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
  Boeing
  Oregon State University

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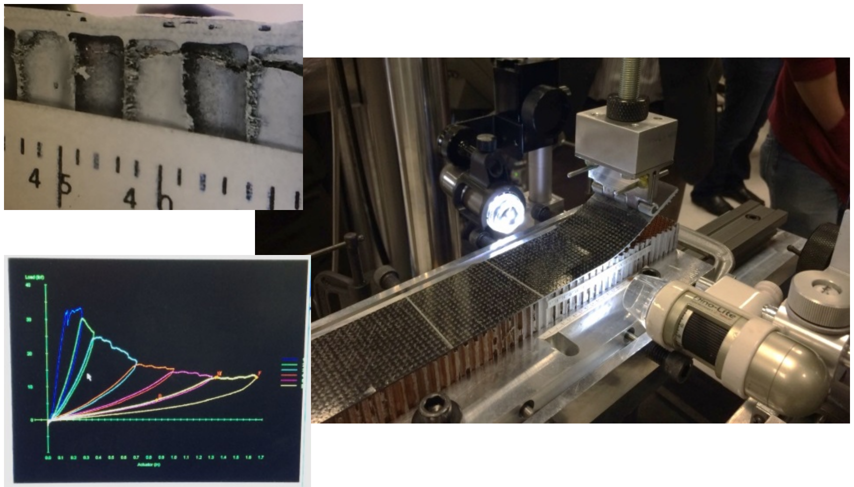
Outline

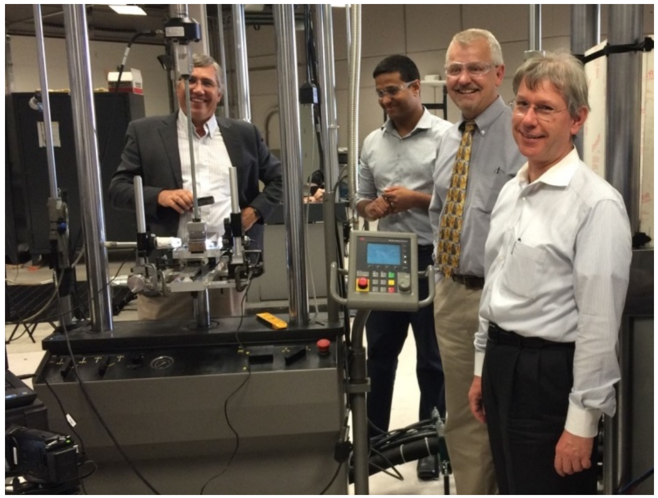
- **Brief updates: Previous research**
  - **Sandwich fracture mechanics**
  - **Sandwich damage tolerance**
- **Sandwich notch sensitivity investigation**
  - **Test method development**
  - **Numerical modeling – progressive damage analysis**

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**

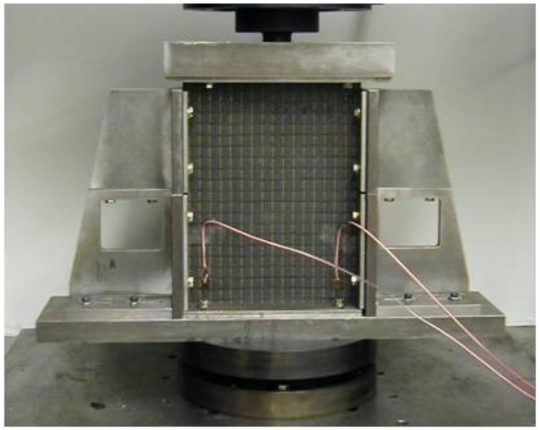




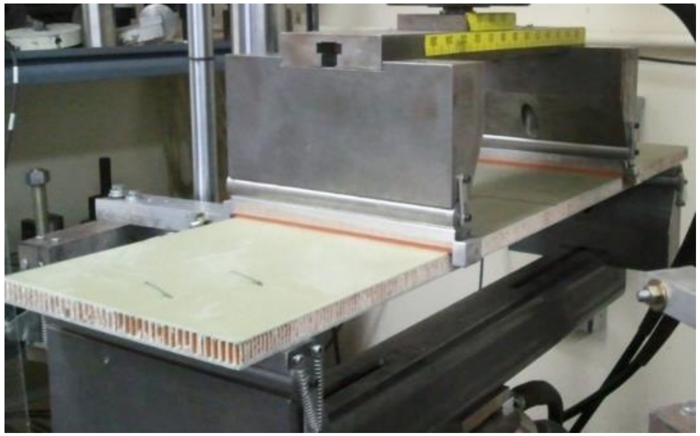
Status Update:

Development of Sandwich Damage Tolerance Test Methods

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



Compression After Impact (CAI)



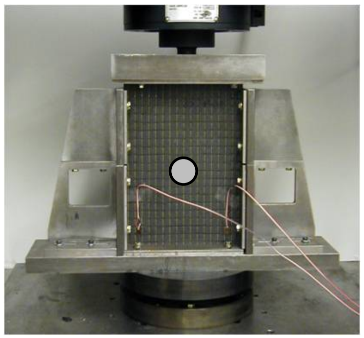
4-Point Flexure After Impact (4-FAI)

Background:
Notch Sensitivity of Sandwich Composites

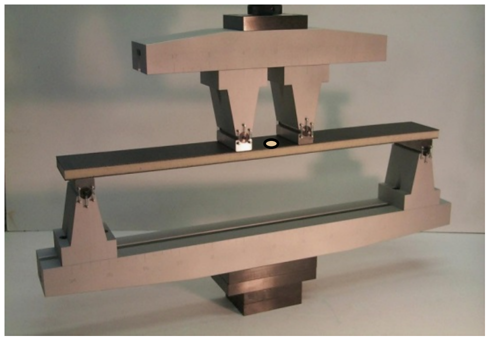
- Notch sensitivity test methods for <u>monolithic composites</u> are reaching relatively high levels of maturity
  - ASTM D 5766 – Open Hole Tension
  - ASTM D 6484 – Open Hole Compression
  - Out-of-plane shear (Parmigiani)
- Less attention to notch sensitivity tests methods of <u>sandwich composites</u>
  - Currently no standardized tests for notch sensitivity
- Failure prediction of notched <u>monolithic composites</u> is receiving considerable attention
  - Reduced focus on analysis of notched <u>sandwich composites</u>

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**



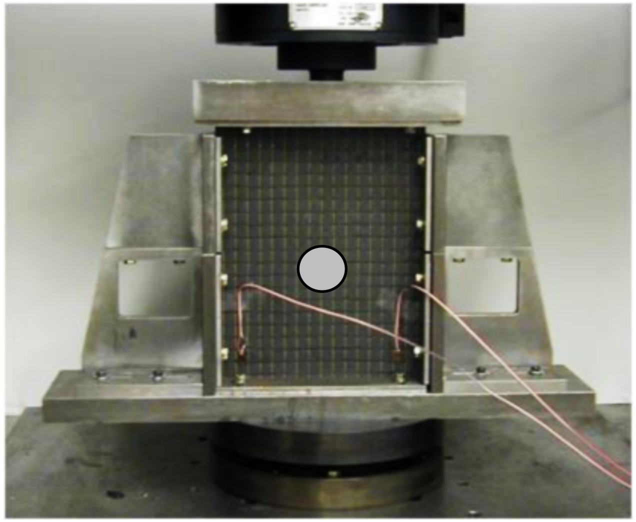
Sandwich Open Hole Compression



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

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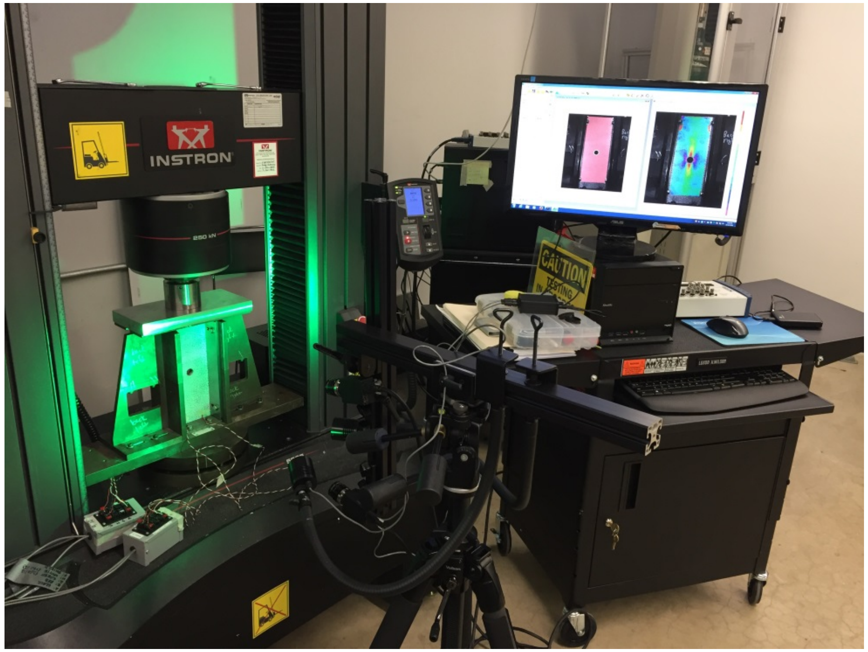
Sandwich Open Hole Compression: Aspect Ratio Investigation

