NOTCH SENSITIVITY OF COMPOSITE SANDWICH STRUCTURES

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FAA Sponsored Project Information

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

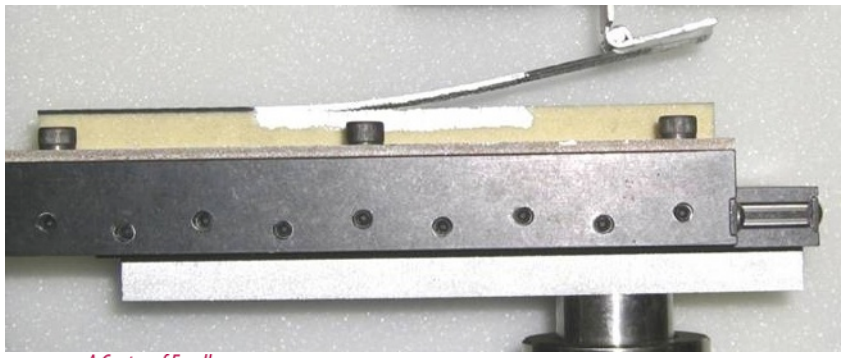
Outline

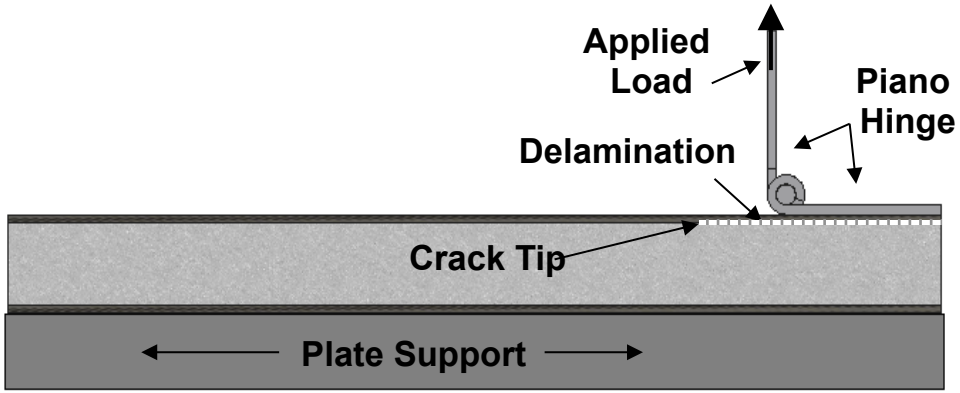
- **Brief updates from previous sandwich composites research**
  - **Sandwich fracture mechanics**
  - **Sandwich damage tolerance**
- **Sandwich notch sensitivity investigation**
  - **Test method development**
  - **Numerical modeling – progressive damage analysis**

Status Update:
Mode I Sandwich Fracture Mechanics Test Method

Single Cantilever Beam (SCB) Test Method

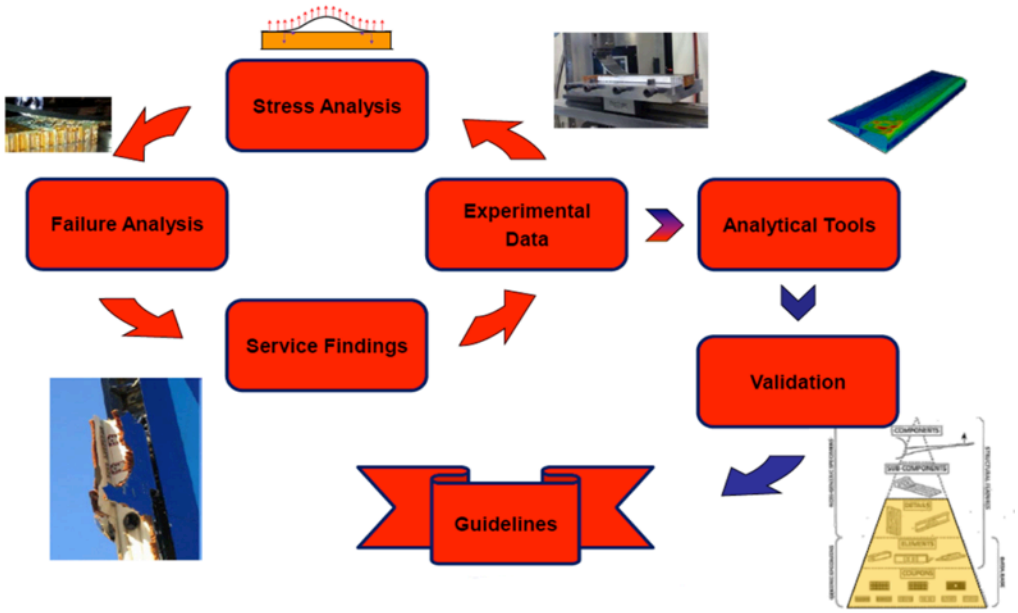
- Draft ASTM standard completed!
- International round-robin test program initiated
  - 7 test labs with previous SCB testing experience
  - Baseline sandwich specimens to be fabricated by NIAR
- Included in sandwich disbond assessment initiative





Status Update:
Sandwich Disbond Assessment Initiative

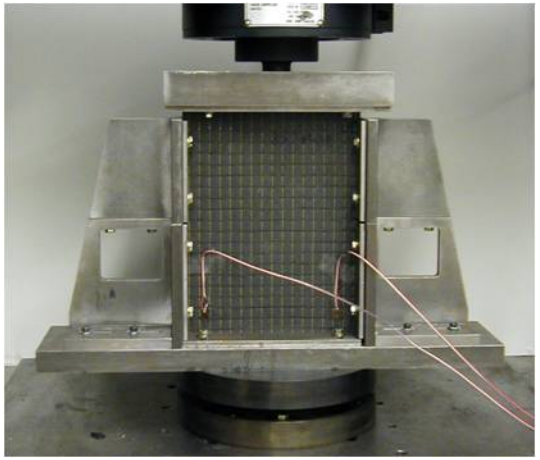
- **Identify, describe and address the phenomenon associated with facesheet/core disbonding and core fracture**
- **Develop a methodology to assess facesheet/core disbonding in sandwich components**
  - **Coupon**
  - **Sub-element**
- **New sections in CHM-17 (Volume 6)**



