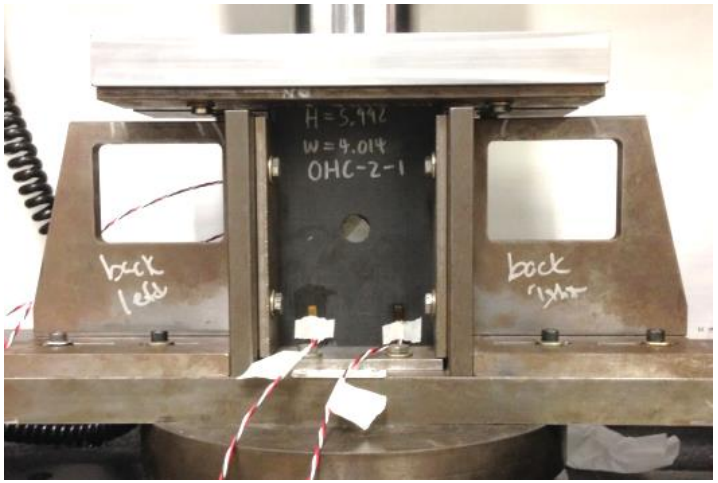


Digital Image Correlation Results

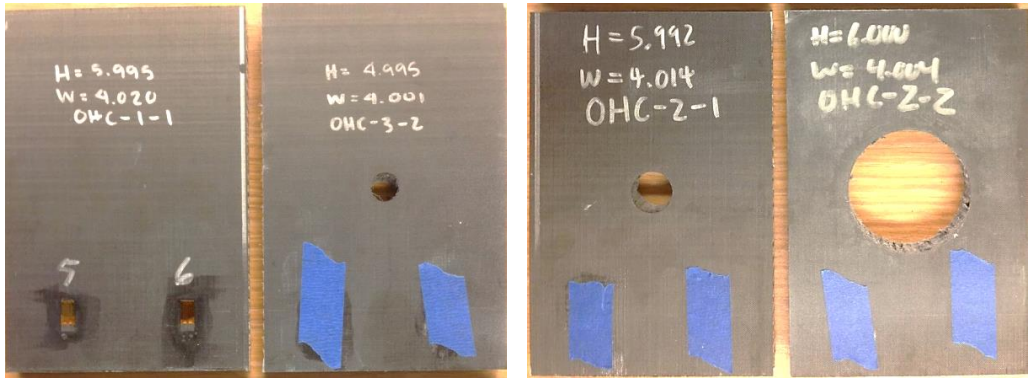


Current Focus:
Notch Size Effects in Sandwich OHC Testing

- **Resized specimen**
  - **4.0 in. x 6.0 in.**
  - **Same fixturing as laminate CAI**



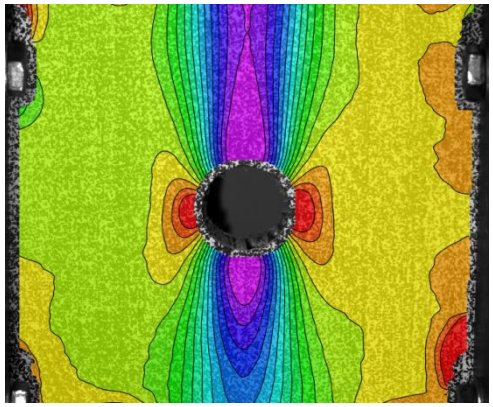
- **Three hole diameters**
  - **1/2 in. dia (W/D = 8)**
  - **2/3 in. dia (W/D = 6)**
  - **2 in. dia (W/D = 2)**
  - **Differences in failure progressions**
  - **Separation of central hole and boundary effects**