- Investigate the separation of central hole to the load boundary effects by examining the strain fields of different H/W ratios
- Select a H/W ratio that produces an acceptable strength reduction
- Provide more test data to calibrate material parameters in ABAQUS/NDBILIN

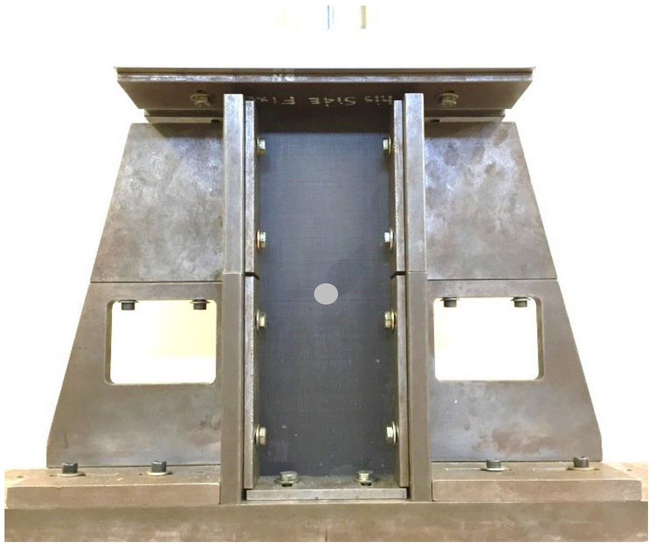


Current Focus:
Investigating Aspect Ratio

- Carbon/epoxy facesheets, Nomex honeycomb core
- Sized to 4.0 in. wide and 2/3 in. hole diameter (W/D = 6)
- Heights of 6.0 in., 8 in., and 10.5 in.

H/W = 1.5

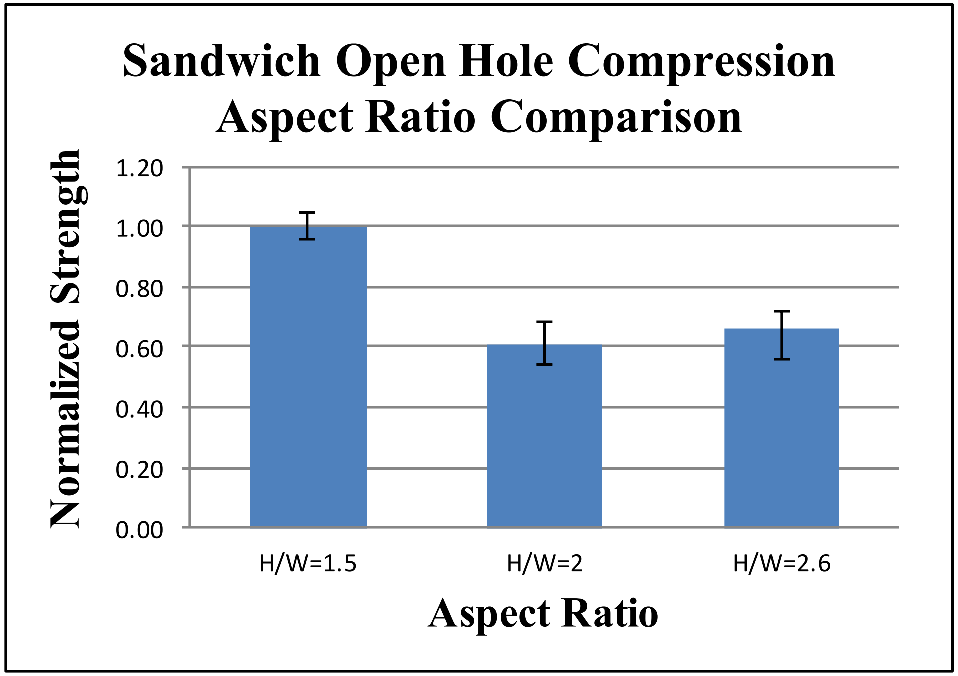
H/W = 2.0

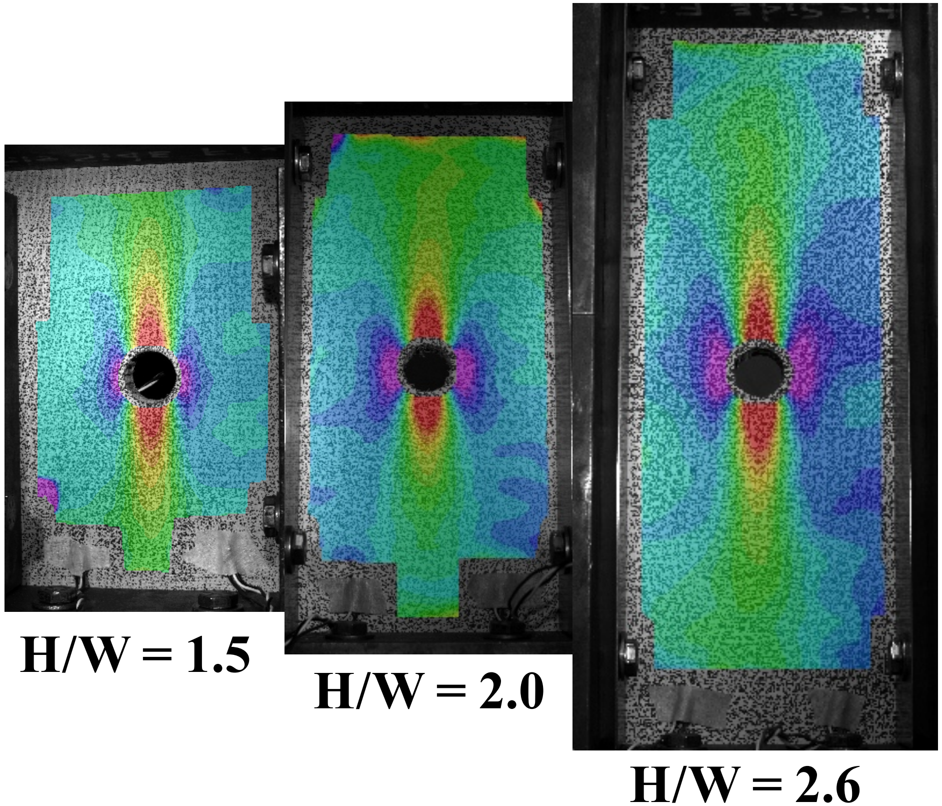


H/W = 2.6

Current Focus: Investigating Aspect Ratio

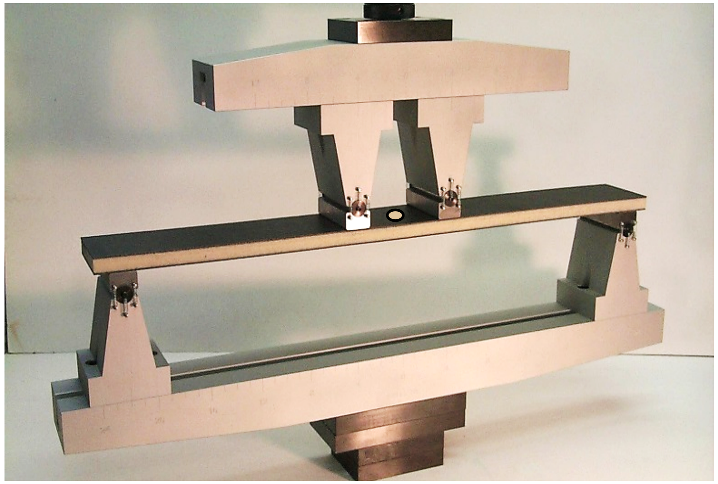
- Max strength decreases significantly from H/W = 1.5 to 2.0
- Separation of notch effect from boundary in strain field

