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Damage Tolerance and Notch Sensitivity Test Method Development for Sandwich Composites

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2014 Technical Review

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FAA Sponsored Project Information

- Principal Investigator: **Dr. Dan Adams**
- Graduate Student Researchers:
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  - **Marcus Stanfield**
- FAA Technical Monitor:
  - **Lynn Pham**
- Collaborators:
  - **Materials Sciences Corporation**
  - **ASTM Committee D30**

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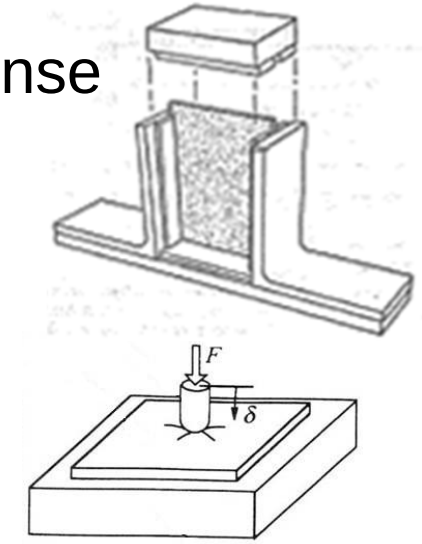
Outline

- ***Summary*: Damage Tolerance Test Method Development for Sandwich Composites**
  - **Sandwich Compression After Impact Test**
  - **Sandwich 4-Point Flexure After Impact Test**
- **Notch Sensitivity of Sandwich Composites**
  - **Investigation of Candidate Test Methods**
  - **Initial Testing and Analysis**

Damage Tolerance Test Method Development For Sandwich Composites



- Damage **Tolerance:** concerned with structural response and integrity associated with given damage state

  versus…

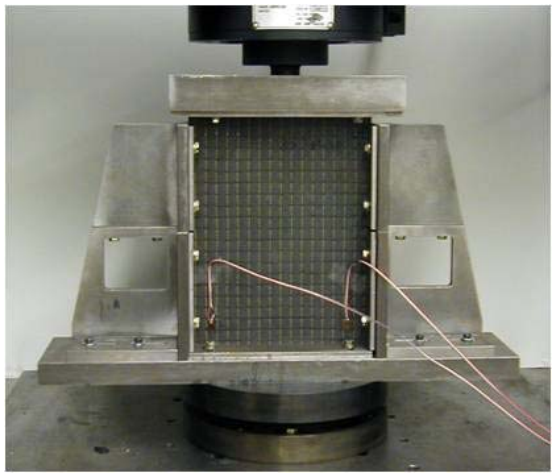
  Damage Resistance - concerned with the creation of damage due to a specific impact event

- Damage tolerance test methods for monolithic composites at a relatively high level of maturity
  - Damage Resistance: ASTM D 7136 – Drop-Weight Impacting
  - Damage Tolerance: ASTM D 7137 – Compression After Impact
- Less attention to sandwich composites… until recently
  - ASTM D7766 (2011) *"Standard Practice for Damage Resistance* Testing of *Sandwich* Constructions"

Research Objectives:

Damage Tolerance Test Methods for Sandwich Composites

- **Identify and evaluate candidate test methodologies**
- **Compare residual strengths of impact damaged sandwich panels using proposed test methods**
- **Develop standardized ASTM test method(s)**
- **Investigate scaling of test results**



Compression After Impact (CAI)

4-Point Flexure After Impact (4-FAI)

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Considerations for Test Method Development:
Damage Tolerance of Sandwich Composites

- **Identify intended usage(s) of test methods**
  - **Material ranking/selection/specification**
    - ***Specify a sandwich panel configuration***
  - **Establishing design properties/allowables**
    - ***Allow a wide range of sandwich panel configurations***
- **Ensure compatibility with existing Damage Resistance Test for Sandwich Composites (ASTM D7766)**
- **Establish suitable range of sandwich configurations**
  - **Facesheet and core parameters**
  - **Specimen size relative to damage size**
  - **Desired degree of strength reduction**

Sandwich CAI Test Method Development:
Summary of Research Performed

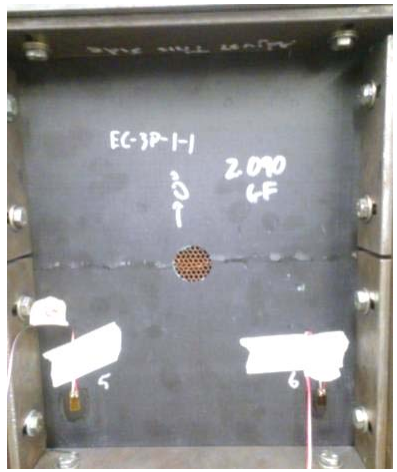
- 8.5 in. wide x 10.5 in. tall specimens
- Glass/epoxy & carbon/epoxy facesheets, 0.5 in. thick Nomex honeycomb core
- Strength reduction relative to baseline (no damage) condition