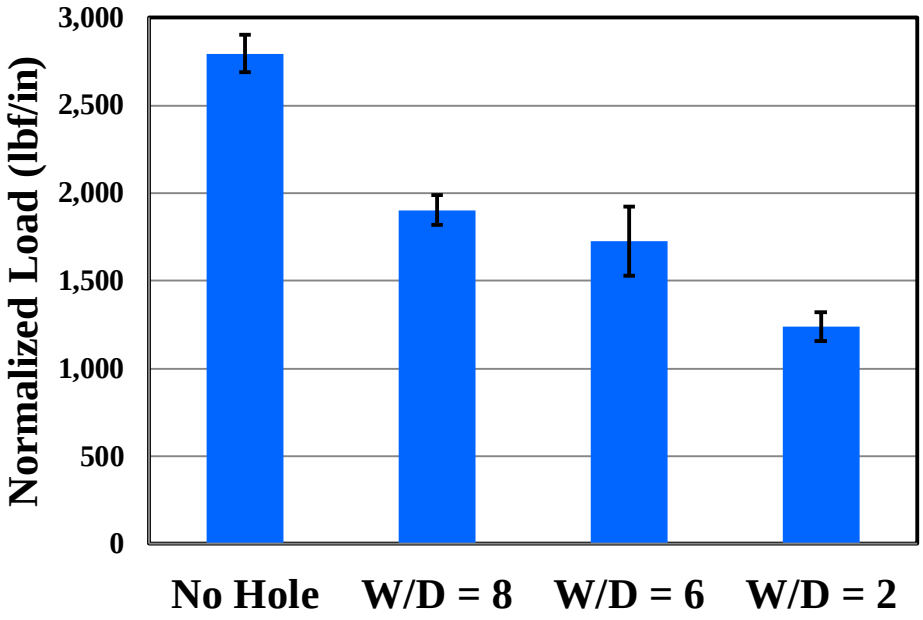


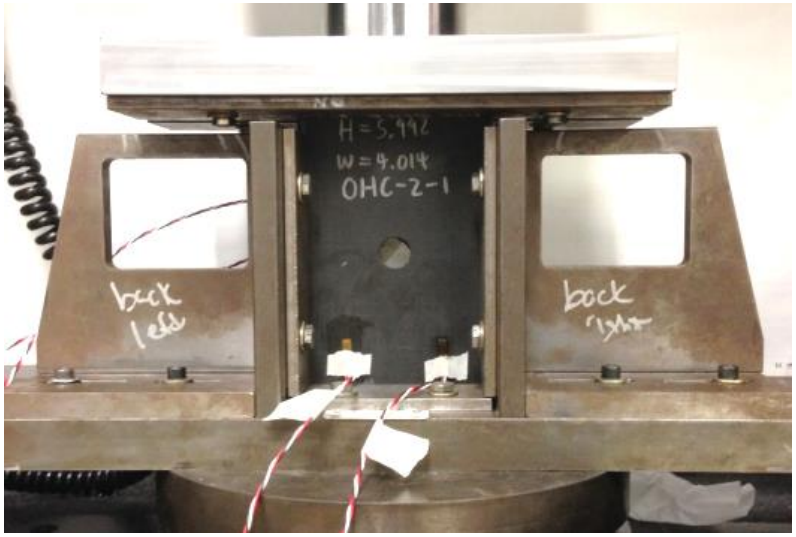
No Hole **W/D = 8** **W/D = 6** **W/D = 2**

Recent Results:
Notch Size Effects in Sandwich OHC Testing

- **Strain profiles obtained using Digital Image Correlation**
- **Numerical simulation underway**

