NOTCH SENSITIVITY OF COMPOSITE SANDWICH STRUCTURES

Dan Adams
Marcus Stanfield
Brad Kuramoto
Department of Mechanical Engineering
University of Utah
Salt Lake City, UT

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FAA Sponsored Project Information

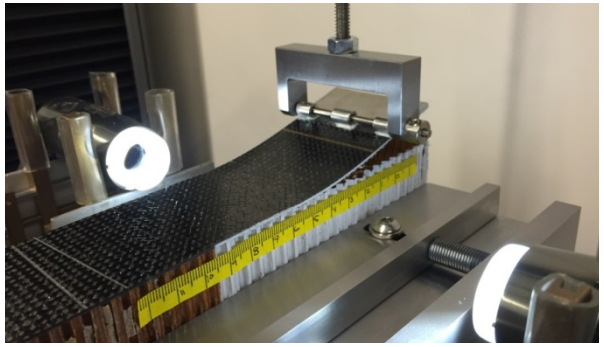
- Principal Investigators: **Dr. Dan Adams**
  Dr. Mike Czabaj
- Graduate Student Researchers:
  Marcus Stanfield
  Brad Kuramoto
- FAA Technical Monitor: **Zhi Chen**
- Collaborators:
  Materials Sciences Corporation
  ASTM D30
  Boeing
  Oregon State University

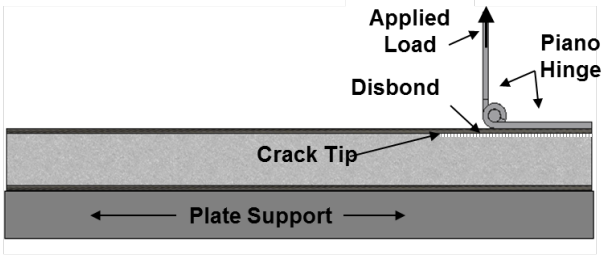
Outline

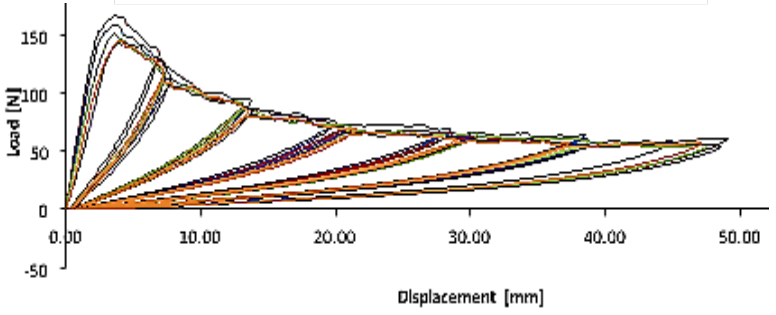
- **Brief updates: Previous research**
  - **Sandwich fracture mechanics**
  - **Sandwich damage tolerance**
- **Sandwich notch sensitivity investigation**
  - **Test method development**
  - **Numerical modeling – progressive damage analysis**

Status Update:
Mode I Sandwich Fracture Mechanics Test Method

- **Single Cantilever Beam (SCB) Test Method**
  - **Draft standard completed**
  - **Round-robin exercise completed**
  - **Results reported at EASA meeting in Cologne Germany last week**
  - **Draft standard being updated for upcoming submission for ASTM balloting**
  - **Follow-on testing and analysis activities underway**

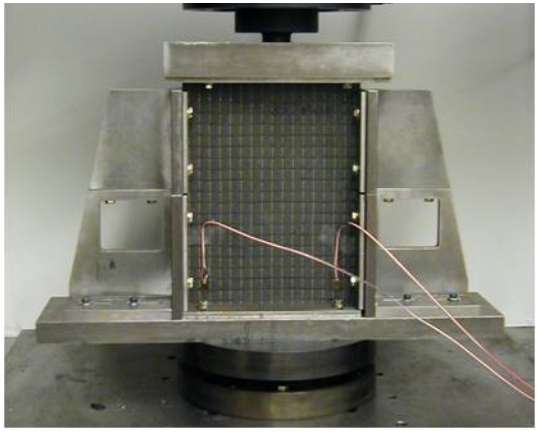




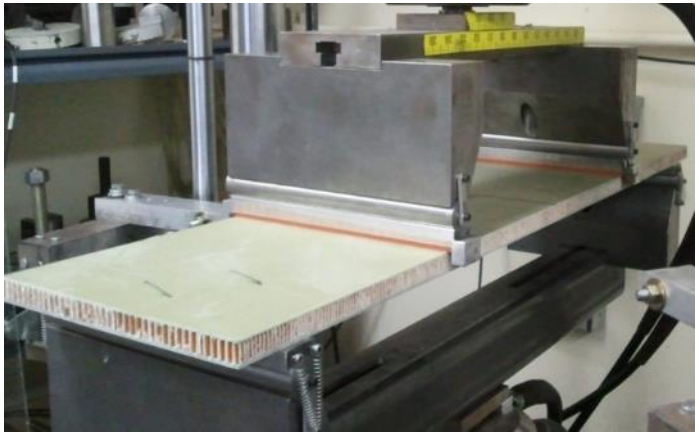


Status Update:
Sandwich Damage Tolerance

- **Draft standards of CAI completed**
- **4-Pt. Flexure After Impact testing underway**
- **Model development using ABAQUS/NDBILIN**



Compression After Impact (CAI)



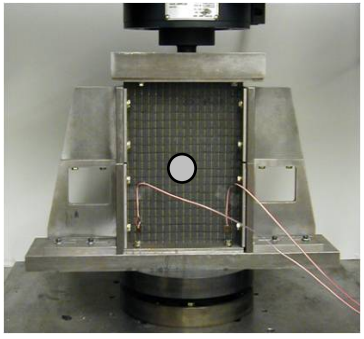
4-Point Flexure After Impact (4-FAI)

Background:
Notch Sensitivity of Sandwich Composites

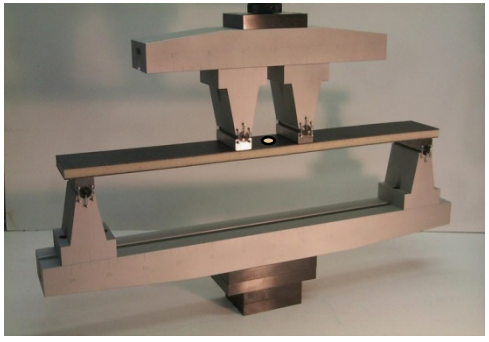
- **Notch sensitivity test methods for monolithic composites are reaching relatively high levels of maturity**
  - **ASTM D 5766 – Open Hole Tension**
  - **ASTM D 6484 – Open Hole Compression**
  - **Out-of-plane shear (Parmigiani)**
- **Less attention to notch sensitivity tests methods of sandwich 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

- **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**



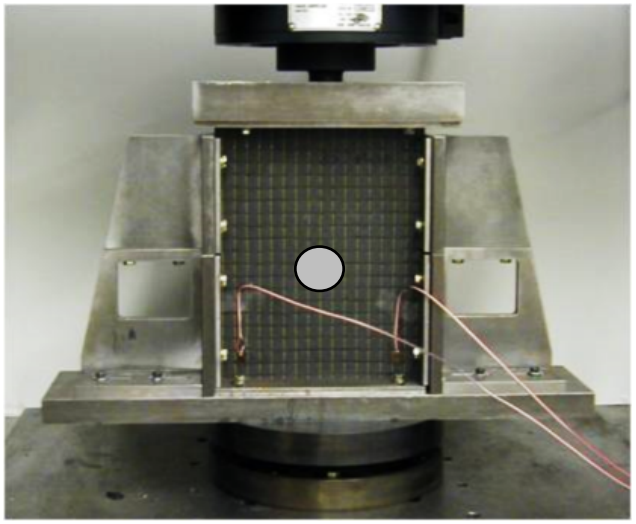
Sandwich Open Hole Compression



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**

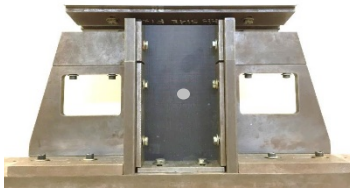


Open hole compression fixture for monolithic composites

Previous Work: Specimen Size

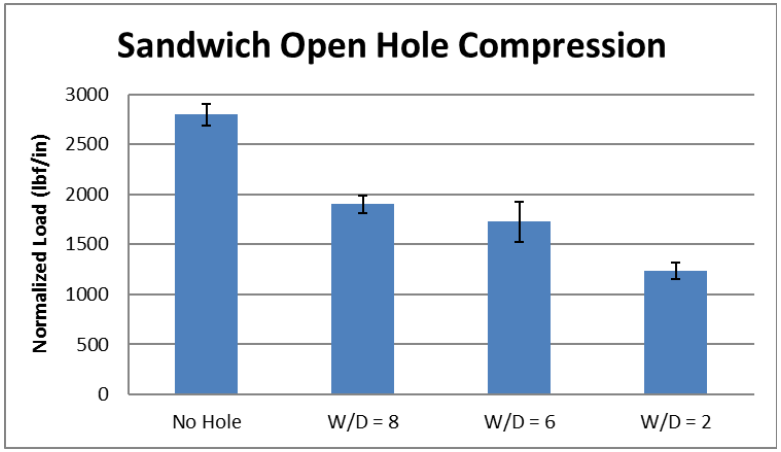
- **Using a width to hole diameter ratio of six (W/D=6) and a height to width ratio of two (H/W=2) was necessary to produce acceptable strength reductions while separating hole and boundary effects**