Initial assessment: Idealized impact damage

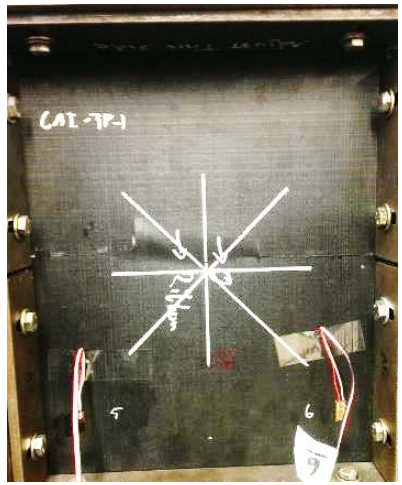
- 1 in. and 3 in. diameter hole in one facesheet

Follow-on assessment: Actual impact damage

- Drop-weight impact following ASTM D7766
- 94 in-lb (glass/epoxy) and 30 in-lb (carbon/epoxy) impact energies
- 0.625 in. impacter diameter
- Digital Image Correlation (DIC) to determine strain distribution around impact damage



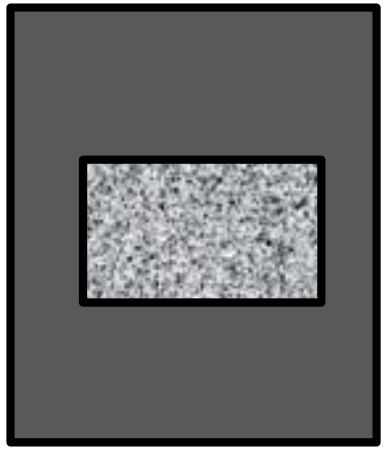
Failure of specimen with idealized damage (1 in. dia. facesheet hole)



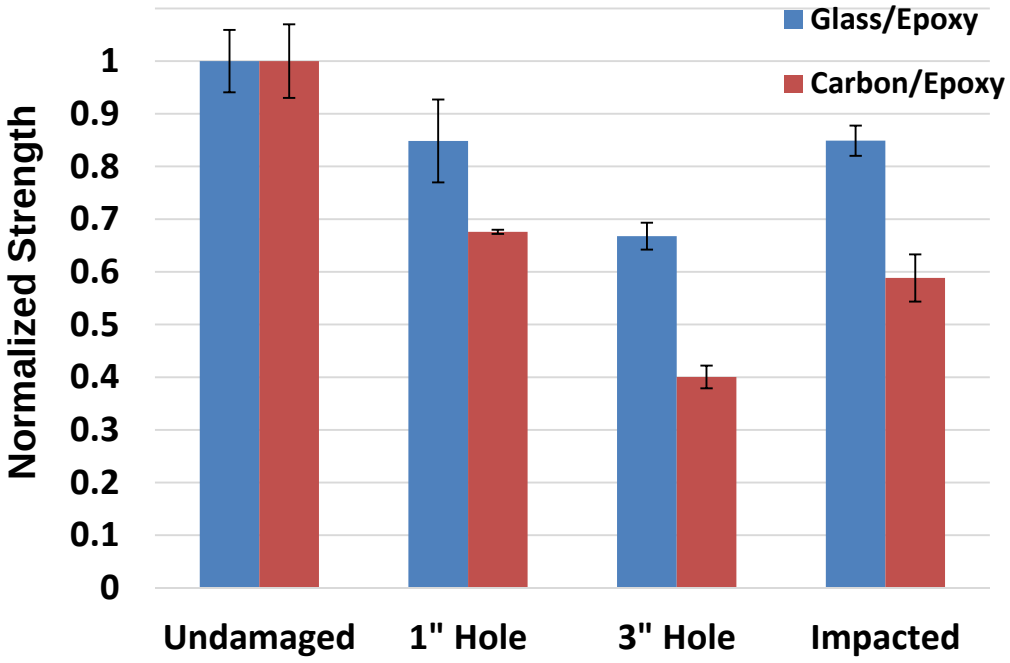
Failure of specimen with actual impact damage