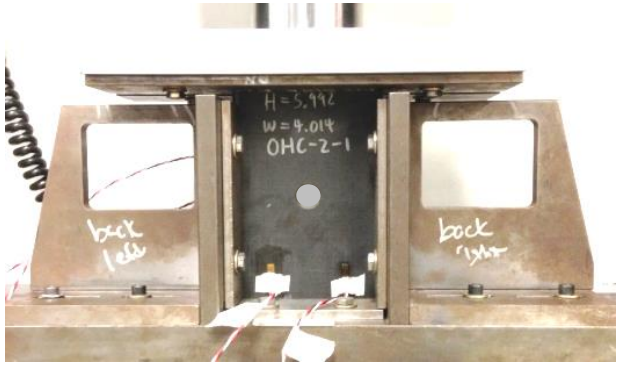




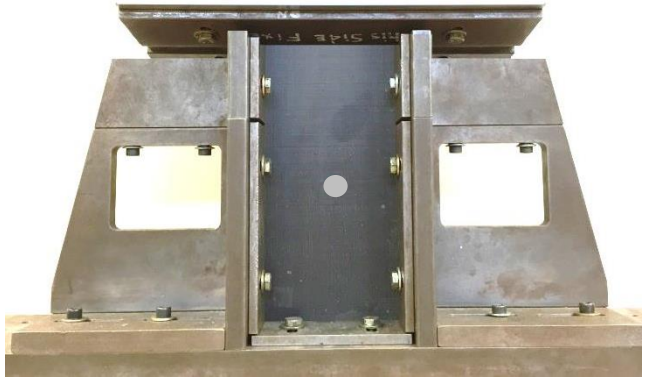


Current Focus:
Notch Size Effects in Sandwich OHC Testing

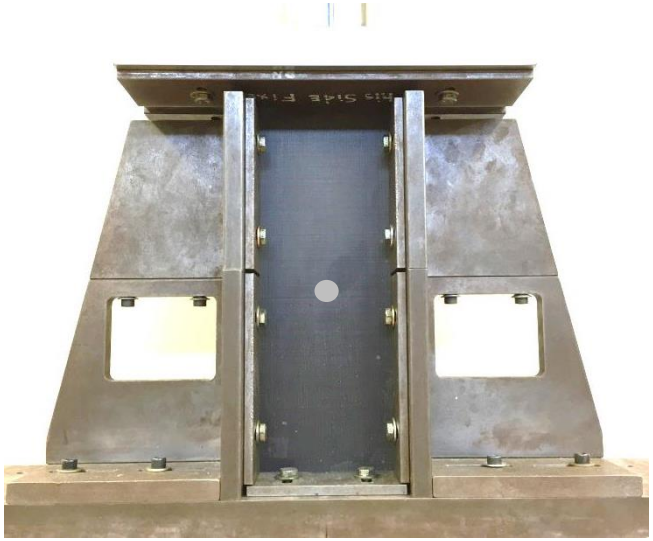
- Investigation of specimen aspect ratio (H/W)
- Specimen width = 4.0 in.
- Hole diameter = 2/3 in. (W/D = 6)
- Investigating three specimen heights
  - 6 in. (H/W = 1.5)
  - 8 in. (H/W = 2.0)
  - 10.5 in. (H/W = 2.6)