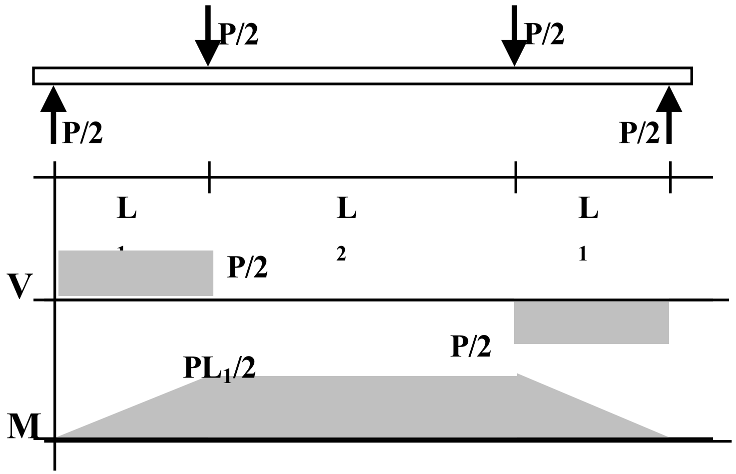




Testing Considerations:
Sandwich Open Hole Flexure

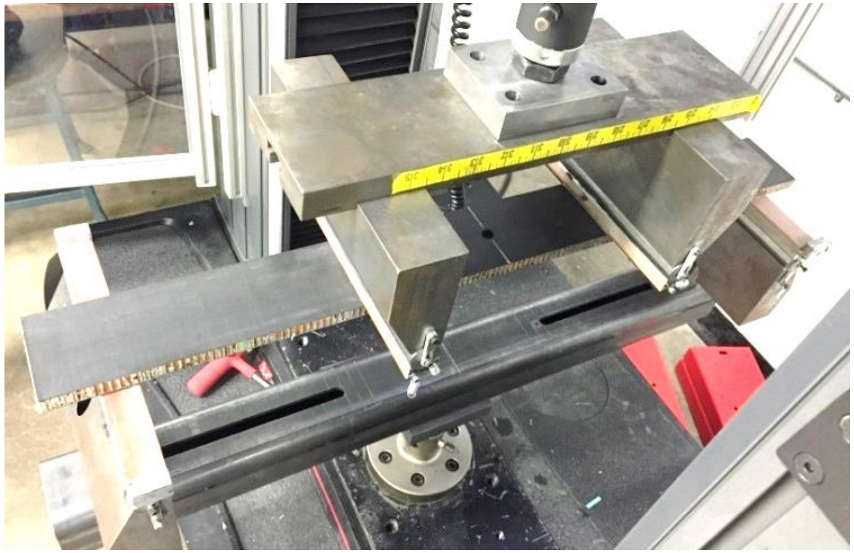
- Test fixture/specimen support
  - Inner span
    - Separation of notch and loading boundary effects
  - Outer span
    - Develop sufficient bending moment
    - Ensure failure in inner span
- Specimen size





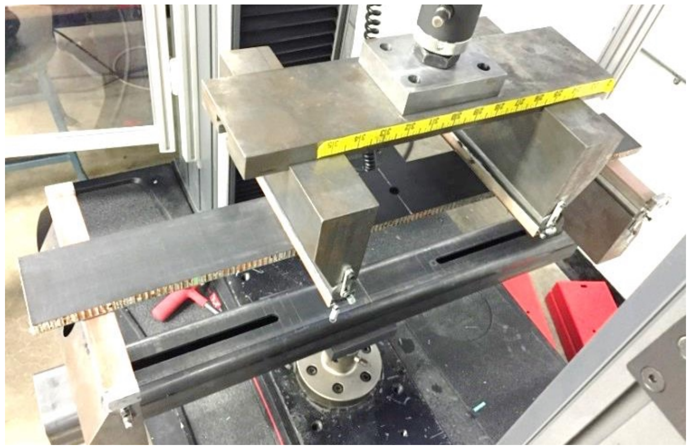
Sandwich Open Hole Compression: Aspect Ratio Investigation

- Investigate the separation of central hole to the load boundary effects by examining the strain fields of different inner span to width (L/W) ratios
- Select a L/W ratio that produces an acceptable strength reduction
- Provide more test data to calibrate material parameters in ABAQUS/NDBILIN



Current Focus: Investigating Aspect Ratio

- **Sandwich configuration:**
  - Carbon/epoxy facesheets, ½ in. Nomex honeycomb core
  - 0.5 in. diameter central circular hole
  - 3 in. width x 32 in. length
- **Investigating effect of inner span**
  - Inner spans of 3 in., 6 in., and 9 in.
  - Constant applied moment
    - Outer span – Inner span = 20 in.



L/W = 3

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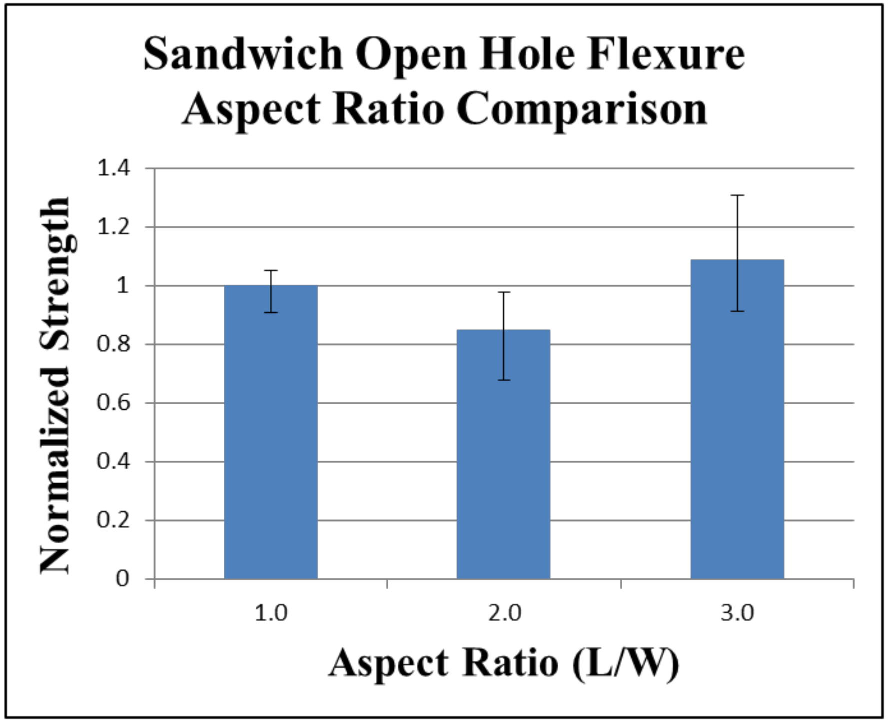
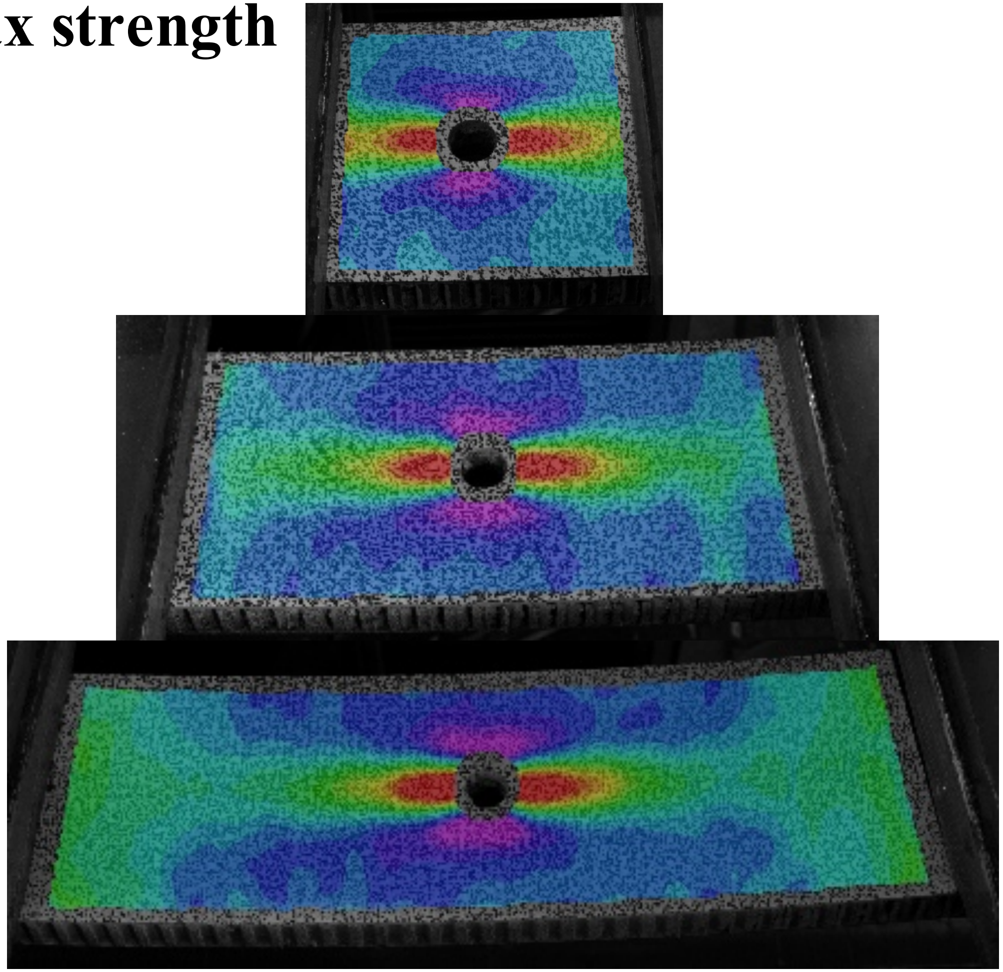
Current Focus:
Investigating Aspect Ratio