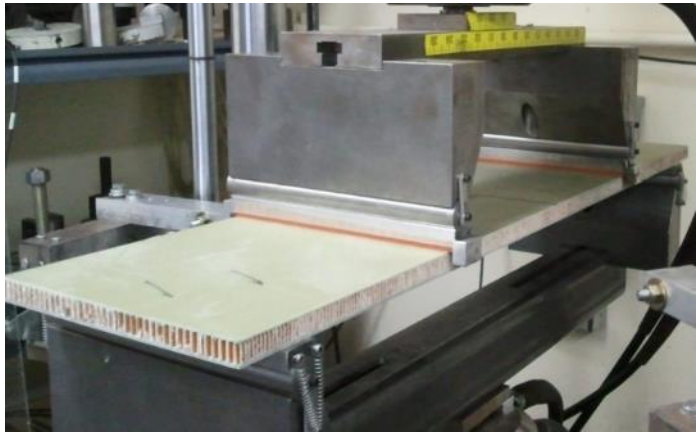
Seneviratne, W., "Fatigue Damage Growth Rate of Sandwich Structures using Single Cantilever Beam (SCB) Test," 2014 JAMS Technical Review

Status Update:
Development of Sandwich Damage Tolerance Test Methods

- **Draft standards to be completed by March 2015 ASTM D30 meeting (Salt Lake City, UT)**
- **Follow-on "scaling" effort underway through Air Force SBIR program**



Compression After Impact (CAI)

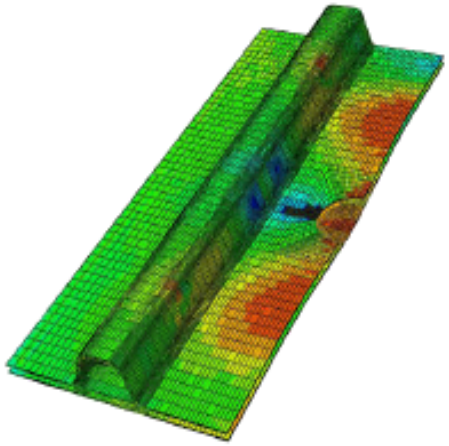


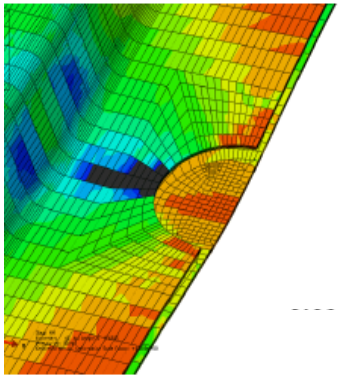
4-Point Flexure After Impact (4-FAI)

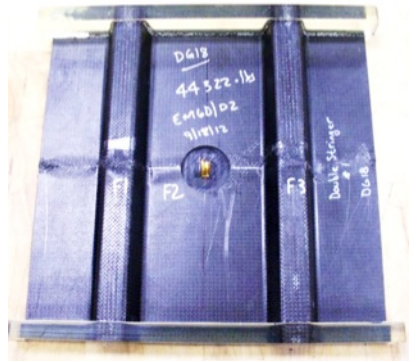
Follow-On Sandwich Damage Tolerance Effort:

Scale-Up of Sandwich Damage Tolerance Test Results

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







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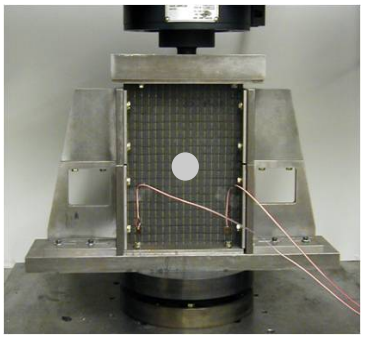
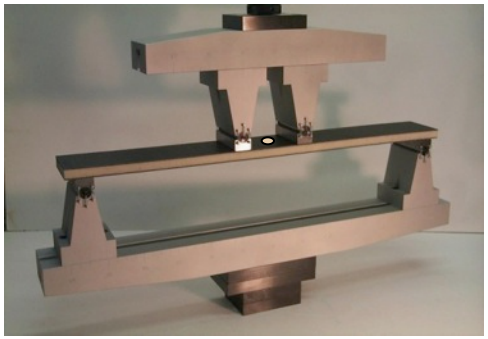
Research Objectives:
Notch Sensitivity of Sandwich Composites

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



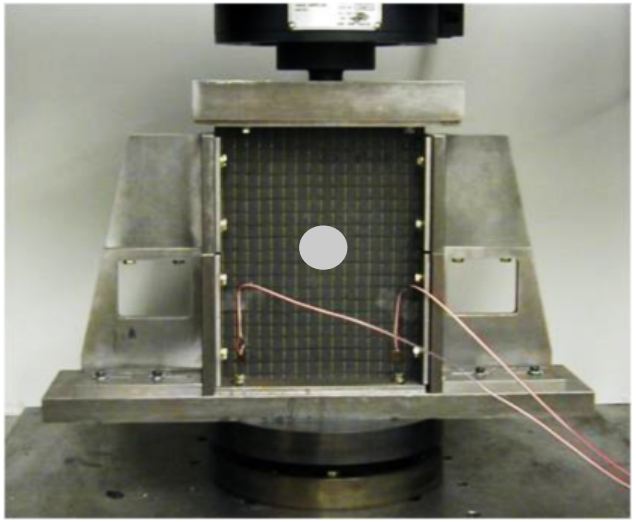
Sandwich Open Hole Compression



Sandwich Open Hole Flexure

Testing Considerations: Sandwich Open Hole Compression

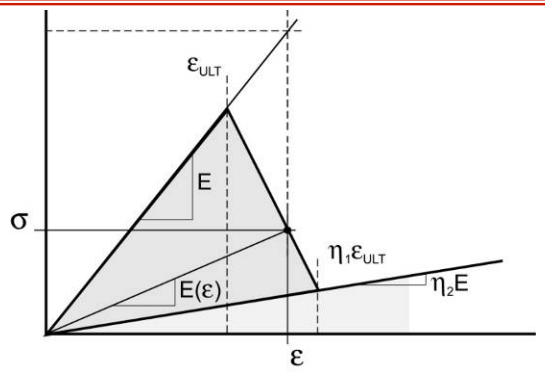
- **Test fixture/Specimen support**
  - **End supports**
    - **Clamping top and bottom**
    - **Potting**
  - **Side supports**
    - **Knife edge**
- **Specimen size**
  - **Separation of central hole and boundary effects**
  - **Production of acceptable strength reductions**
- **Specimen alignment**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