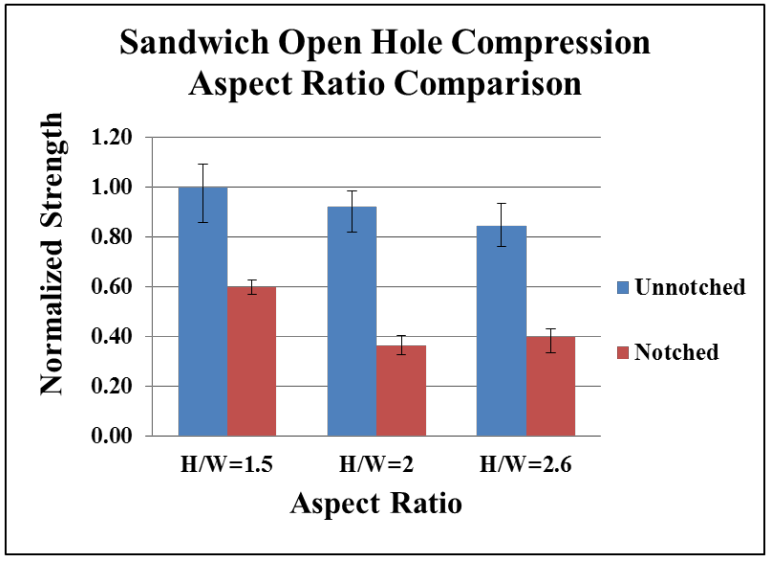
H/W = 1.5



H/W = 2.0

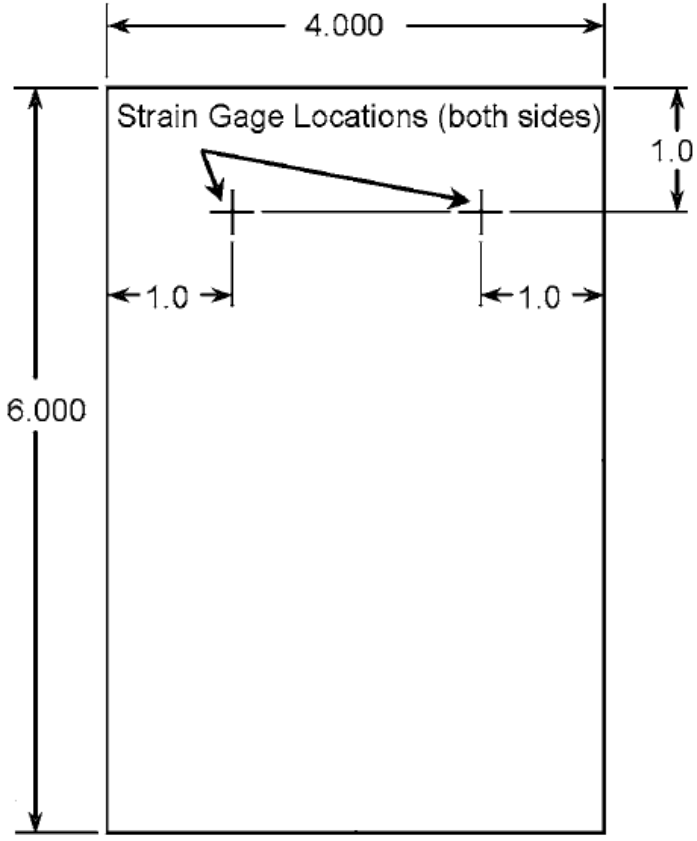
H/W = 2.6





Sandwich Open Hole Compression: Specimen Size

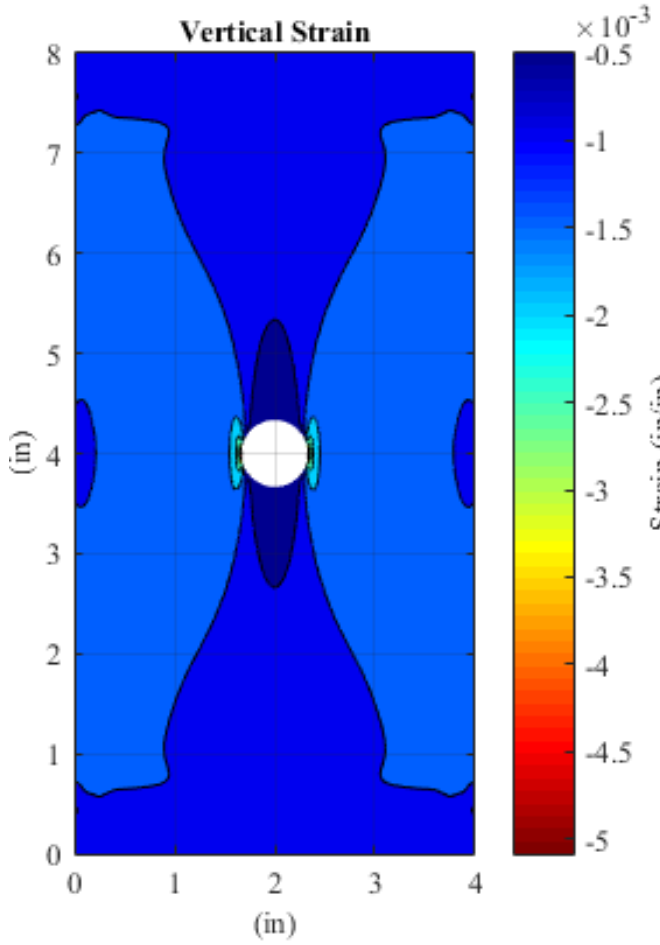
- **Investigate minimum width**
  - **Strain gage locations for specimen alignment**
  - **Low strain gradient**
  - **Low shear strain**
- **ASTM D7137 CAI: 4 strain gages located 1 inch from each edge**



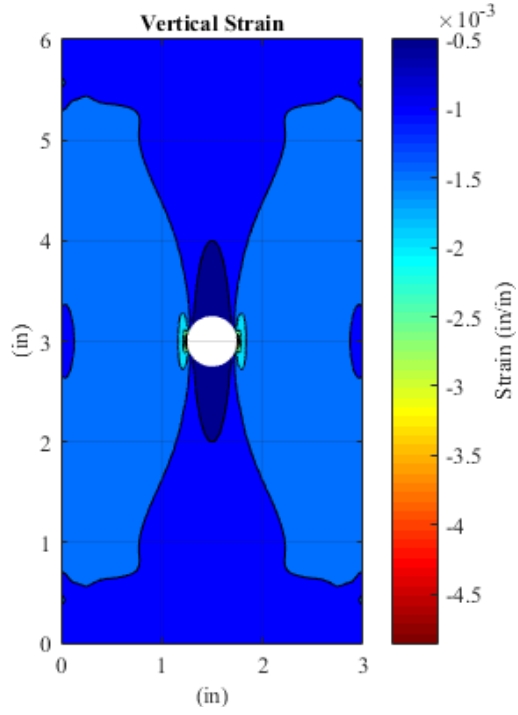
ASTM D7137

Sandwich Open Hole Compression: Specimen Size

- **Since H/W and W/D are constant, the vertical strain scales linearly except at:**
  - **~1/2 inch potting**
  - **¼ inch edge restraints**