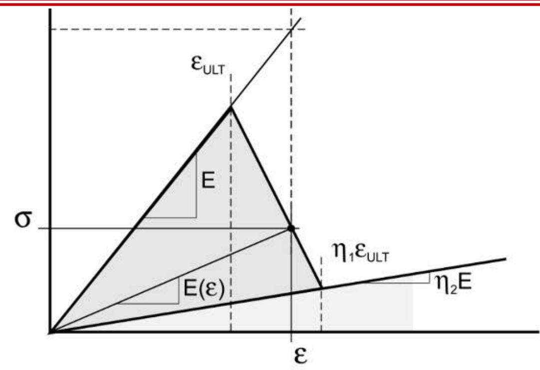
- No significant difference in max strength
- Far field reached at L/W = 2.0

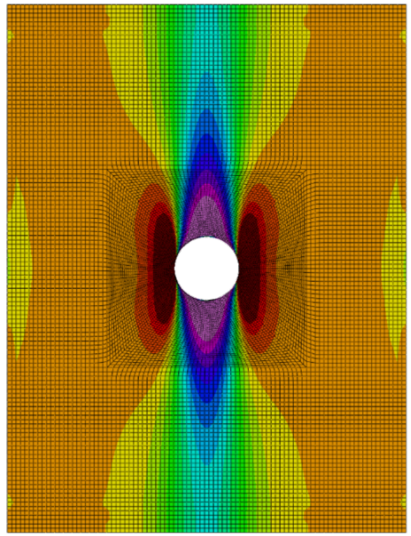




Analysis of Notched Sandwich Specimens
ABAQUS with NDBILIN:

- 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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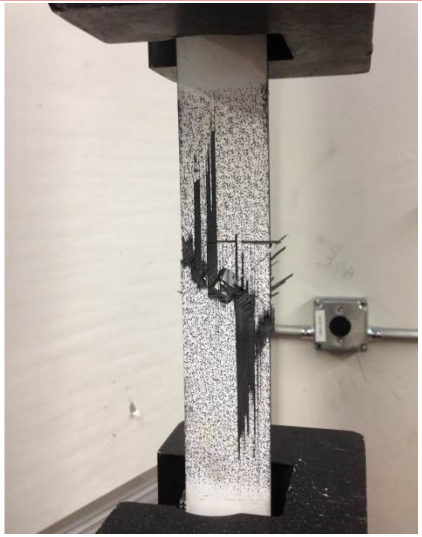
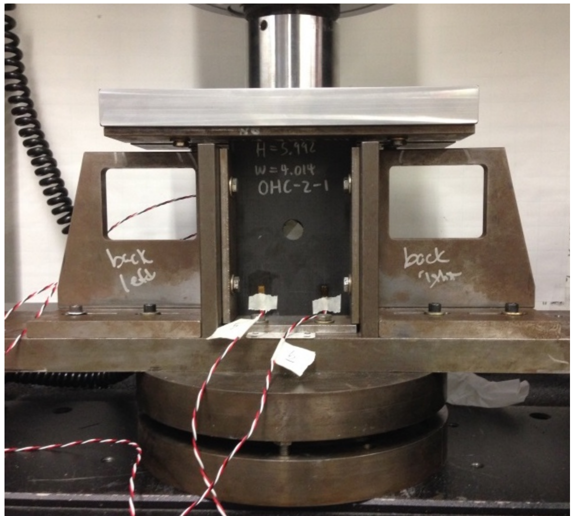
Development of Modeling Approach

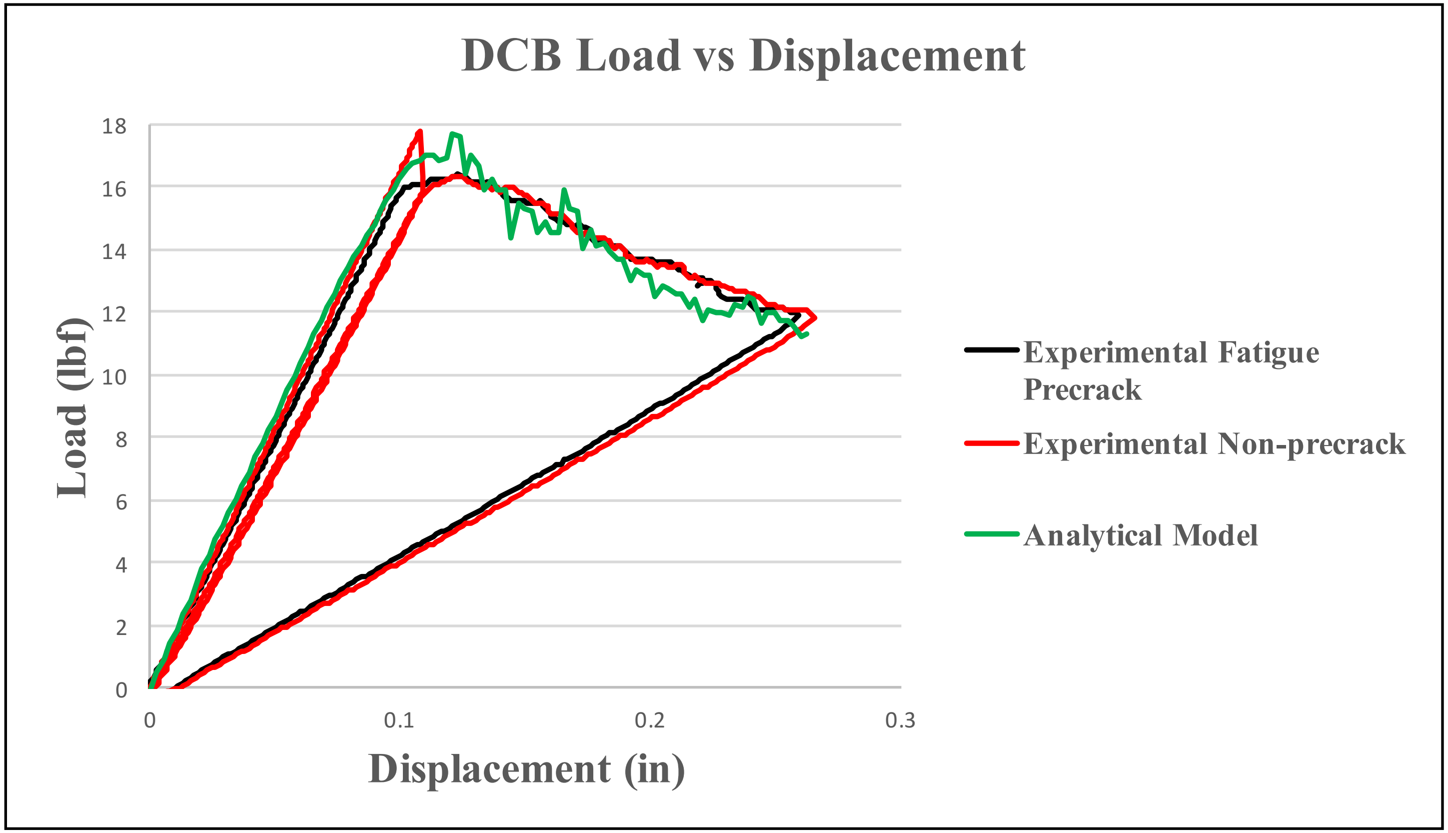
- **Modeling of damage progression in facesheets**
  - Analysis of interlaminar disbond (Mode I and Mode II)
  - Analysis of laminate open-hole <u>tension</u> test
  - Analysis of laminate open-hole <u>compression</u> test
- **Modeling of damage progression in sandwich composites**
  - Sandwich interface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