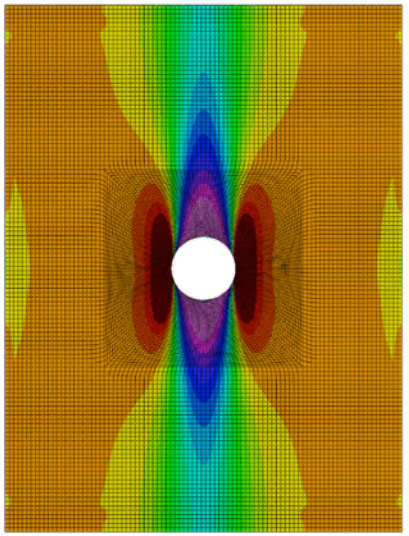


Open hole compression fixture for monolithic composites

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





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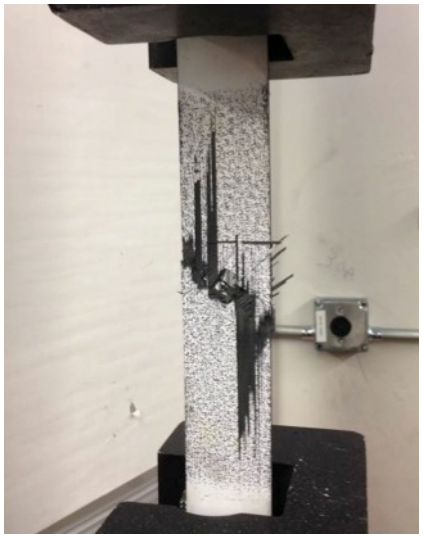
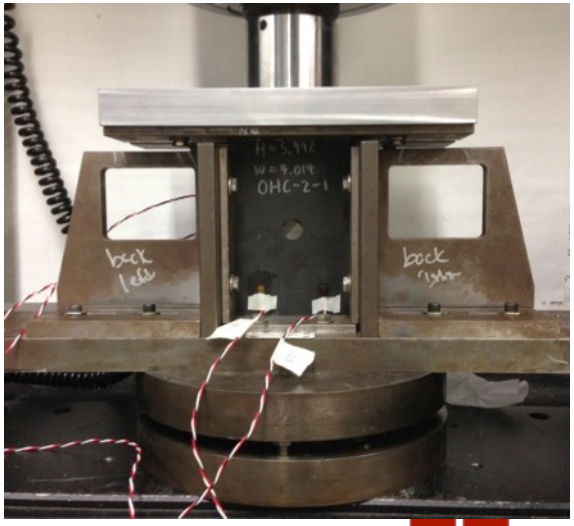
Failure Analysis of Notched Sandwich Specimens

Development of Modeling Approach

- **Modeling of damage progression in facesheets**
  - **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 open hole compression test**

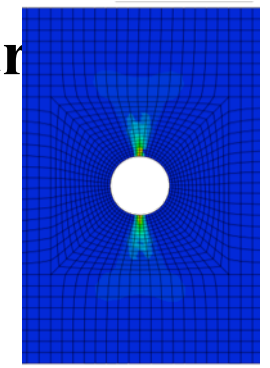




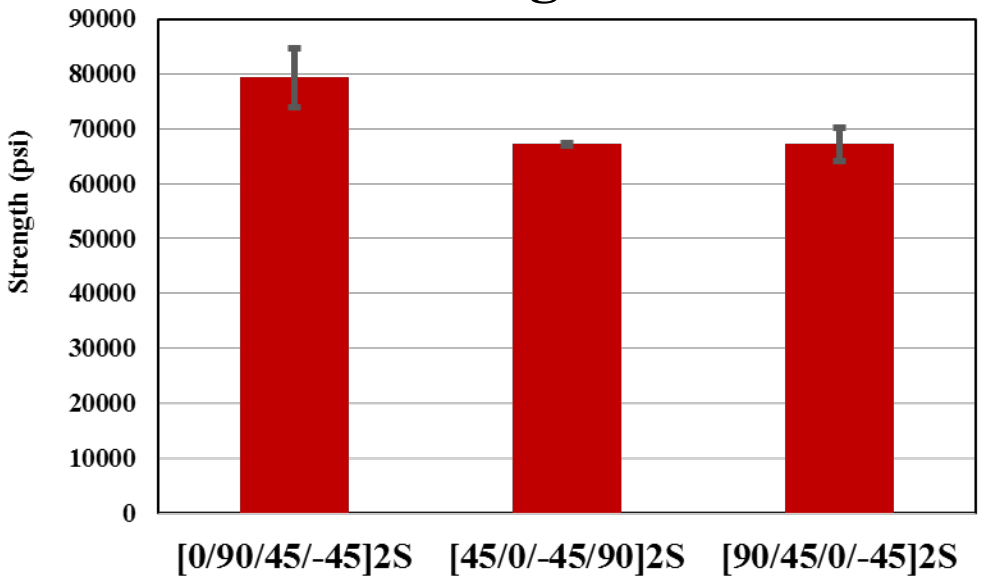
Damage Progression in Facesheets: Analysis of Open Hole Tension Tests