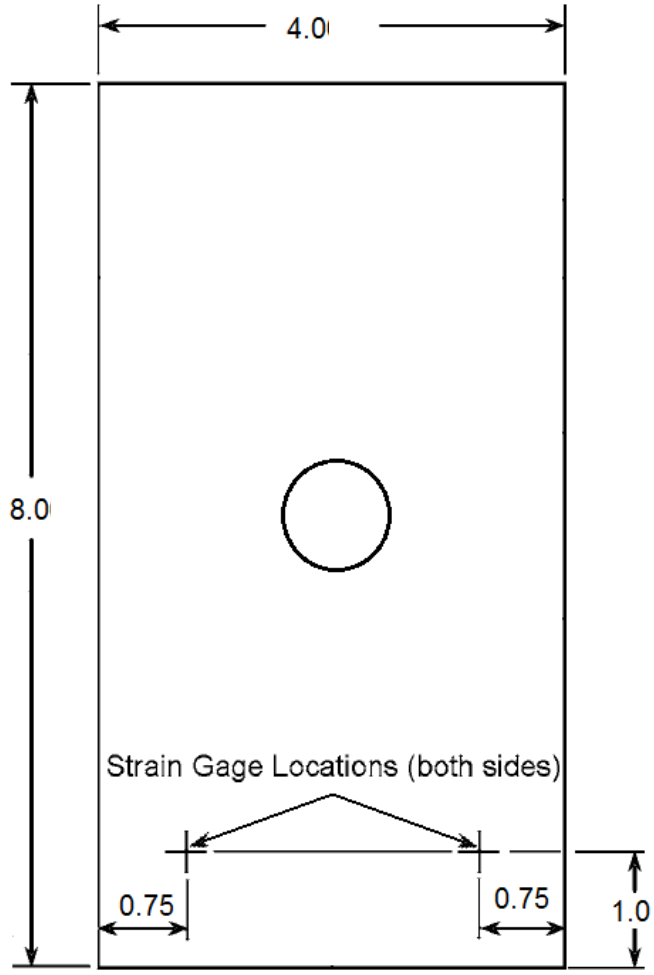
4”W x 8”H



3”W x 6”H

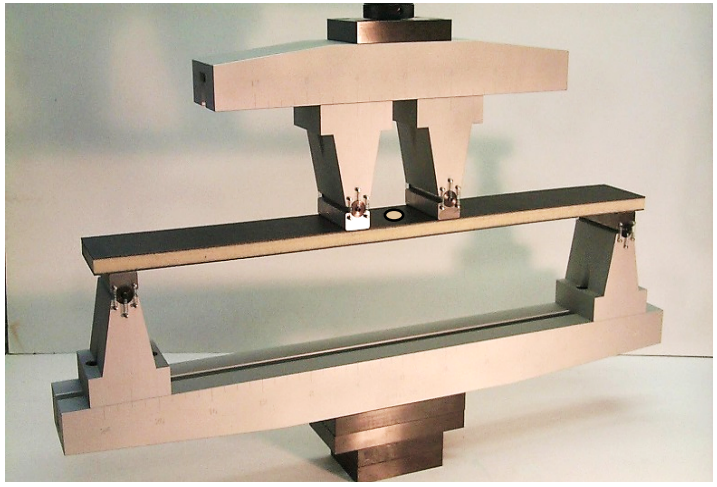
Sandwich Open Hole Compression:
Specimen Size

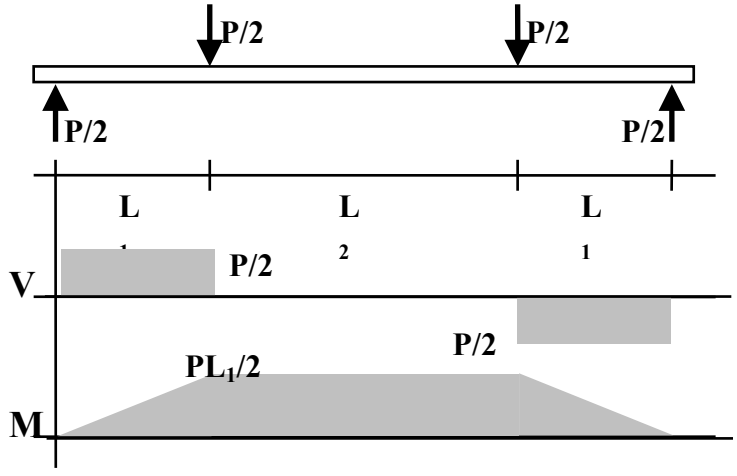
- Strain gage placement 1 inch from top or bottom of specimen is necessary
- A minimum width of 4 inches was found to be sufficient
- Recommend changing strain gage location from 1 inch from sides to ¾ inch
- For 3 inch wide specimen, move the gages to ½ inch from each side



Testing Considerations: Sandwich Open Hole Flexure

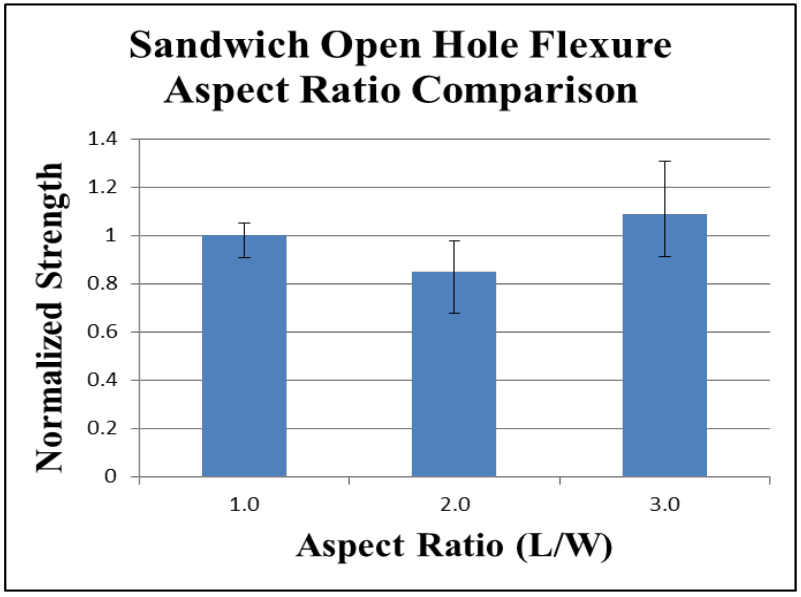
- **Test fixture/specimen support**
  - **Inner span**
    - **Separation of notch and loading boundary effects**
  - **Outer span**
    - **Develop sufficient bending moment**
    - **Ensure failure in inner span**
- **Specimen size**

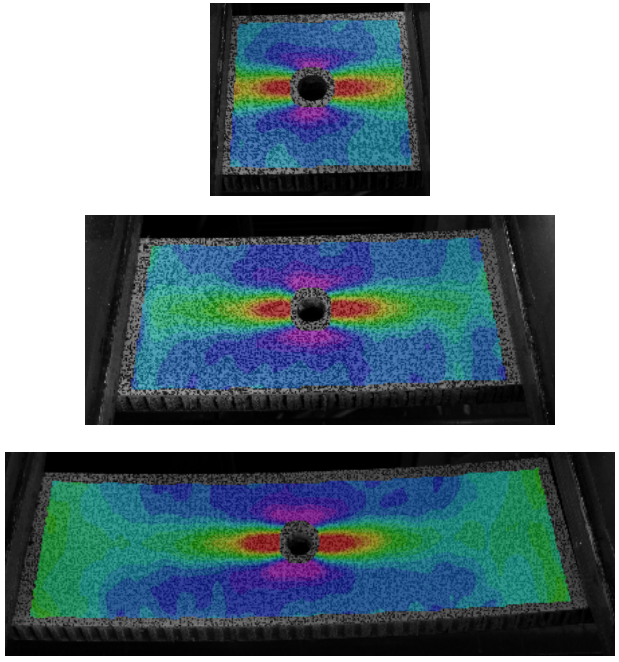




Previous Work: Inner Span

- **Maximum facial strength was not sensitive to higher aspect ratios (inner span to width)**
- **Higher aspect ratios (L/W=2) allow DIC to measure far field strains**