Damage Progression in Facesheets: Analysis of Interlaminar Disbond

- **IM7/8552 testing using ASTM D5528**



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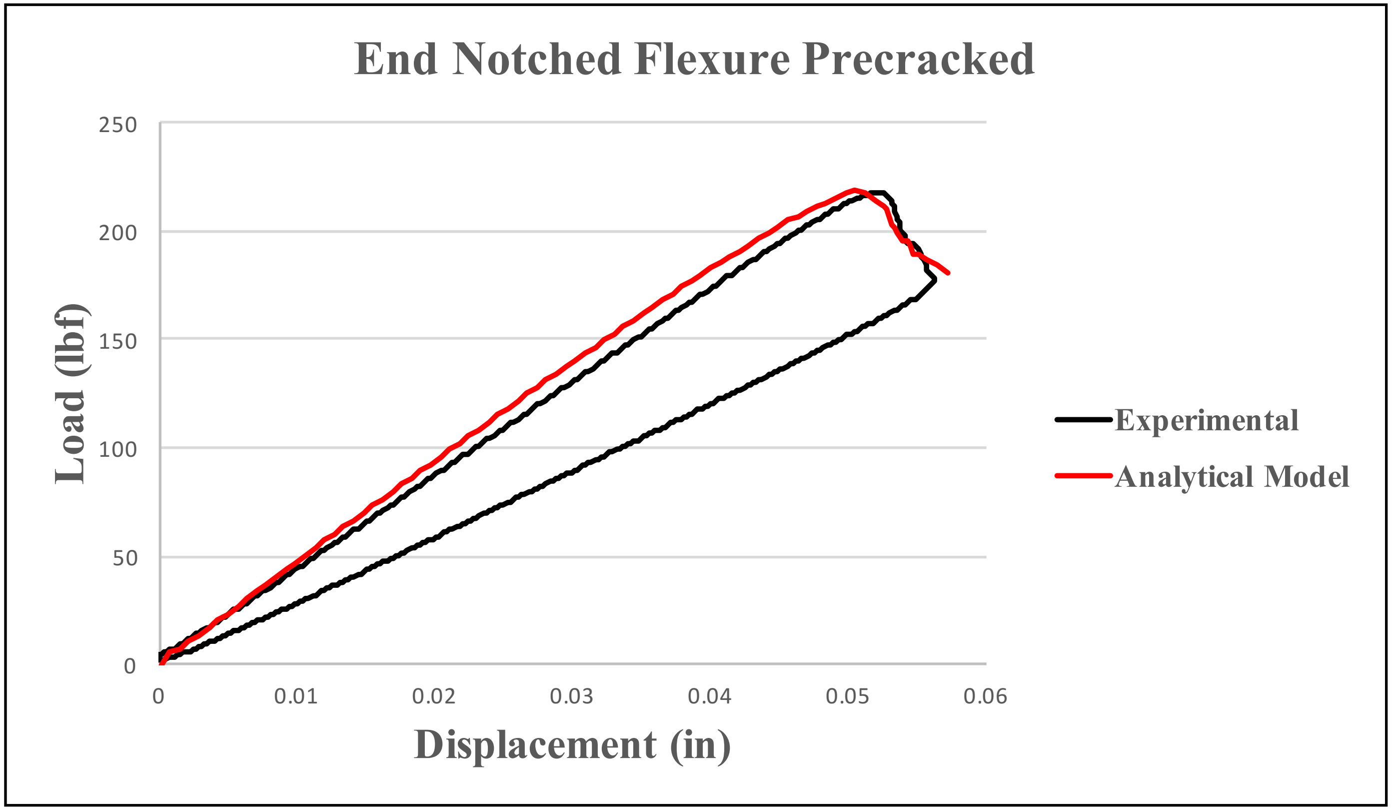
Damage Progression in Facesheets: Analysis of Interlaminar Disbond