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

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

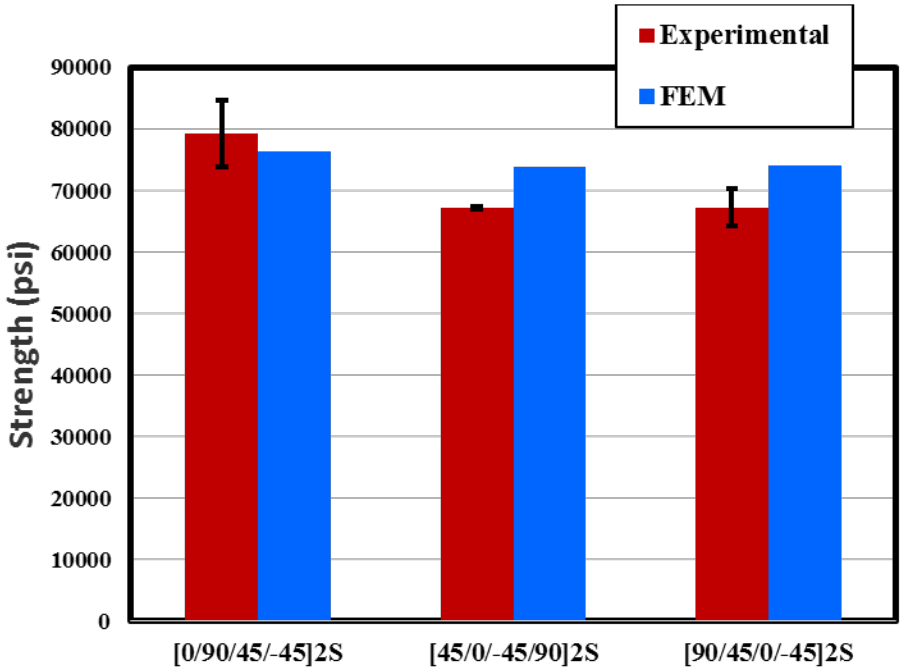


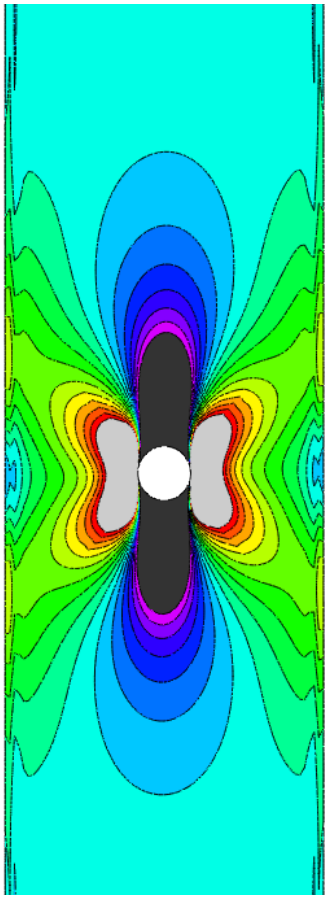
- **Comparison with results from mechanical testing**
  - **–Ultimate strength**
  - **–Stress vs. strain plots**
  - **–Strain fields from Digital Image Correlation**



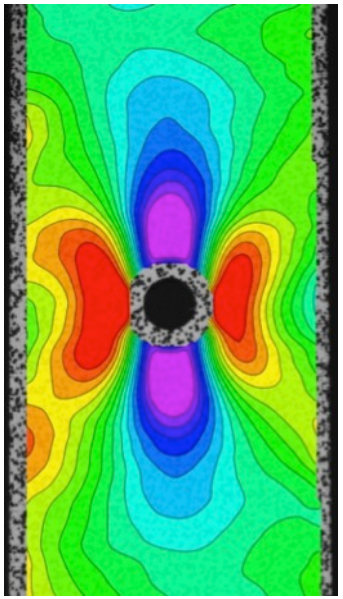
Initial Analysis of Open Hole Tension Tests: Comparison With Experimental Results

- Good agreement for $[0/90/\pm45]_{2S}$ laminate
- Not able to model measured strength reductions in other laminates