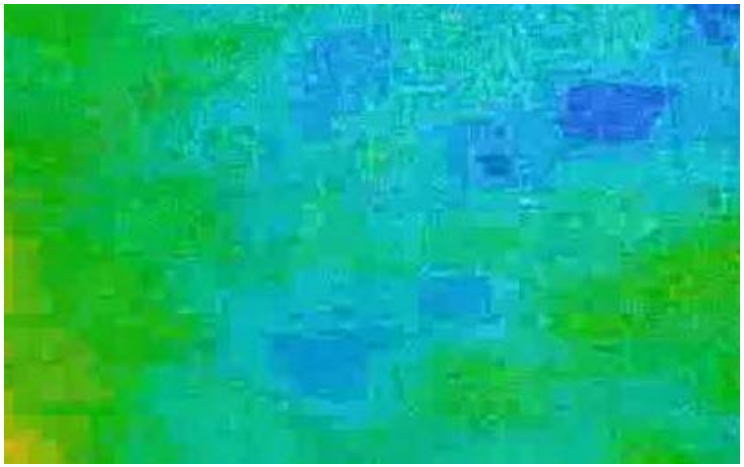
Sandwich CAI Test Method Development:
Summary of Results

- **Compression failures on 1 in. hole and impact damaged specimens**
- **3 in. diameter changes failure mode (buckling)**
- **Continue work using DIC to further investigate specimen width to damage diameter ratios**



Monitored Region

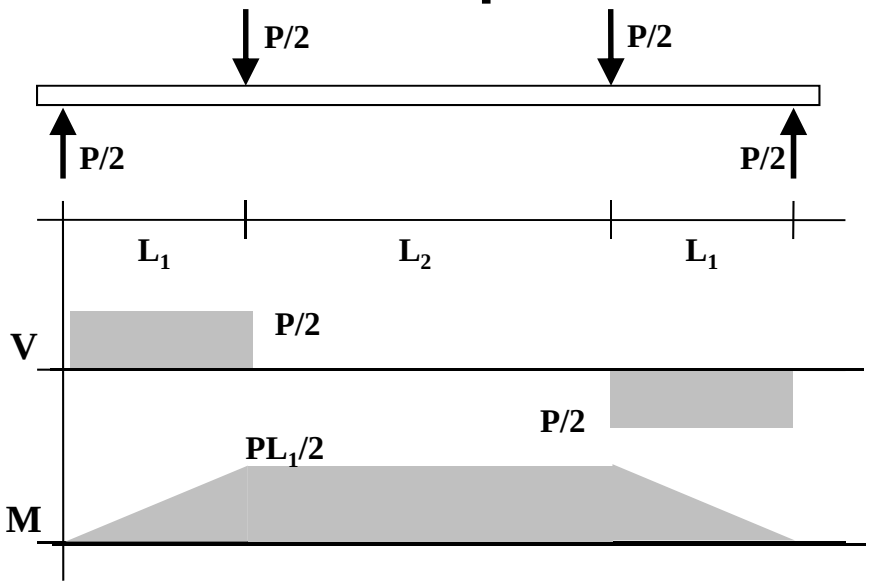




Digital Image Correlation Results: Sandwich CAI of Carbon-Epoxy/Nomex Honeycomb

Sandwich 4-Point Flexure After Impact Development:
Testing Considerations

- **Location of damage: tension or compression loading**
- **Sandwich panel dimensions (length & width)**
- **Required length of central test section (damage region) of panel**
  - Separation of damage and loading point/boundary effects
- **Required length of outer regions to develop bending moment**
- **Core requirements for shear stress - outer panel sections**
- **Facesheet /core requirements at loading points**



Sandwich 4-Point Flexure After Impact Development:
Summary of Research Performed

- 8.5 in. wide x 34 in. long sandwich specimens
- 9 in inner span
- Carbon/epoxy facesheets, Nomex honeycomb core
- Strength reduction relative to baseline (no damage) condition
- <u>Initial assessment</u>: Idealized impact damage
  - 1 in. and 3 in. diameter hole in compression-loaded facesheet
  - Spliced cores for higher shear strength and reduced stress concentrations at loading points
- <u>Follow-on assessment</u>: Impact damaged specimens (in progress)
  - Impacted in accordance to ASTM D7766