H/W = 1.5



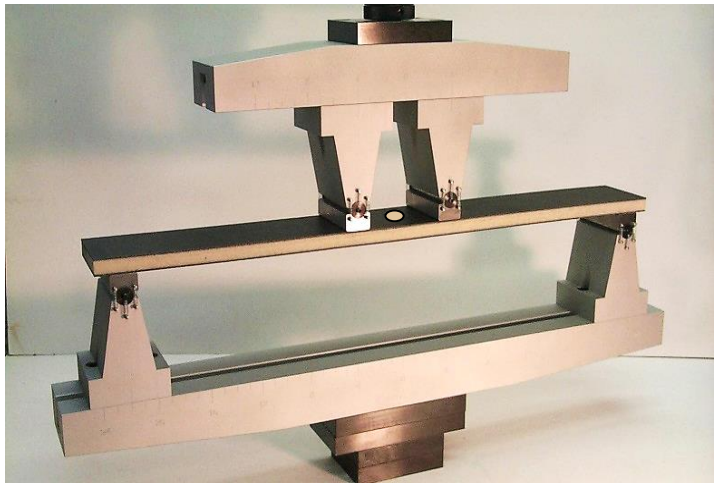
H/W = 2.0

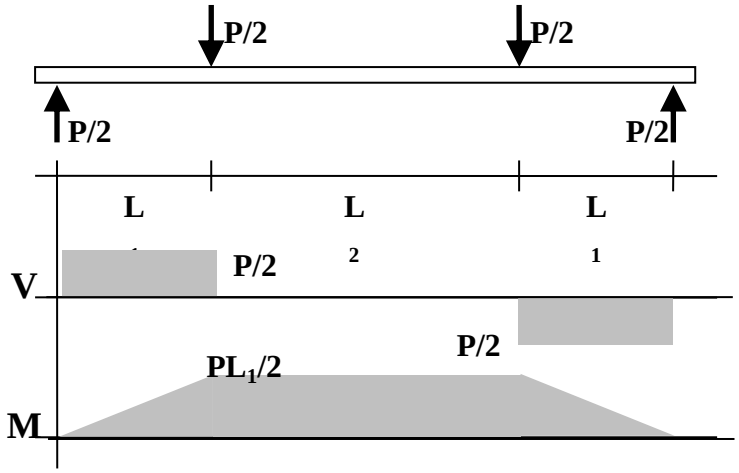


H/W = 2.6

Testing Considerations: Sandwich Open-Hole Flexure Test

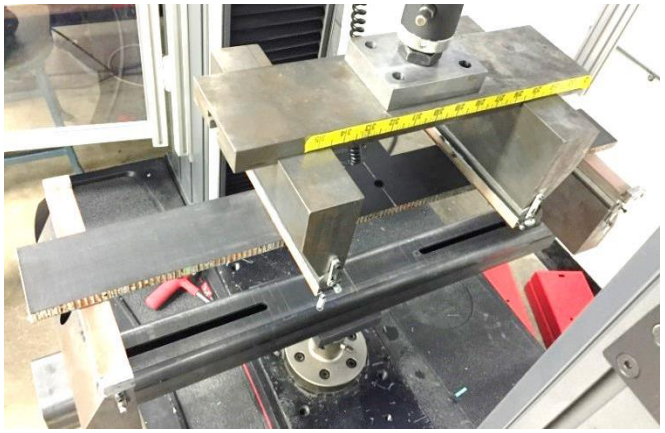
- **Test fixture/Specimen support**
  - **Inner span**
    - **Separation of notch and loading boundary effects**
  - **Outer span**
    - **Develop sufficient bending moment**
    - **Ensure failure in inner span**
- **Specimen size**

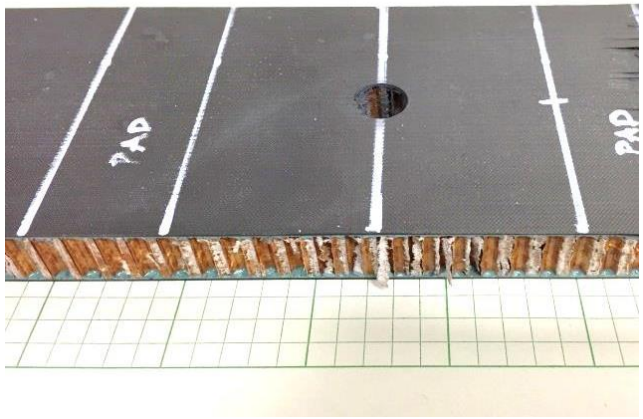




Sandwich Open-Hole Flexure Test: Initial Testing

- **Specimens dimensioned according to long-beam flexure test method ASTM D7249**
  - **Carbon/epoxy facesheets**
  - **0.5 in. Nomex honeycomb core**
  - **3 in. width x 30 in. length**
  - **4 in. inner span**
  - **28.5 in. outer span**
  - **0.5 in. dia. central circular hole**
- **Investigating effect of inner span length**