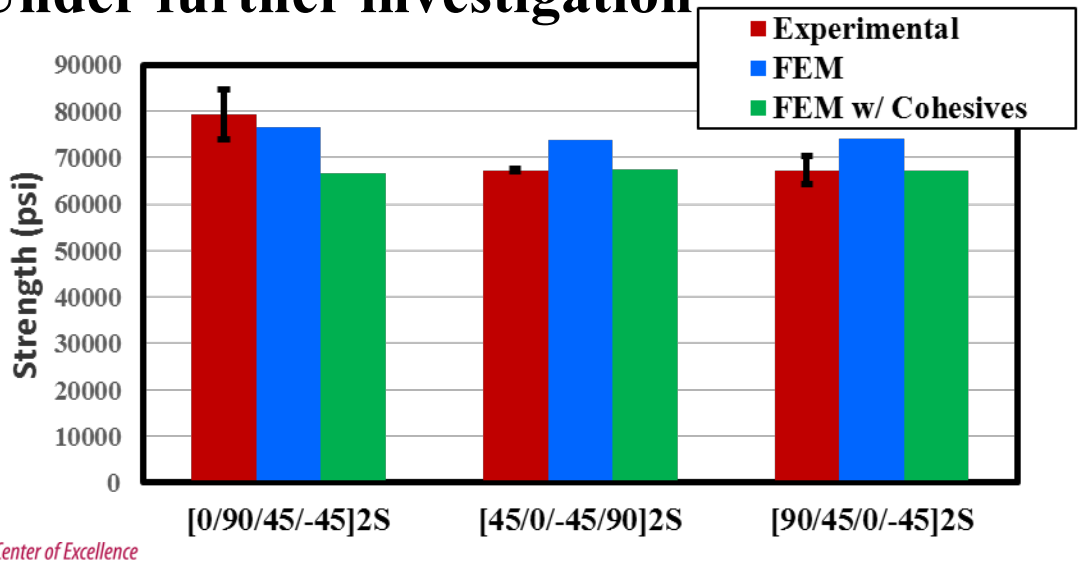
Finite Element Prediction

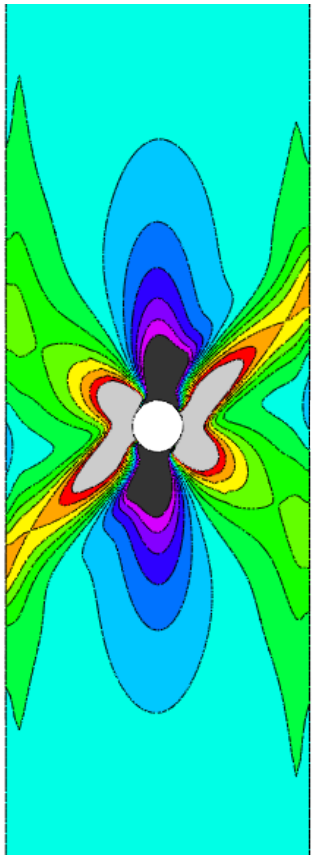


Experimental Result

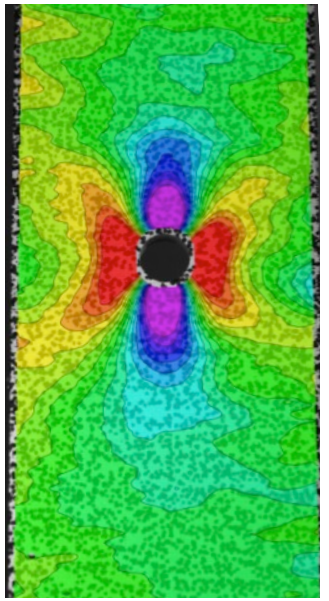
Follow-On Analysis of Open Hole Tension Tests: Incorporation of Cohesive Elements

- ABAQUS cohesive elements added between plies
- Good agreement with $[45/0/-45/90]_{2S}$ and $[90/45/0/-45]_{2S}$ laminates
- Not able to adequately model measured strength differences within laminates
- Under further investigation





Finite Element Prediction

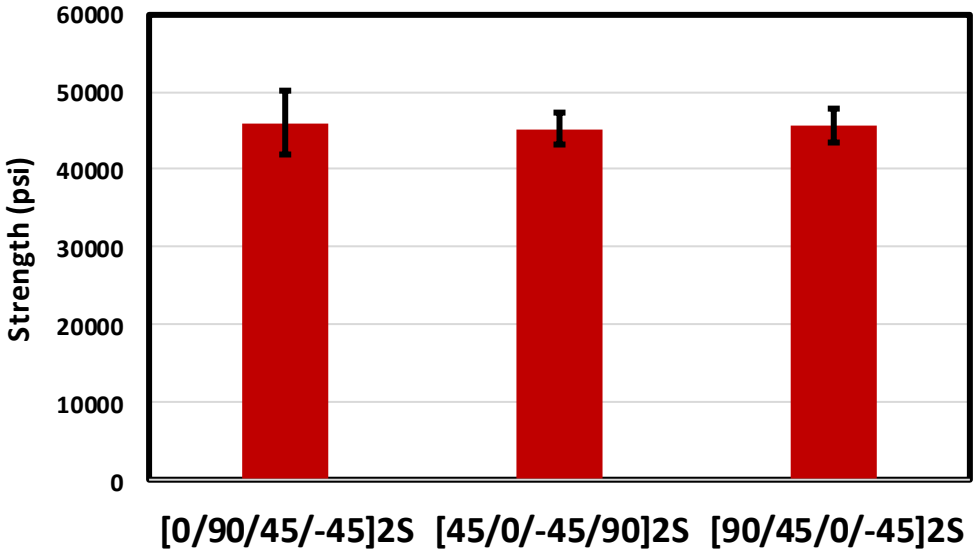


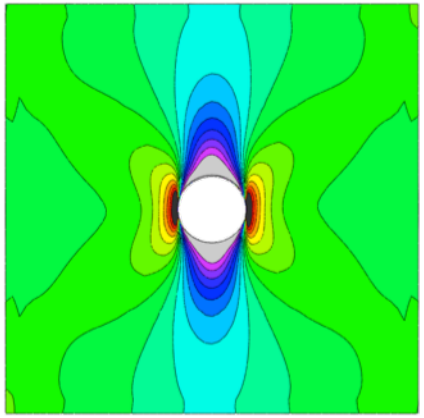
Experimental Result

Damage Progression in Facesheets:
Open Hole Compression Testing & Analysis

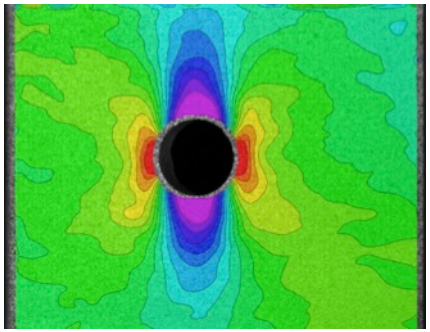
- **Mechanical testing of 1.5 in. wide specimen, 0.25 in. dia center hole (ASTM 6484)**
- **Three IM7/8552 carbon/epoxy laminates:**