- **IM7/8552 testing using ASTM D7905**

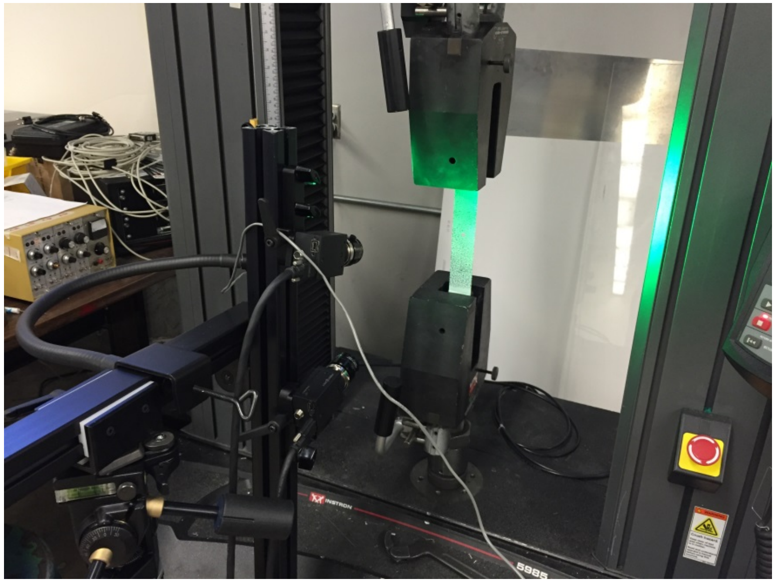


Damage Progression in Facesheets: Analysis of Open Hole Tension Tests

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

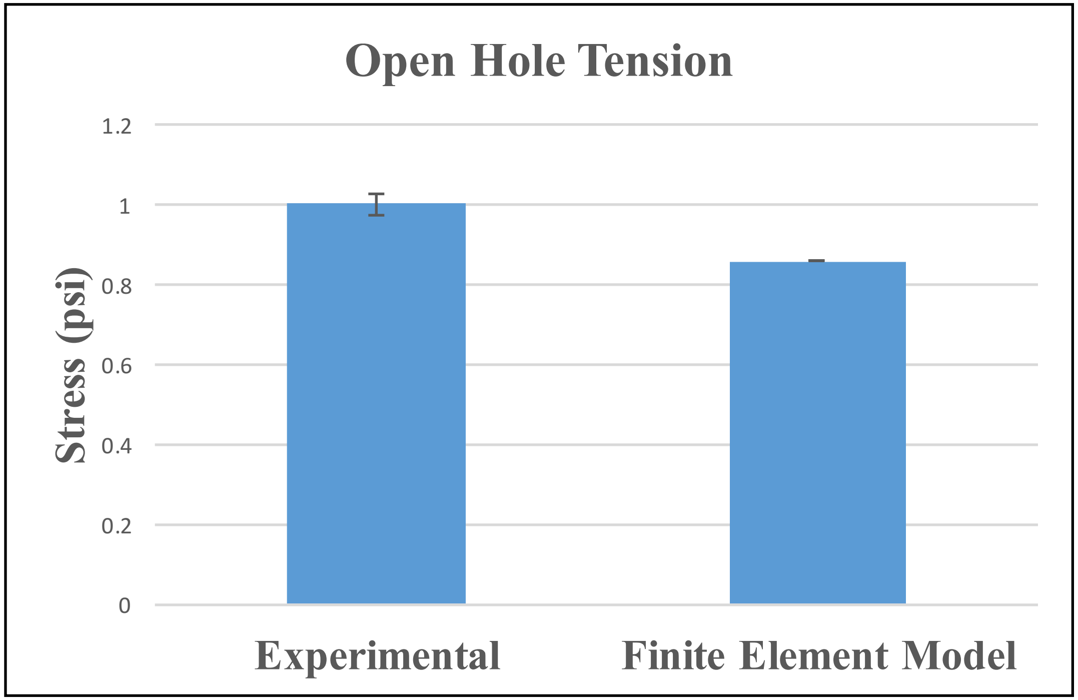
  $[0/90/0]_T$

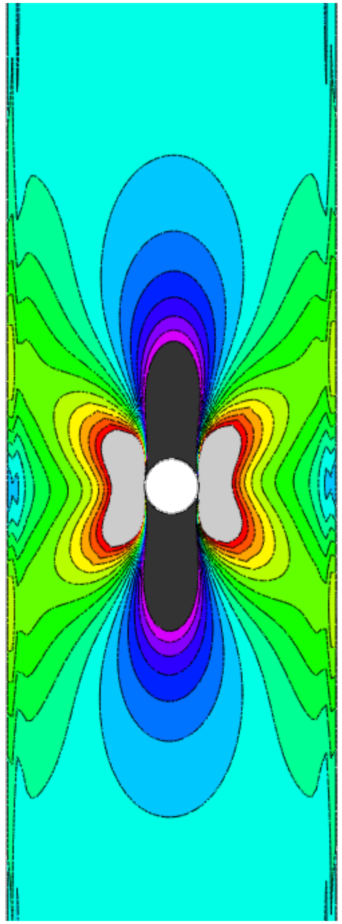
- **Comparison with results from mechanical testing**
  - **Ultimate strength**
  - **Stress vs. strain plots**
  - **Strain fields from Digital image correlation**
  - **Damage progression using X-ray CT**



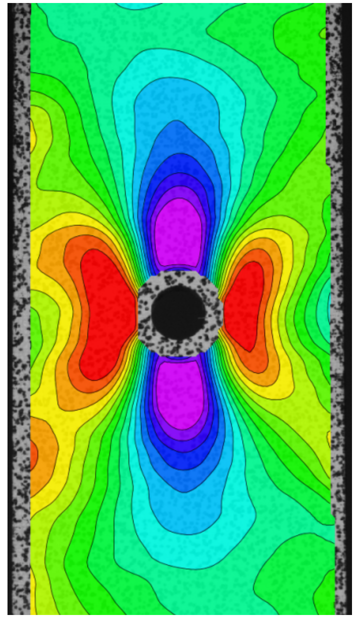
Damage Progression in Facesheets: Analysis of Open Hole Tension Tests

- Good agreement on stiffness response
- Similar full field strain response





Finite Element Prediction



Experimental Result

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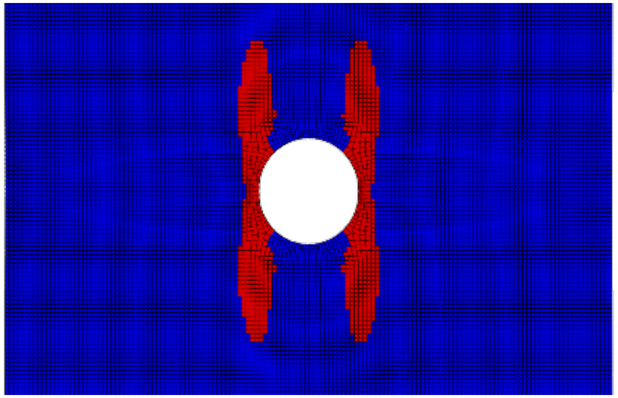
Damage Progression in Facesheets: Analysis of Open Hole Tension Tests

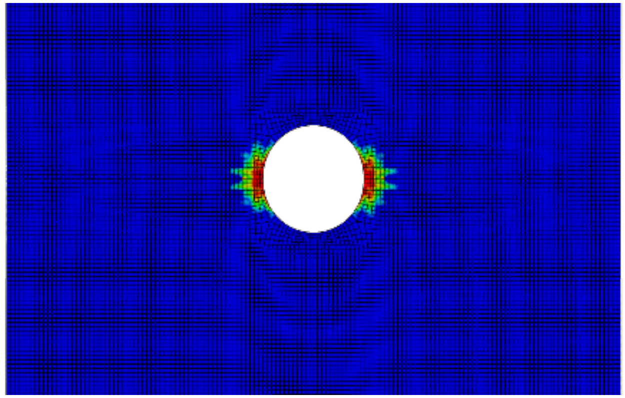
90% max load

Matrix damage

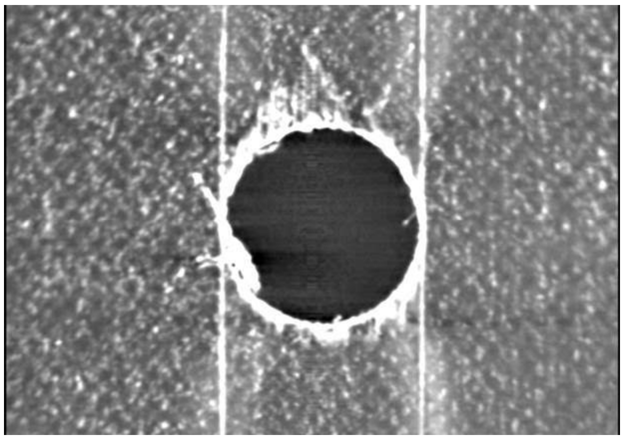
Delamination

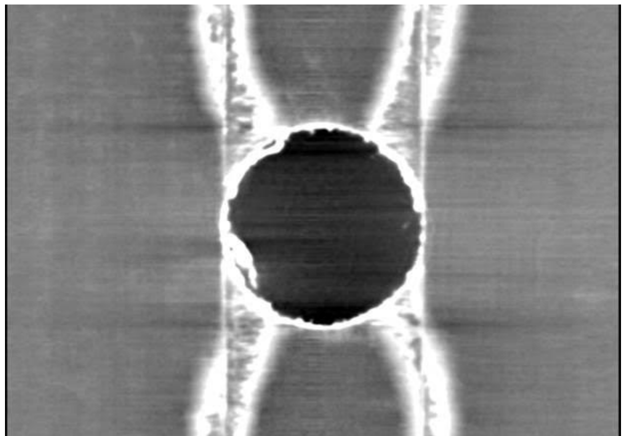
NDBILIN





X-ray CT





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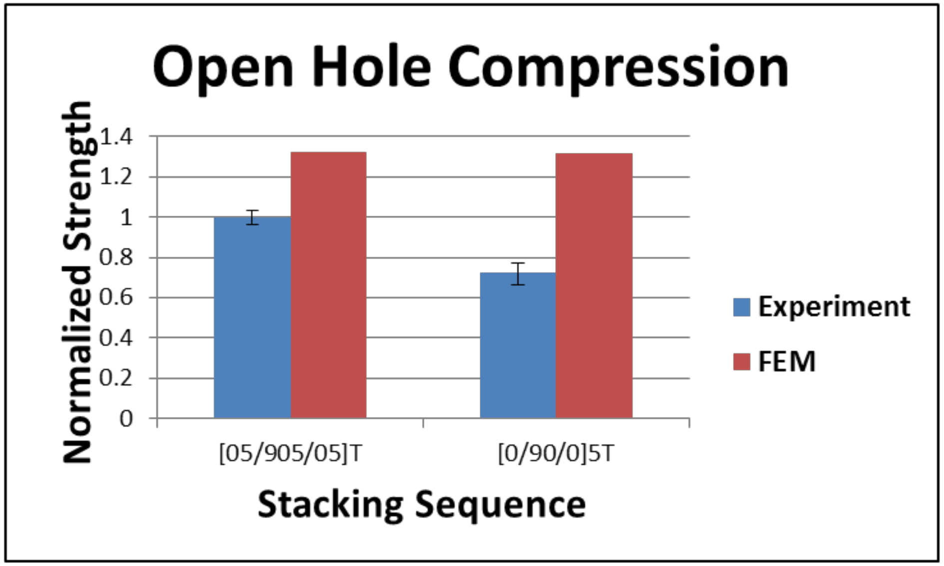
Damage Progression in Facesheets: Open Hole Compression Testing & Analysis

- Mechanical testing of 1.5 in. wide specimen, 0.25 in. dia center hole (ASTM D6484)

- Two IM7/8552 carbon/epoxy laminates:

  $[0_5/90_5/0_5]_T$ $[0/90/0]_{5T}$

- Comparison with results from mechanical testing
  - Ultimate strength
  - Damage state using X-ray CT