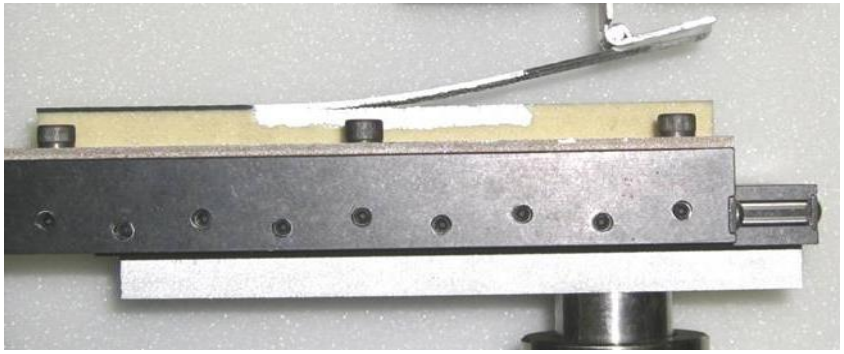


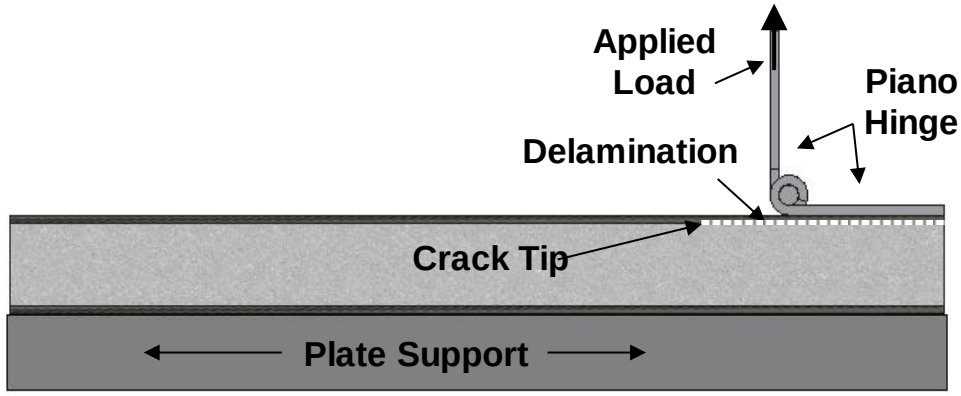


Status Update:
Mode I Sandwich Fracture Mechanics Test Method

Single Cantilever Beam (SCB) Test Method

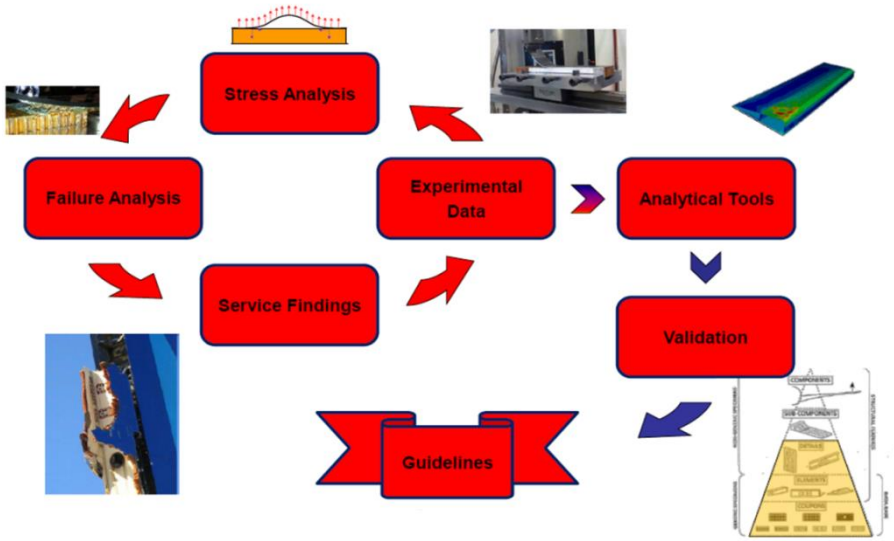
- Draft ASTM standard completed!
- International round-robin test program initiated
  - 7 test labs with previous SCB testing experience
  - Baseline sandwich specimens to be fabricated by NIAR
- Included in sandwich disbond assessment initiative





Status Update:
Sandwich Disbond Assessment Initiative

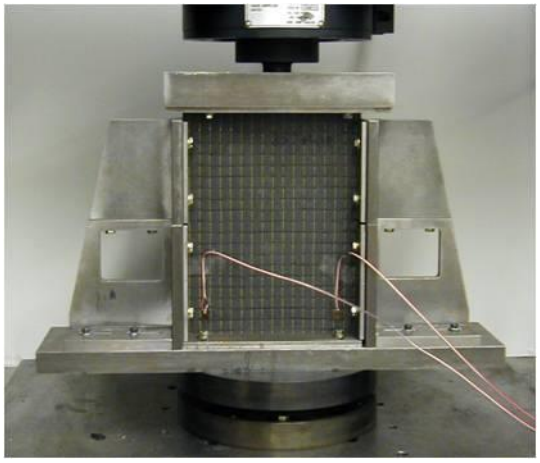
- **Identify, describe and address the phenomenon associated with facesheet/core disbonding and core fracture**
- **Develop a methodology to assess facesheet/core disbonding in sandwich components**
  - **Coupon**
  - **Sub-element**
- **New sections in CHM-17 (Volume 6)**