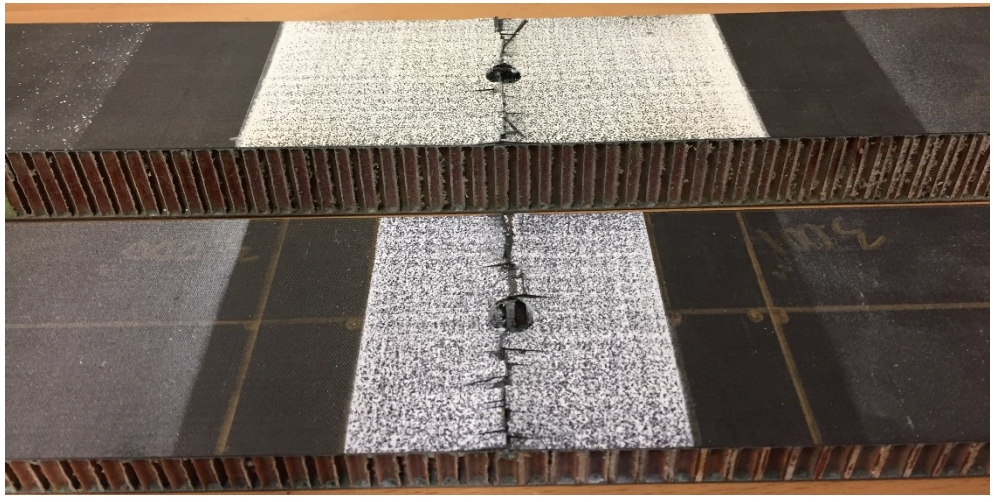
L/W = 1

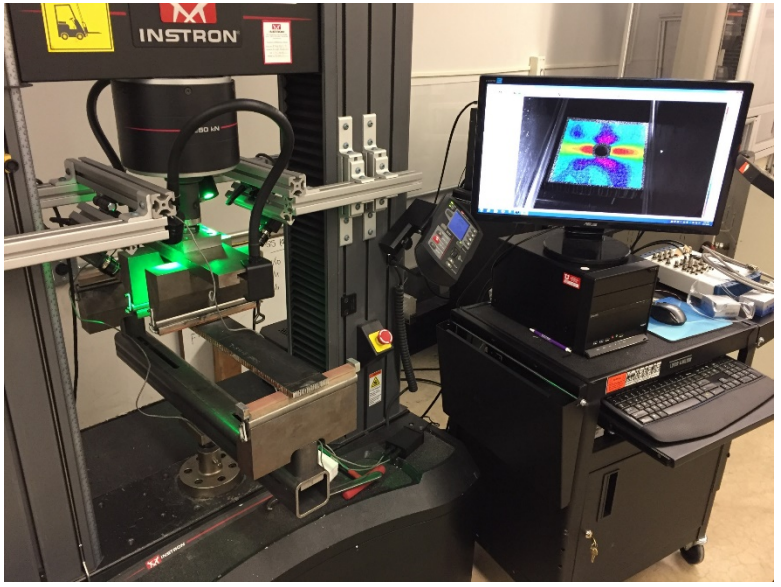
L/W = 2

L/W = 3

Current Focus:
Thick Core Testing

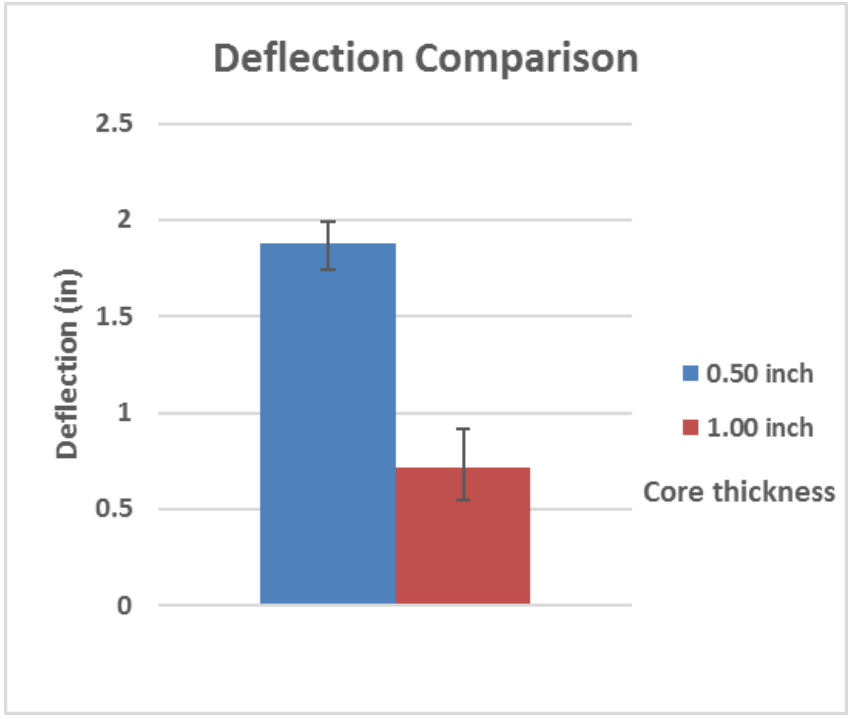
- **Sandwich configuration:**
  - **Carbon/epoxy facesheets, Nomex honeycomb core**
  - **0.5 in. diameter central circular hole**
  - **3 in. width x 32 in. length**
- **Investigating thicker core to reduce deflection**
  - **½ inch and 1 inch core**

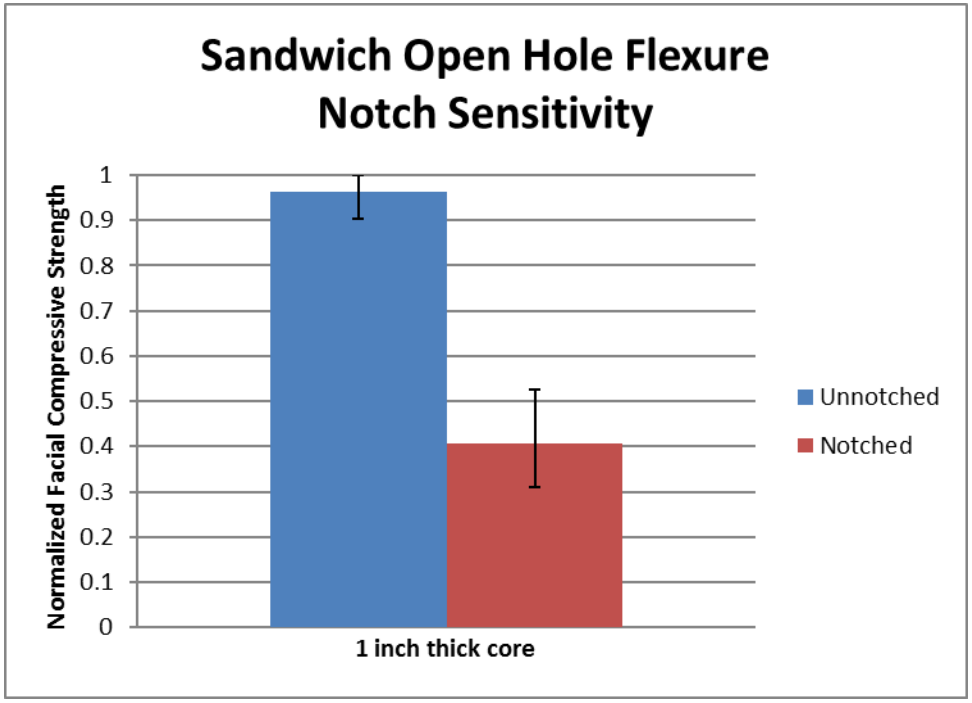




Current Focus:
Thick Core Testing

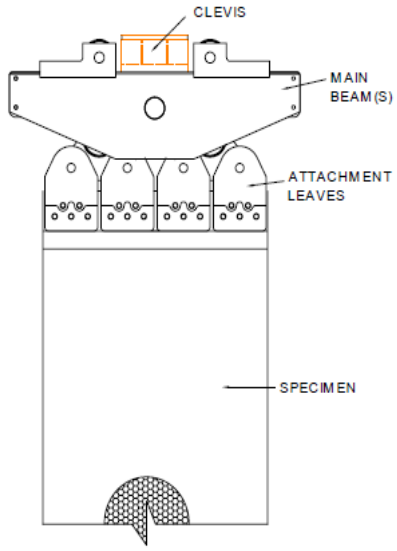
- As expected, less deflection for thicker core, smaller rotation angle at outer span
- Similar facial strength reductions as Sandwich OHC