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





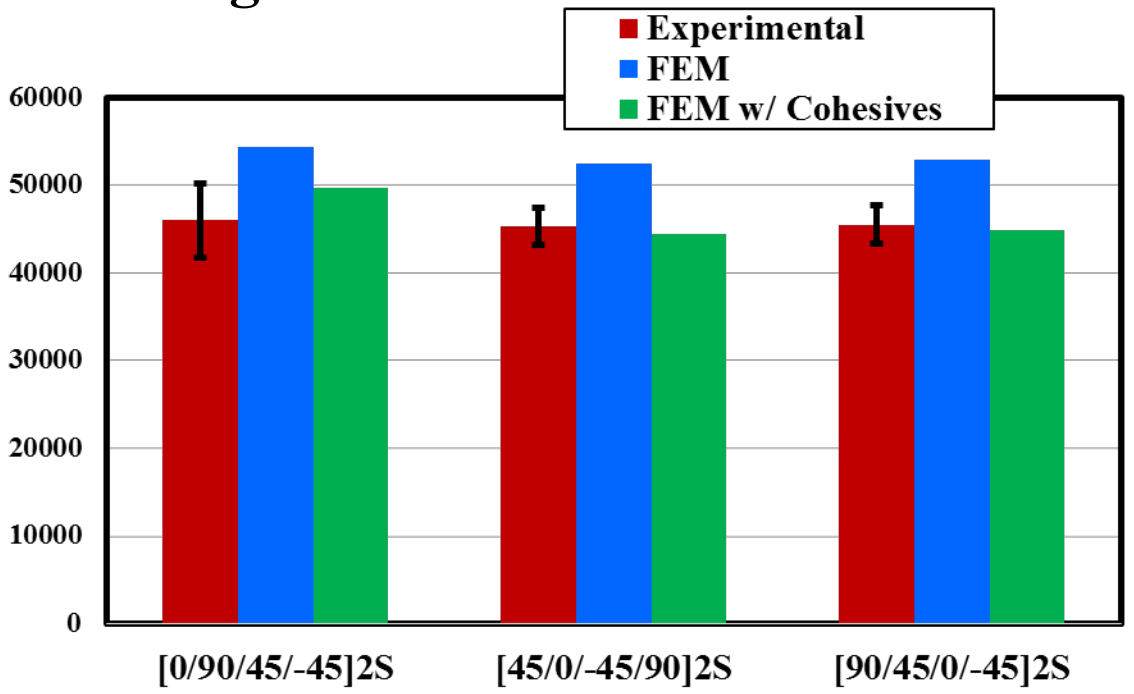
Finite Element Prediction



Experimental Result

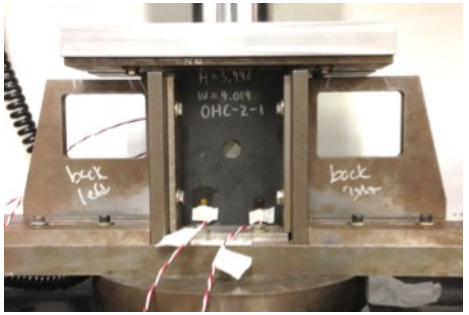
Analysis of Open Hole Compression Tests:
Comparison With Experimental Results

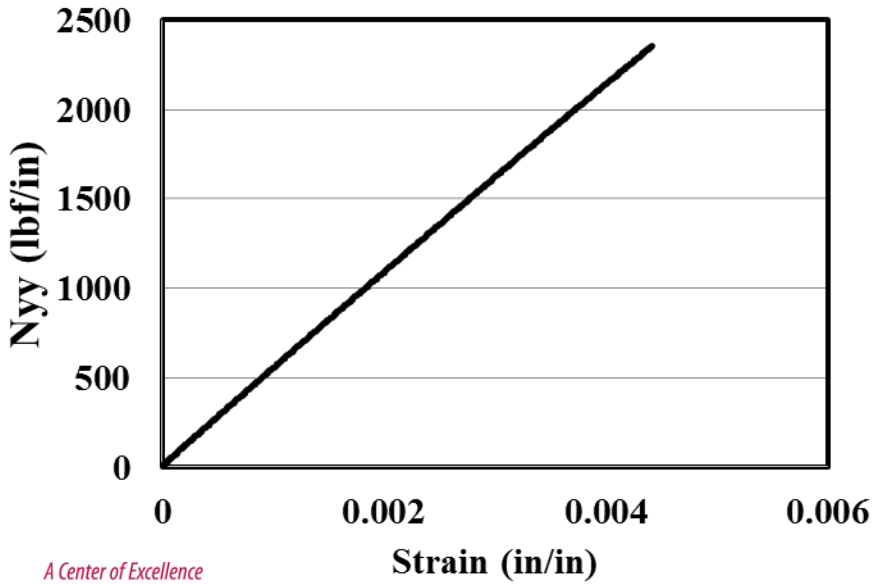
- Over-prediction of strengths without cohesive elements
- Improved agreement with cohesive elements added between plies
- Under further investigation

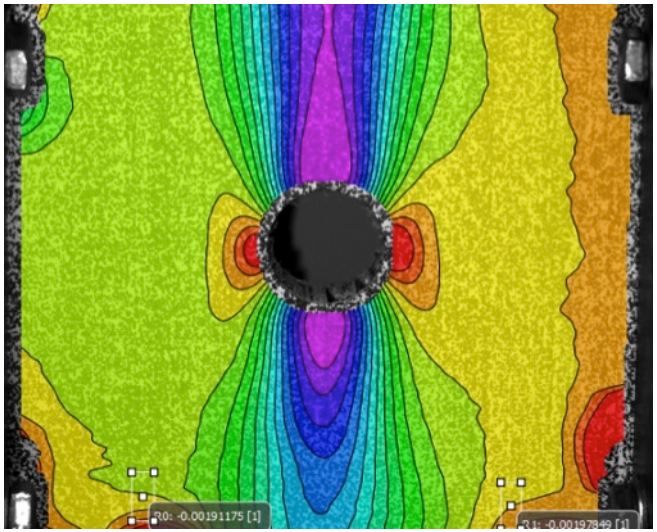


Damage Progression in Sandwich Composites: Analysis of Sandwich Open Hole Compression Test

- 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)



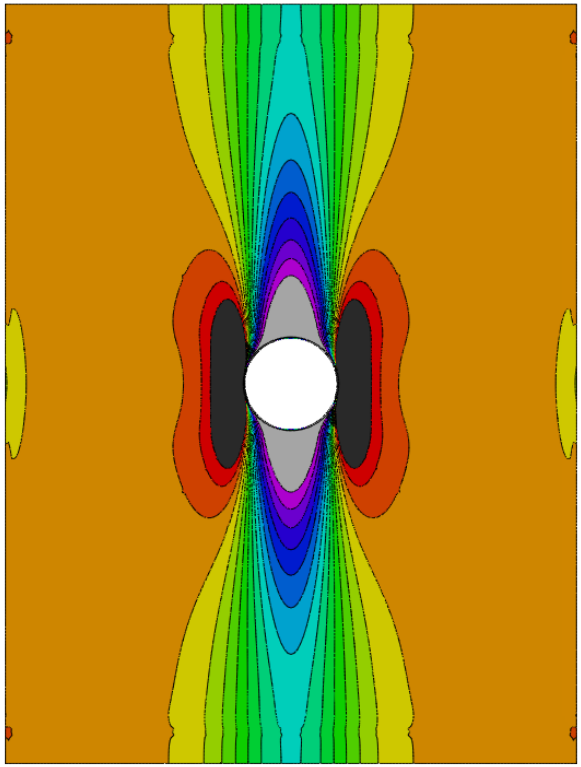




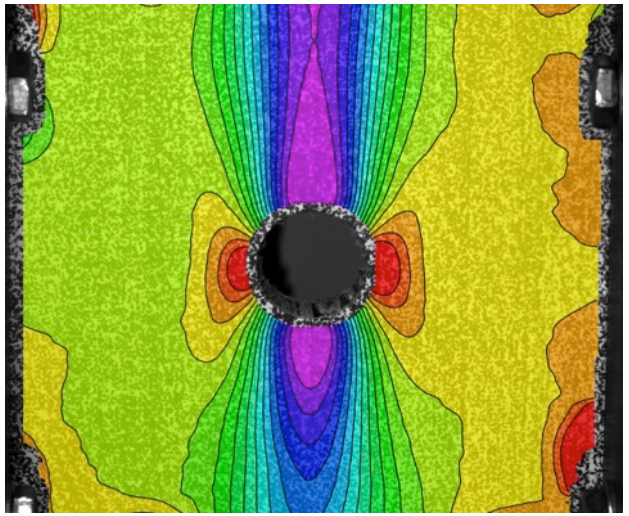
Digital Image Correlation Results

Initial Analysis:
Sandwich Open Hole Compression Test

Comparison of ε_y Strain Fields (W/D = 6)