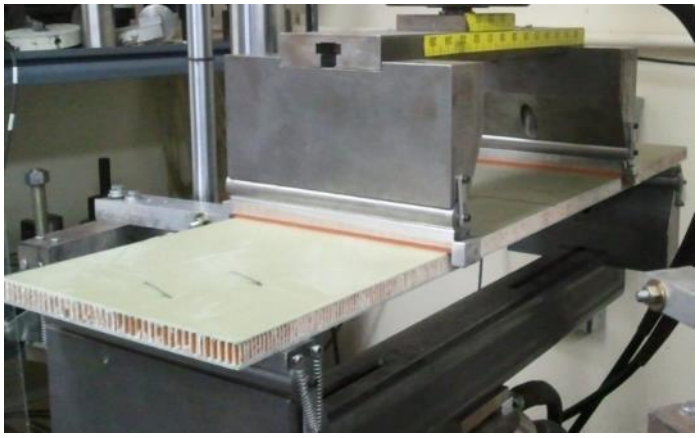
Seneviratne, W., "Fatigue Damage Growth Rate of Sandwich Structures using Single Cantilever Beam (SCB) Test," 2014 JAMS Technical Review

Status Update:
Development of Sandwich Damage Tolerance Test Methods

- **Draft standard of Sandwich CAI completed**
- **Presented to ASTM D30 (Salt Lake City March 2015)**
- **Follow-on "scaling" effort underway through Air Force SBIR program**



Compression After Impact (CAI)

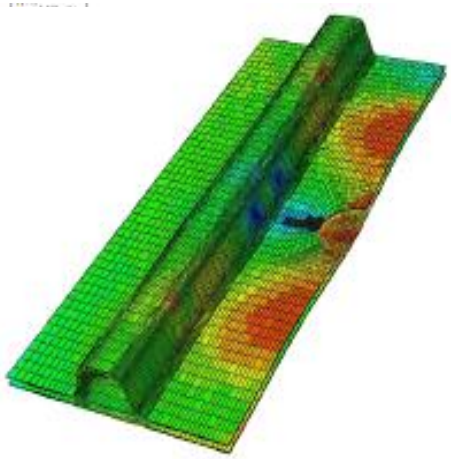


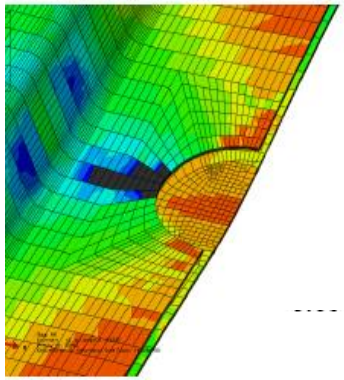
4-Point Flexure After Impact (4-FAI)

Follow-On Sandwich Damage Tolerance Effort:

Scale-Up of Sandwich Damage Tolerance Test Results

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





msc Materials Sciences Corporation

CECAM center of excellence for composites and advanced materials

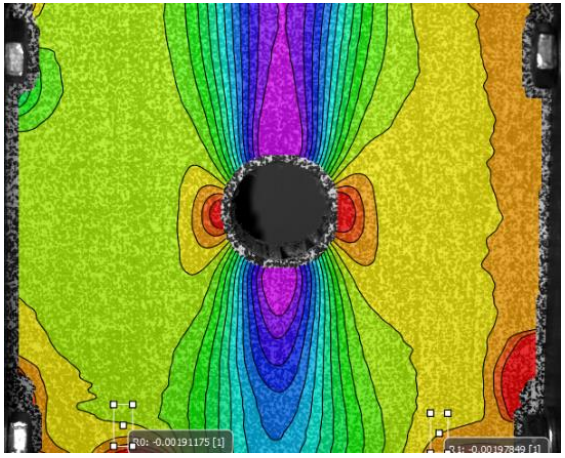
JAMS Joint Advanced Materials & Structures Center of Excellence

A Center of Excellence AMTAS Advanced Materials in Transport Aircraft Structures

THE UNIVERSITY OF UTAH

Summary:
Benefits to Aviation

- **Development of notch sensitivity testing and analysis methods for sandwich composites**
- **Standardized test methods for fracture mechanics, damage tolerance, and notch sensitivity of sandwich composites**
- **Scaling of test results for application on composite sandwich structures**



Thank you for your attention!

Questions?