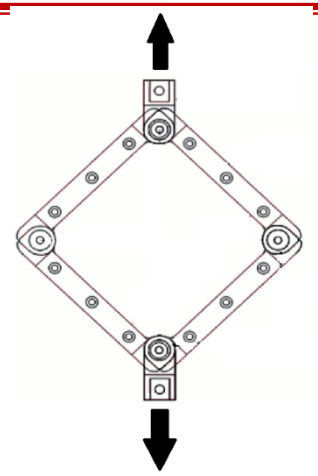


Future Work:
Third Loading Configuration

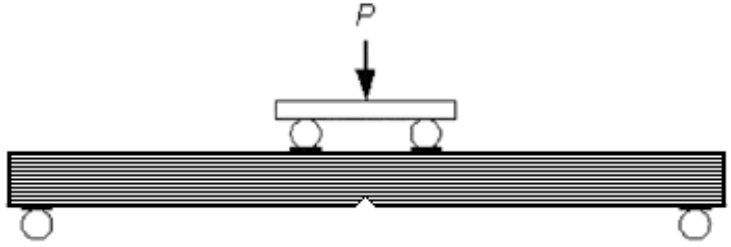
- **Investigate additional notch configurations**
  - **Compression one sided (single facesheet) hole**
  - **Open hole tension**
  - **In-plane shear picture frame**
  - **In-plane bending edge v-notch**
  - **Out of plane shear (Mode III)**
  - **In-plane biaxial tension/compression**



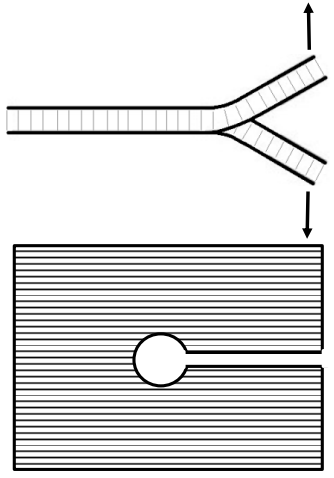
Open-hole tension



In-plane shear



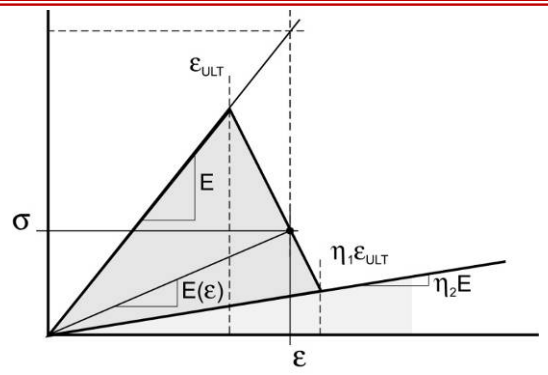
In-plane bending

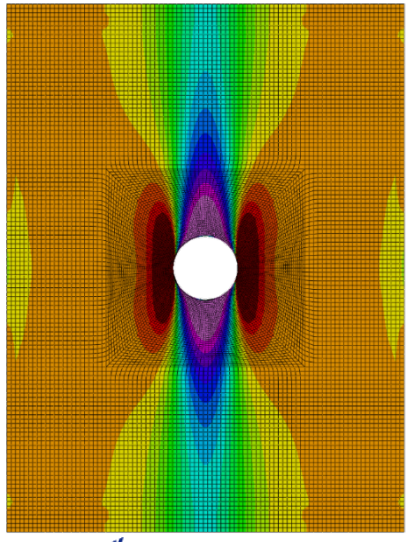


Out-of-plane shear

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

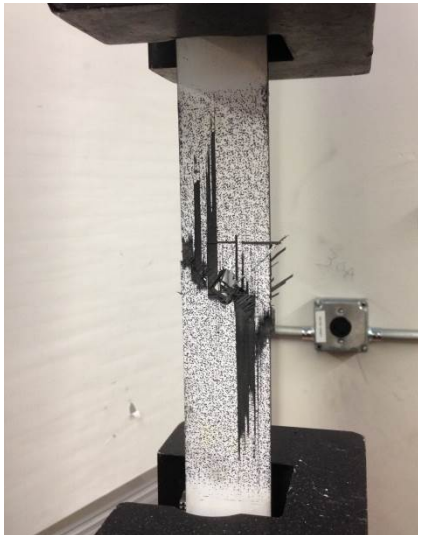


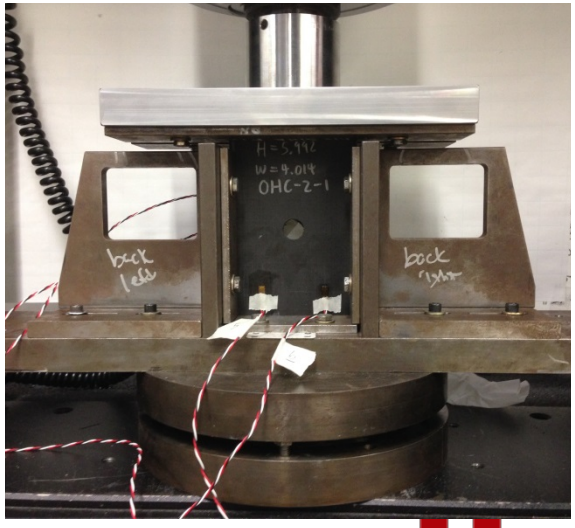


Failure Analysis of Notched Sandwich Specimens

Development of Modeling Approach

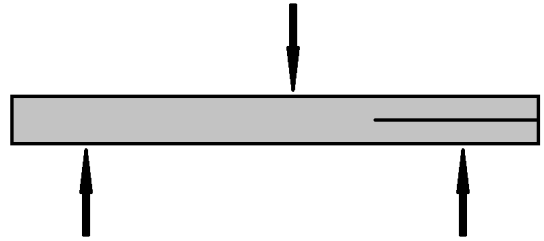
- **Modeling of damage progression in facesheets**
  - **Analysis of interlaminar disbond (Mode I and Mode II)**
  - **Analysis of +/-45 laminate tension test**
  - **Analysis of laminate open-hole tension test**
  - **Analysis of laminate open-hole compression test**
- **Modeling of damage progression in sandwich composites**
  - **Sandwich interface disbond (Mode I and II)**
  - **Sandwich flexure test**
  - **Sandwich open hole compression test**