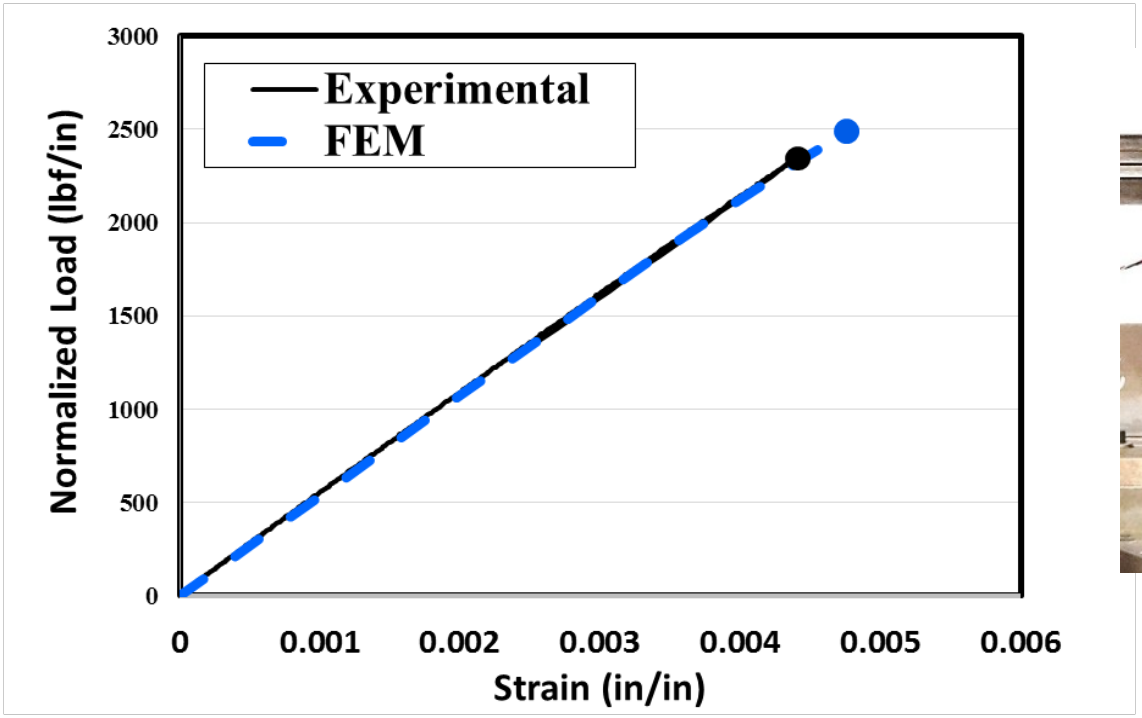
ABAQUS/NDBILIN Prediction

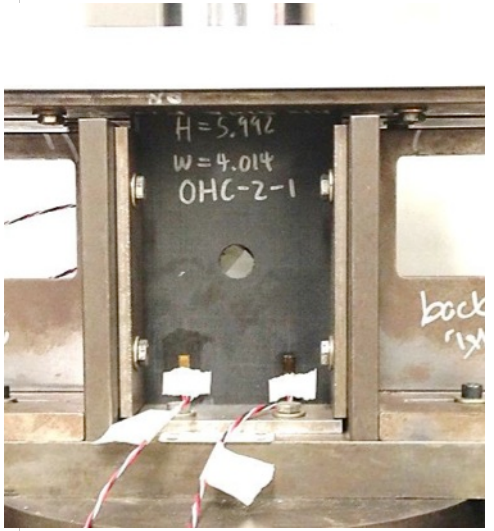


Digital Image Correlation Results

Initial Comparisons of Compression Strength: Sandwich Open Hole Compression Test

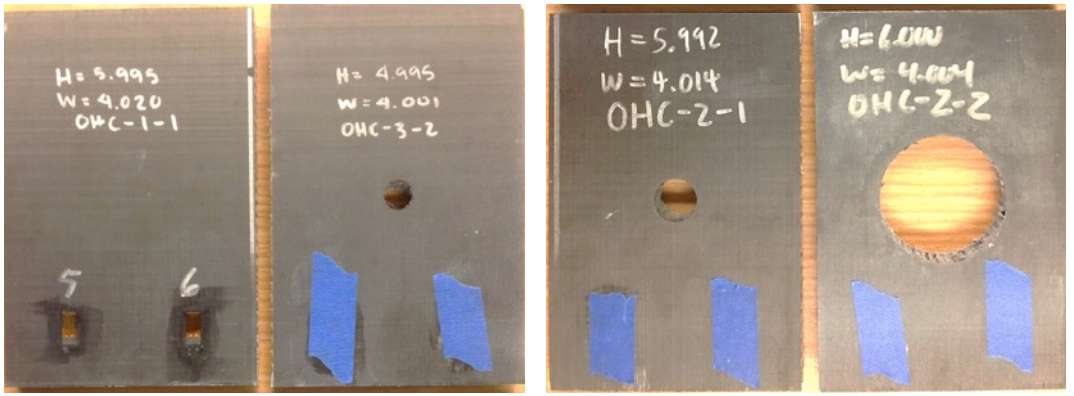
- Good agreement with measured stiffness
- Over-prediction of notched compression strength
- Currently incorporating facesheet/core cohesive elements





Current Focus:
Investigating Effects of Notch Size (W/D Ratio)