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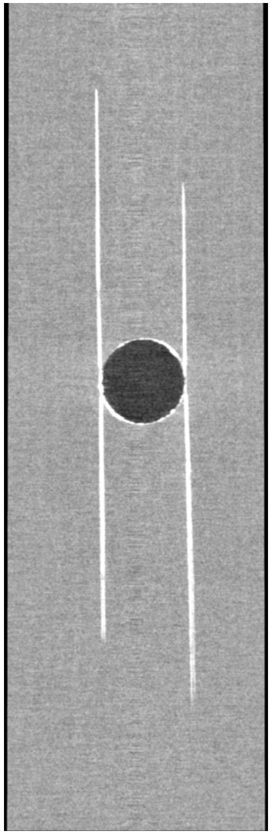
Damage Progression in Facesheets: Open Hole Compression Analysis $[0_5/90_5/0_5]_T$

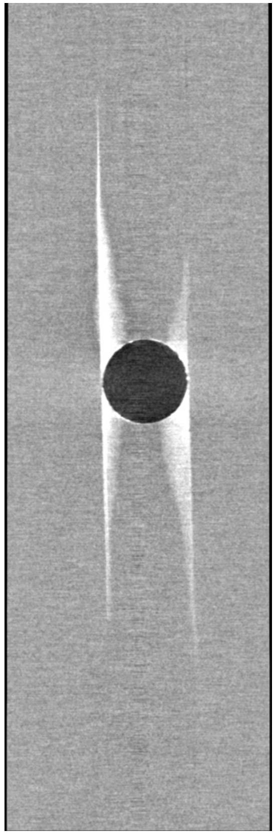
90% max load

X-ray CT

Matrix damage

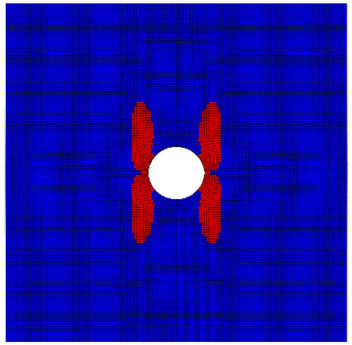


Delamination

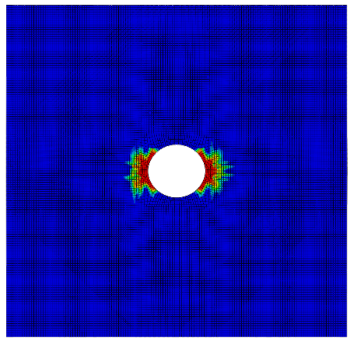


NDBILIN

Matrix damage



Delamination

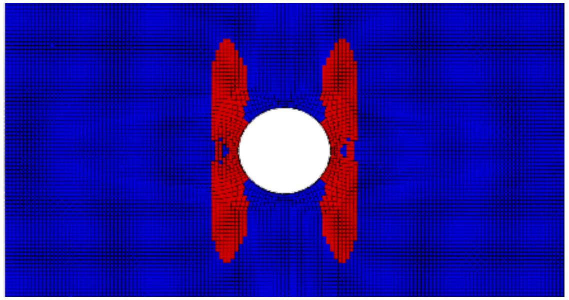


Damage Progression in Facesheets: Open Hole Compression Analysis $[0/90/0]_{5T}$

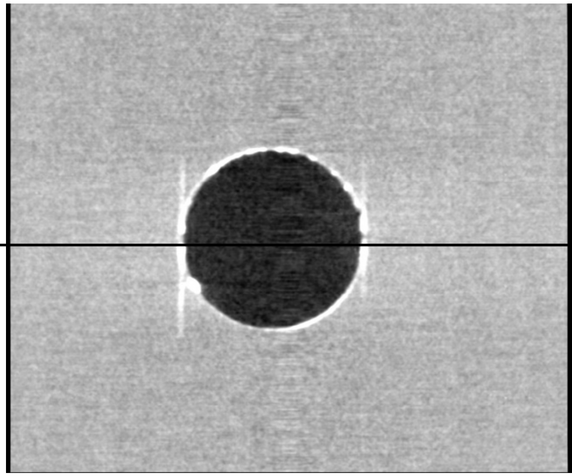
90% max load

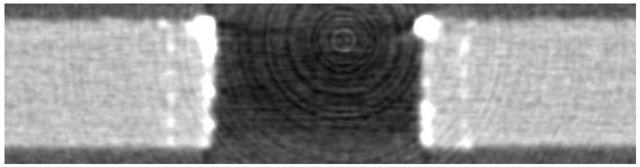
Matrix damage

NDBILIN



X-ray CT





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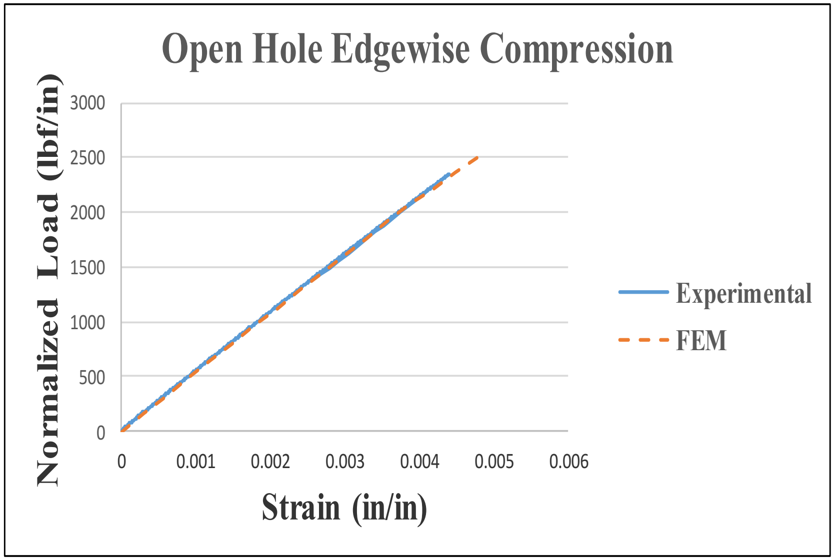
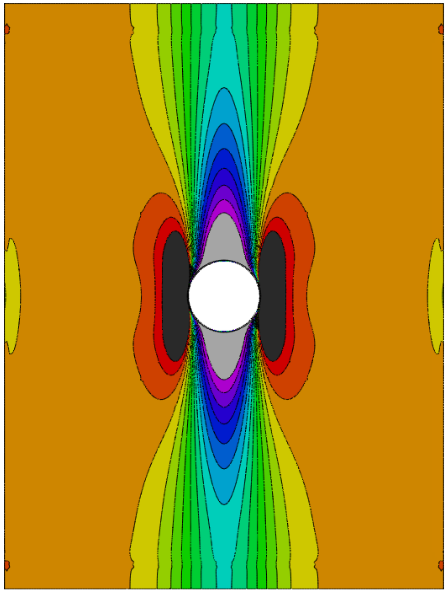
Damage Progression in Facesheets: Comparison with Experimental Results

- Similar damage progression and strength in tension test
  - Little difference between model with and without cohesive elements
- Model over predicting strength on OHC specimens
- Compression failure modes not predicted in model
  - Investigating ABAQUS buckling solution

Initial Failure Analysis: Sandwich Open Hole Compression Test

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





ABAQUS/NDBILIN Prediction

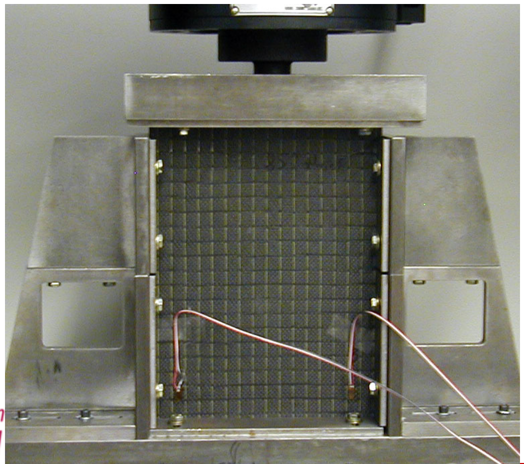
DIC Results

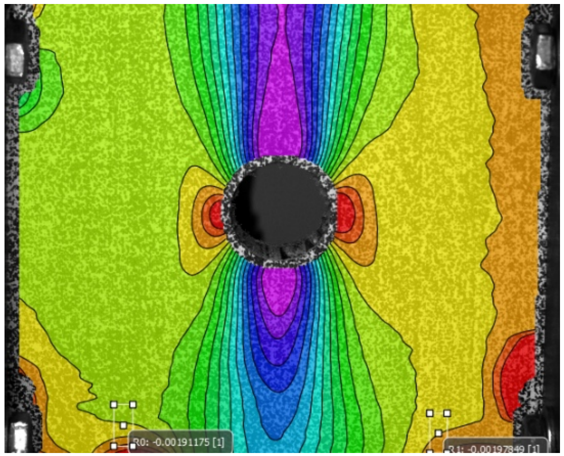
Future Work:
Notch Sensitivity of Composite Sandwich Structures

- Investigate buckling solution for compression tests
- Inclusion of ABAQUS cohesive elements at facesheet/core interface
- Investigate additional notch configurations

SUMMARY:
Benefits to Aviation

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





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Thank you for your attention!