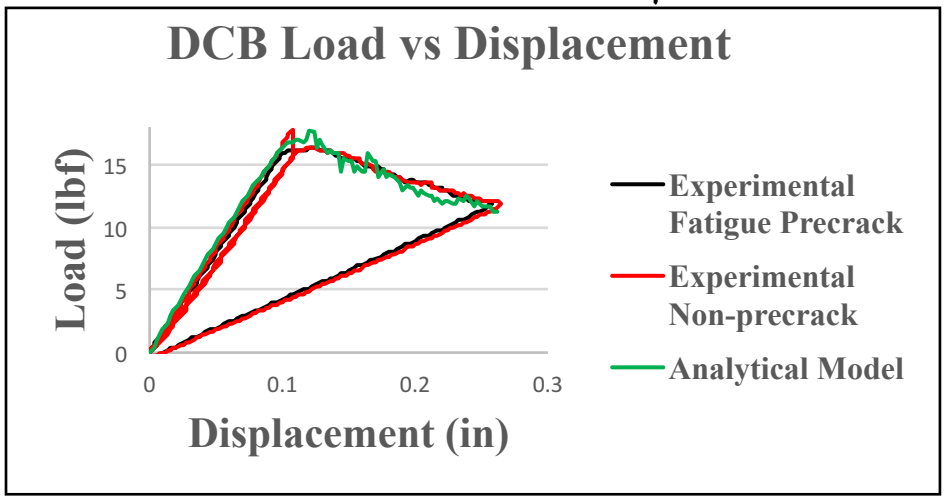


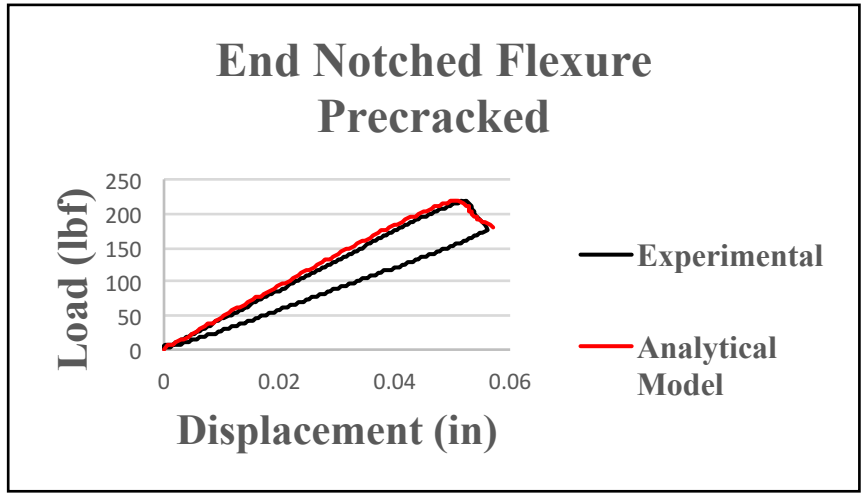


Damage Progression in Facesheets: Analysis of Interlaminar Disbond

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





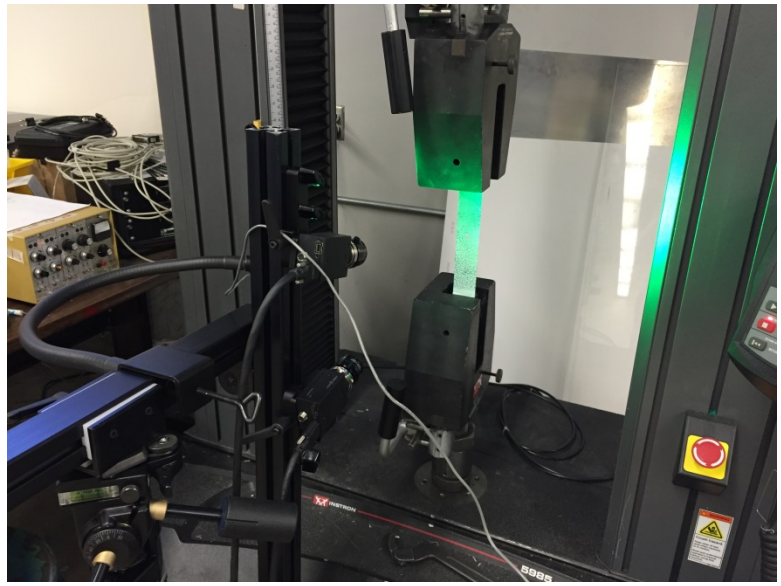


Damage Progression in Facesheets: Analysis of +/-45 Laminates

- **Simulation of tension testing of IM7/8552 carbon/epoxy laminates (ASTM D5766), no hole and open hole**

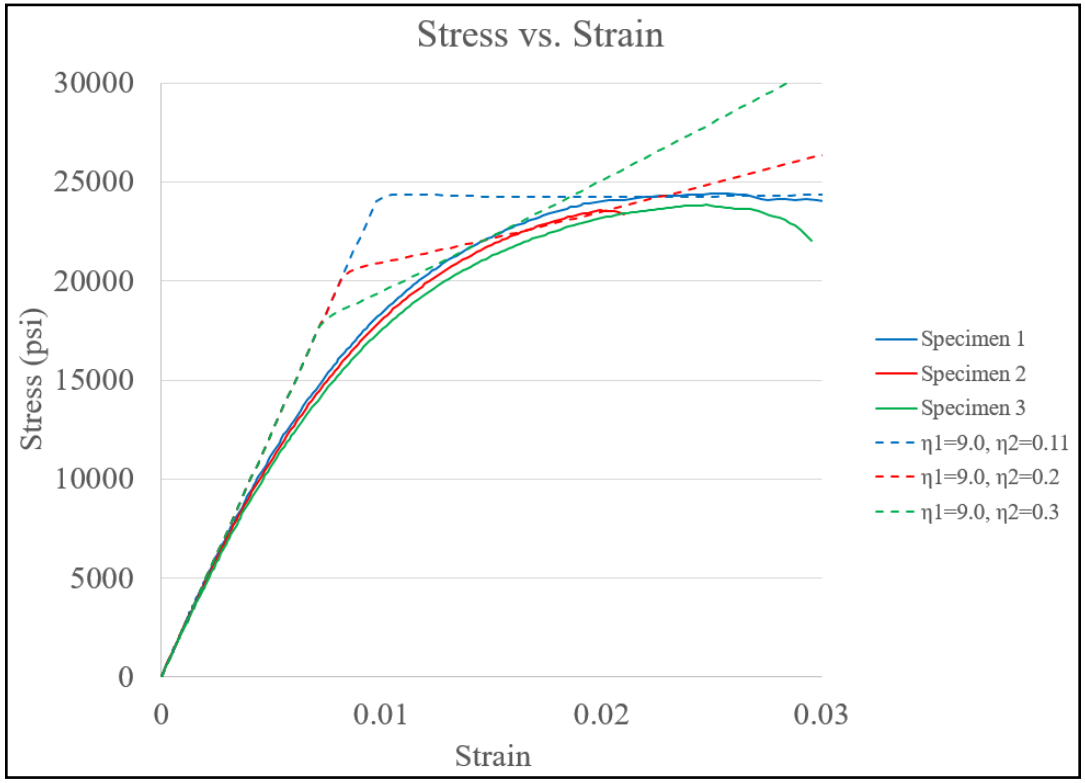
  $[45/-45]_{2S}$

- **Comparison with results from mechanical testing**
  - **Ultimate strength**
  - **Stress vs. strain plots**
  - **Strain fields from Digital image correlation**
  - **Damage progression using X-ray CT**



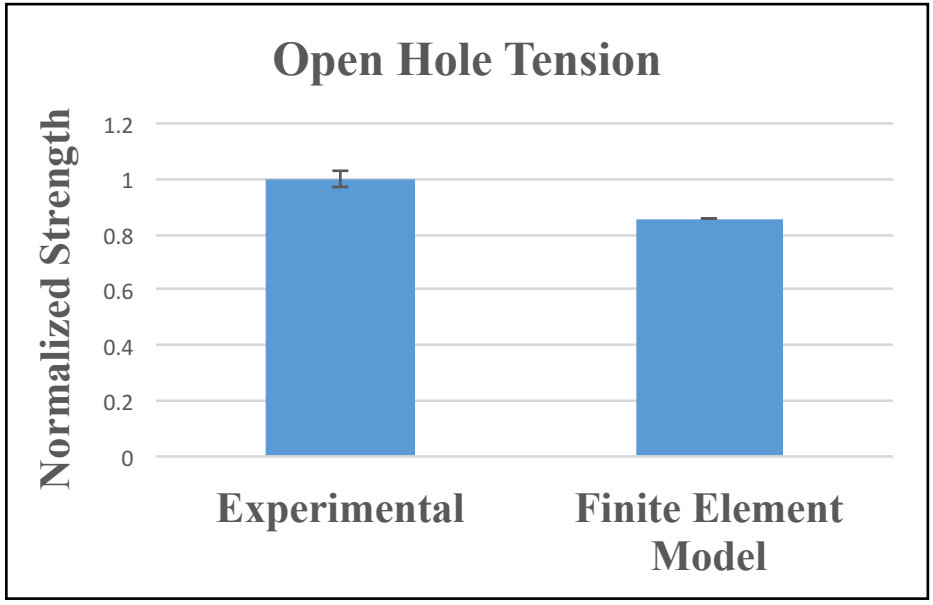
Damage Progression in Facesheets: Analysis of +/-45 Laminates