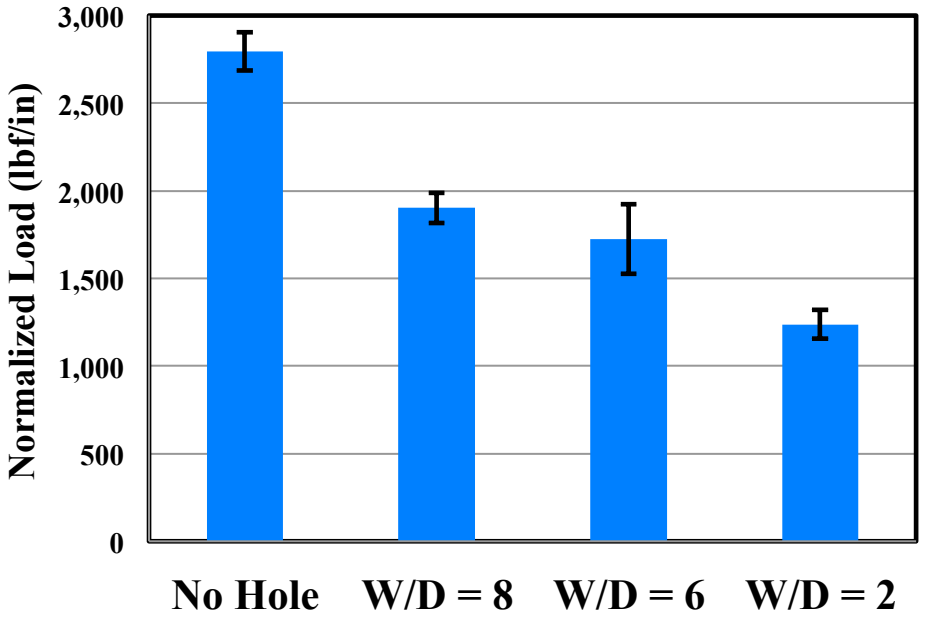
- **Resized specimen to 4.0 in. x 6.0 in. (ASTM D 7137 - CAI)**
- **Investigate additional hole diameters**
  - **1/2 in. dia (W/D = 8)**
  - **2/3 in. dia (W/D = 6)**
  - **2 in. dia (W/D = 2)**
  - **Differences in anticipated failure progressions**
  - **Separation of central hole and boundary effects**

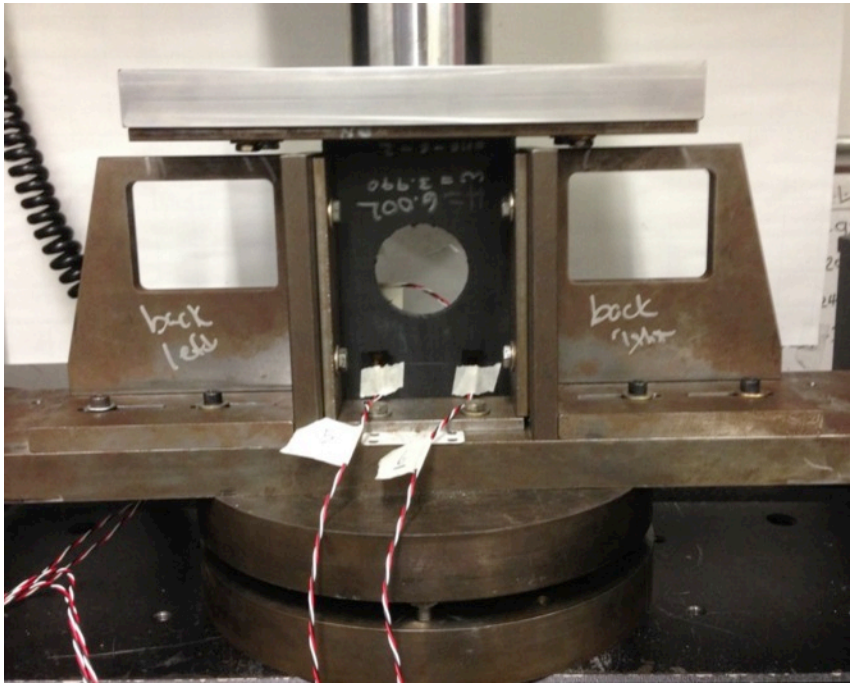


No Hole **W/D = 8** **W/D = 6** **W/D = 2**

Initial (Recent) Results: Effect of Notch Size on Compression Strength

- Three specimens for each condition
- Stain profiles obtained using Digital Image Correlation
- Numerical modeling underway





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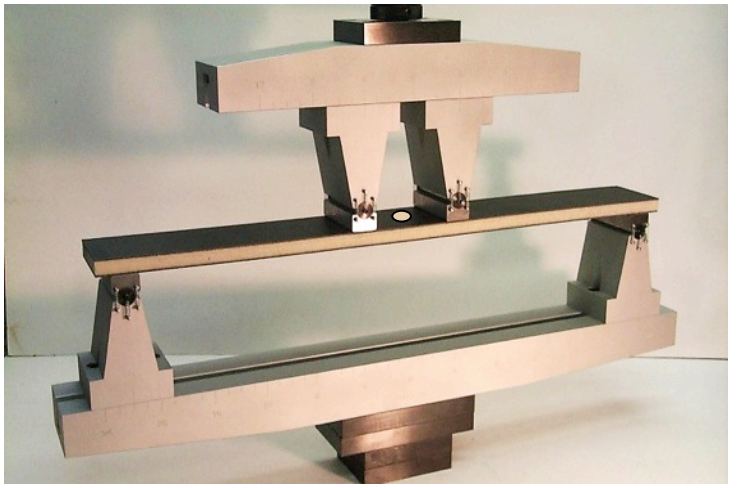
Upcoming Work:
Sandwich Open Hole Flexure Test

- **Sandwich specimens dimensioned according to long-beam flexure test method, ASTM D7249**
- **Proposed sandwich configuration:**
  - **Carbon/epoxy facesheets, ½ in. Nomex honeycomb core**
  - **0.5 in. diameter central circular hole**
  - **3 in. width x 24 in. length (standard configuration)**
  - **4 in. central test section**
  - **22 in. span**
  - **1 in. maximum displacement (predicted)**



Thank you for your attention!

Questions?