Questions?

Future Work:
Notch Sensitivity of Composite Sandwich Structures

- Investigate additional notch configurations
  - One sided (single facesheet) hole
  - Tension
  - Edge v-notch flexure
  - Out of plane shear (Mode III)
  - In-plane biaxial tension/compression

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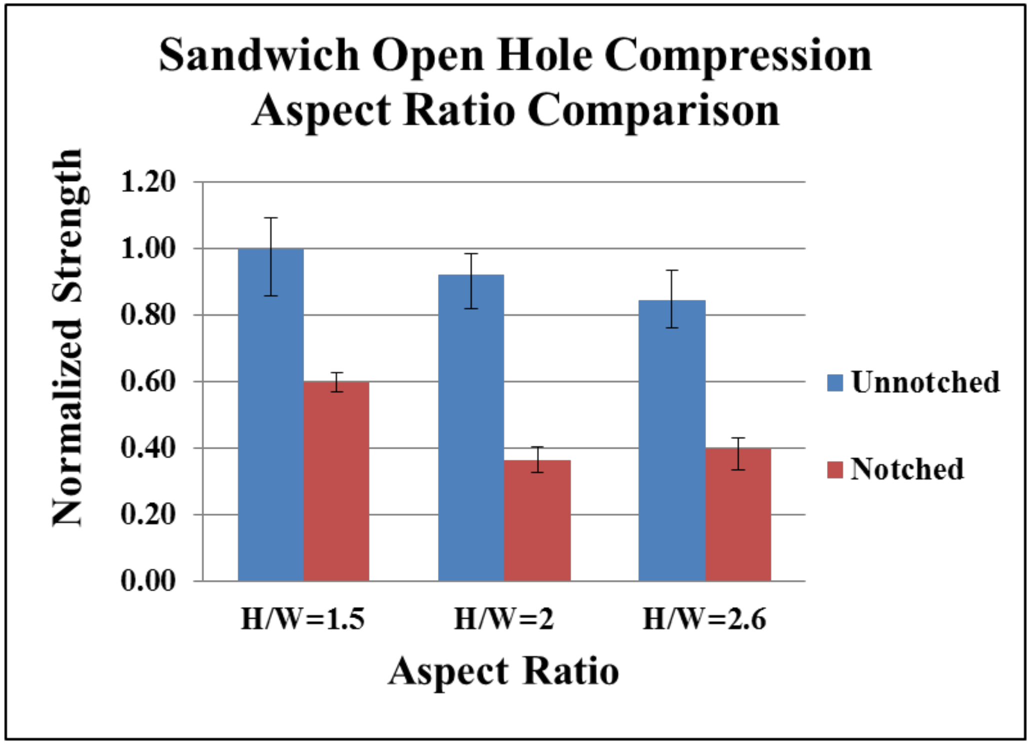
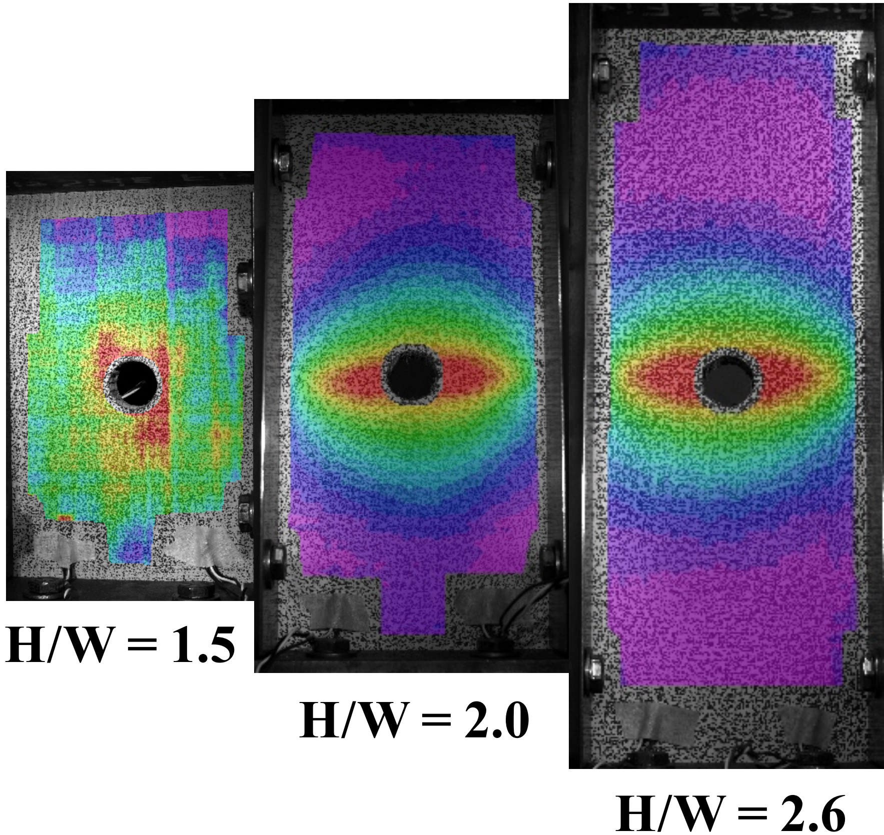
Sandwich Open Hole Compression: Investigating Aspect Ratio

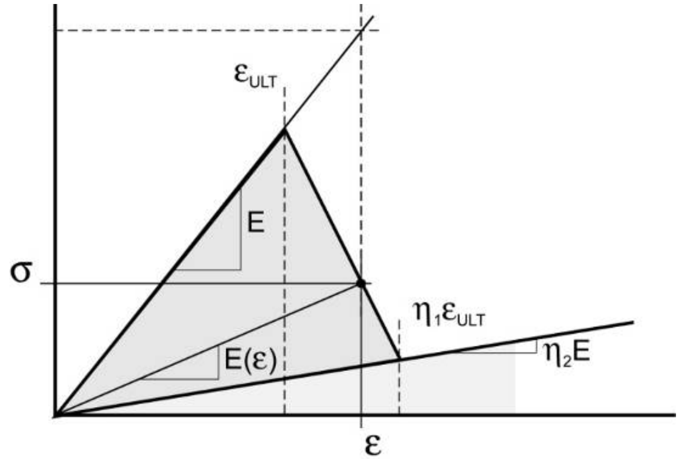
- Notch strength decreases relatively more than unnotched
- Out of plane deformation



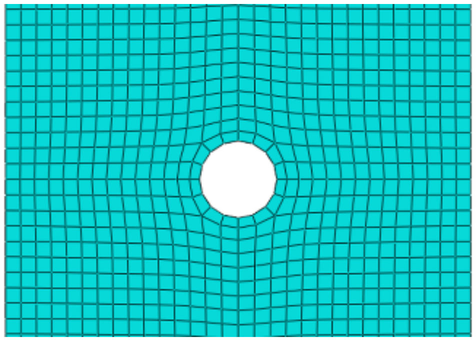


Analysis of Notched Sandwich Specimens:
Sensitivity Study

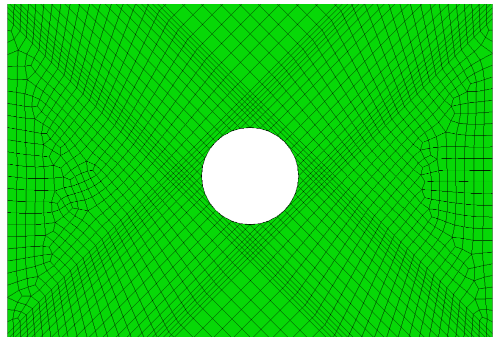
- Material properties
  - Tension/compression
- Mesh density
- Mesh orientation
  - Notch centric
  - Fiber aligned mesh
- Solution type
- Solution parameters
  - Step size
  - Viscous damping



Damage parameters



Notch-centric mesh



Fiber-aligned mesh

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