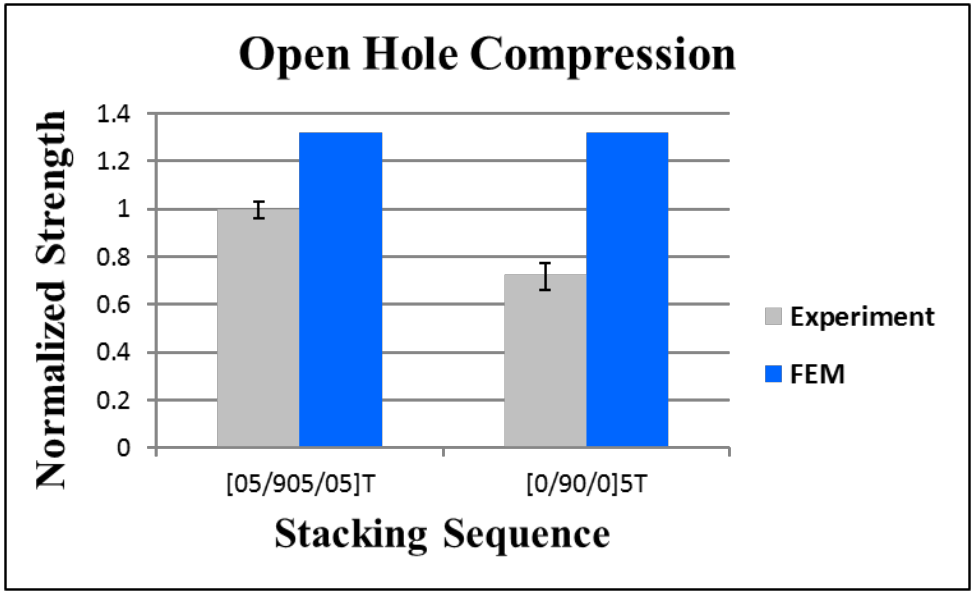
- **Matrix shear strength and damage parameters were modified to model the test behavior**



Damage Progression in Facesheets: Future Work

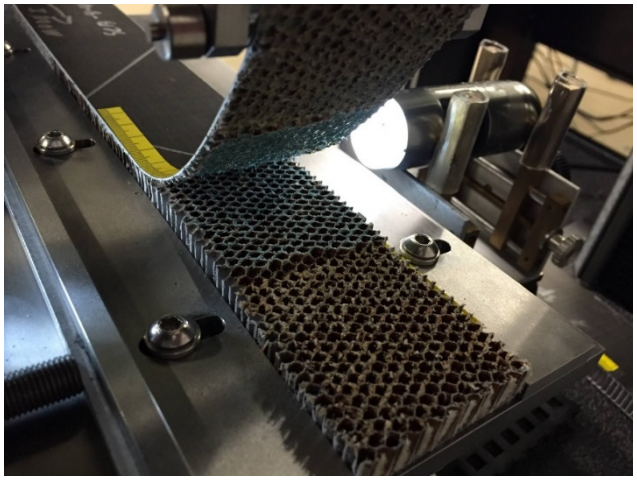
- **Revisit open hole results with updated cohesive element parameters and matrix damage parameters**



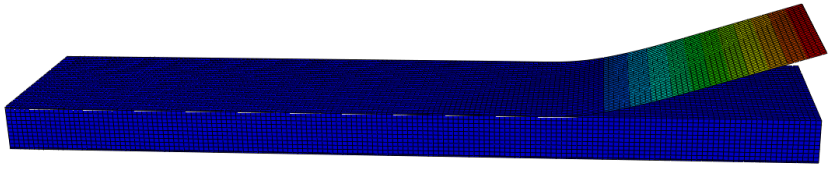


Damage Progression in Sandwich Composites: Analysis of Interfacial Disbond

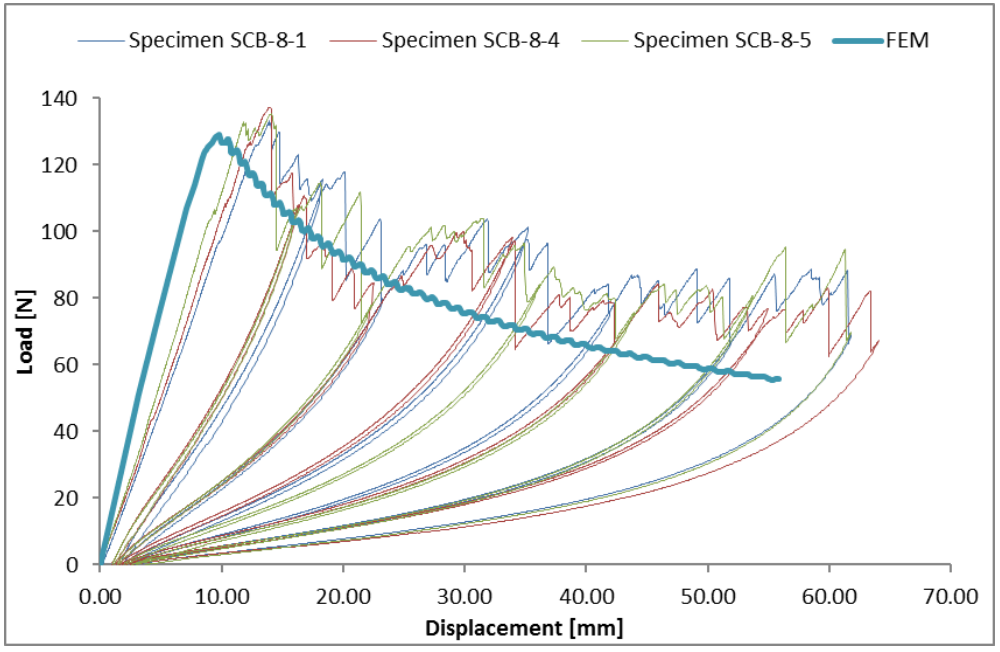
- **Calibration of interfacial cohesive elements**
  - **Mode I Sandwich SCB**



Single Cantilever Beam Test



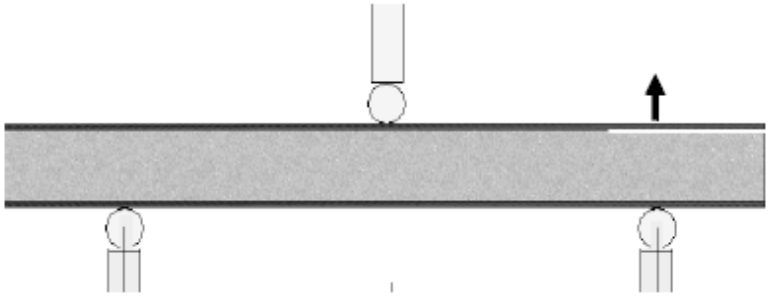
Single Cantilever Model Displacements



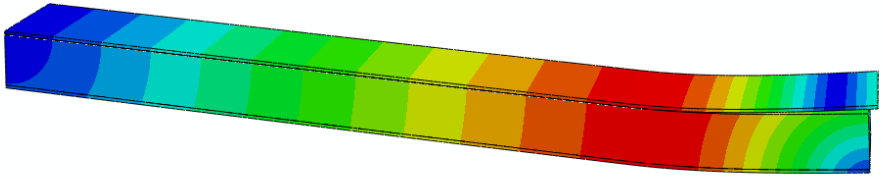
Load vs Displacement Data

Damage Progression in Sandwich Composites: Current Focus

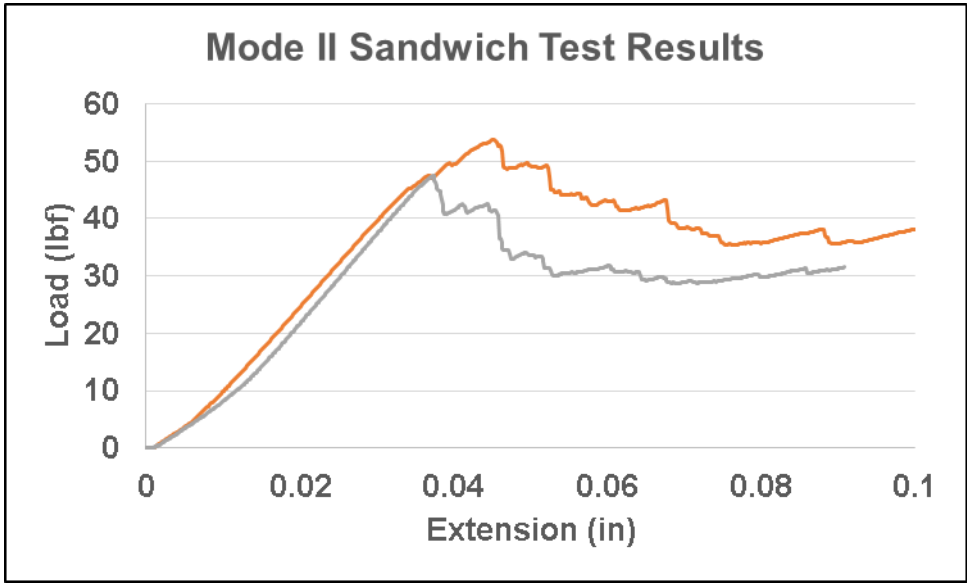
- **Calibration of interfacial cohesive elements**
  - **Mode II Sandwich ENF**



ENF Beam Test



Sandwich Model Displacements

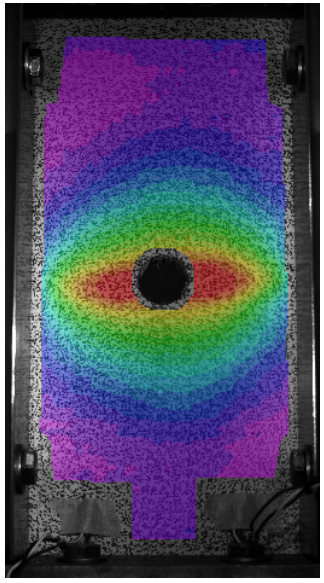


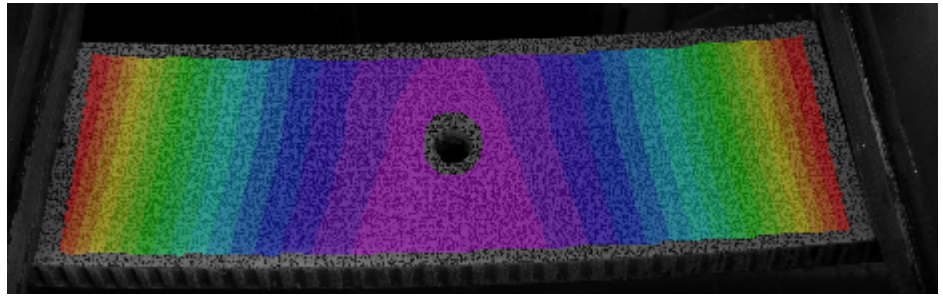
Load vs Extension Data

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

- **Modeling Sandwich Open Hole Flexure**
  - **No observed out of plane buckling from DIC results**
  - **Does not need a Riks Buckling analysis**

DIC Out-of-plane deformation



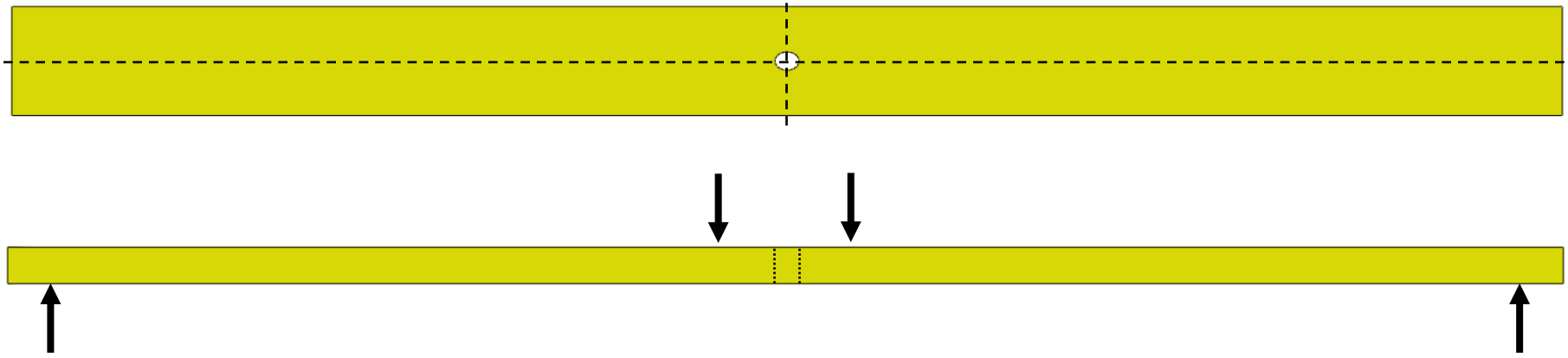


Sandwich Open Hole Flexure

Sandwich Open Hole Compression

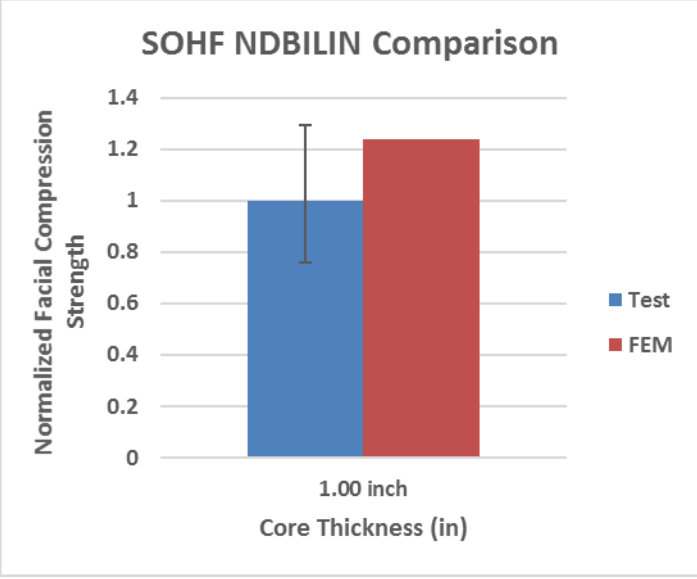
Damage Progression in Sandwich Composites: Analysis of Sandwich Open Hole Test

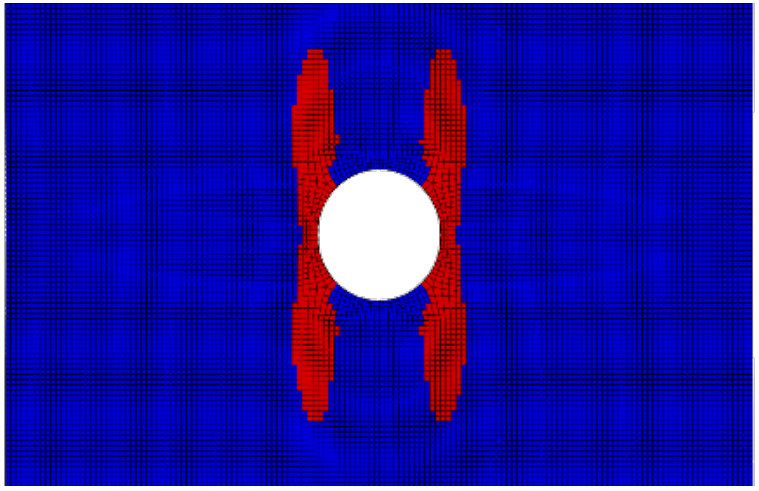
- **Sandwich Open Hole Flexure model validation**
  - **Flexure is a larger specimen than compression specimen which means a larger finite element model**
  - **¼ model with symmetry boundaries**
  - **Model full length to avoid finite length effects**
  - **Line load assumption for supports**



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

- **Modeling Sandwich Open Hole Flexure**
  - **Ultimate strength**
  - **Strain fields from DIC measurements**
  - **Damage progression from X-ray CT (in progress)**
    - **Images captured at 70% and 90% of ultimate load**





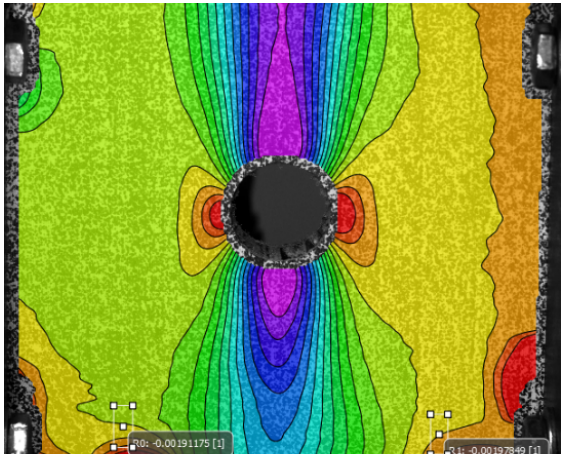
NDBILIN Matrix Damage

Future Work:
Notch Sensitivity of Composite Sandwich Structures

- **Development of sizing guidelines for sandwich open hole compression and flexure tests**
- **Investigate third test configuration**
- **Incorporate updated material/model parameters in laminate open hole tension/compression simulations**
- **Explore best practices for modeling core**
- **Investigate buckling solution for facesheet delamination compression tests**

SUMMARY:
Benefits to Aviation

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



Thank you for your attention!

Questions?