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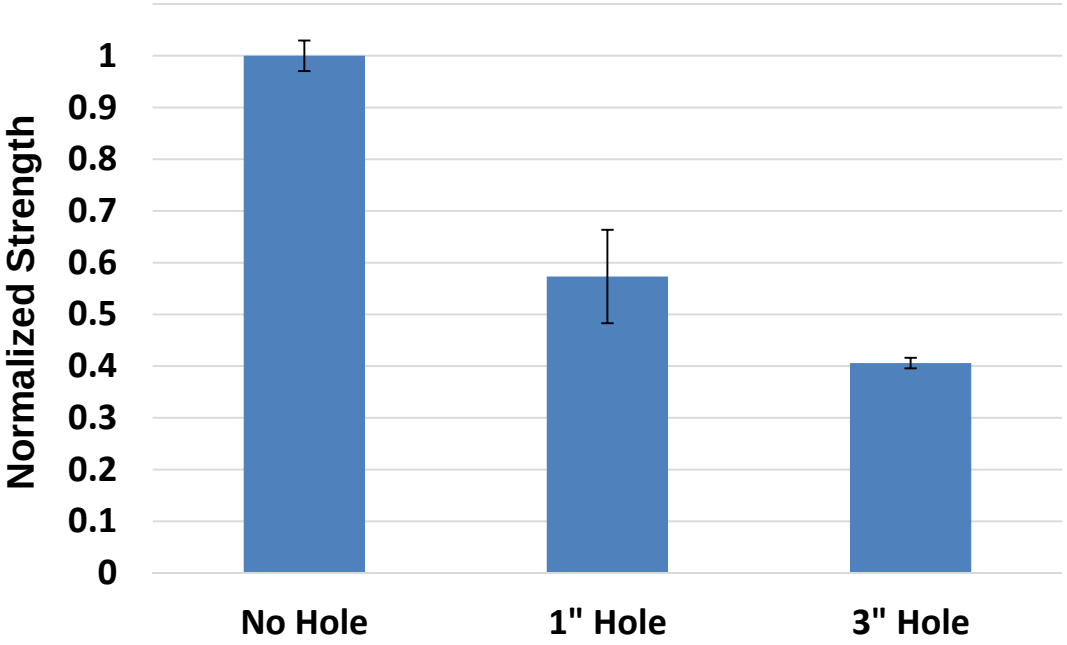
Sandwich 4-Point Flexure After Impact Development: Summary of Results

- **Initial results from thin carbon/epoxy facesheets completed**
- **Current focus: impact damaged specimens optimized with thicker cores**



Failure of specimen with 1 in. hole

Failure of specimen with 3 in. hole

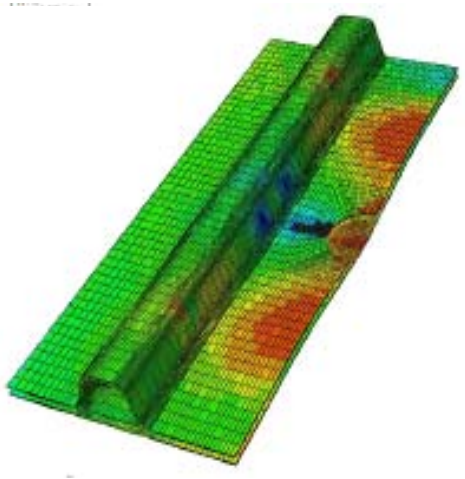
Sandwich Damage Tolerance Test Method Development: Current Focus

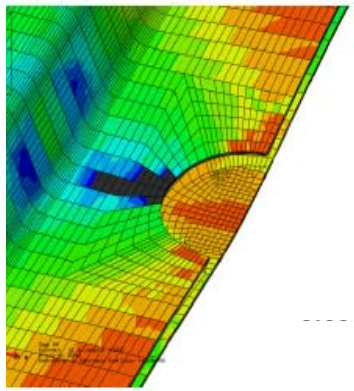
- **Complete testing with actual impact damage**
  - **Impact procedure defined in ASTM D7766**
  - **Strain distributions via Digital Image Correlation**
  - **Numerical modeling: prediction of residual strength**
- **Incorporate input provided by ASTM Committee D30**
  - **Harmonize with ASTM D7766 for Damage Resistance of Sandwich Composites**
  - **Determine/specify default sandwich specimen dimensions**
  - **Provide guidance for selecting alternate specimen dimensions**
    - **Thickness of sandwich configuration**
    - **Specimen dimensions**
- **Develop draft standard test methods**

Future Work:

Scale-Up of Sandwich Damage Tolerance Test Results

- **Air Force SBIR Phase II program**
- **Collaborative research with Materials Sciences Corp.**
- **Univ. of Utah focus on sandwich damage tolerance**





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Outline

- ***Summary*: Damage Tolerance Test Method Development for Sandwich Composites**
  - **Sandwich Compression After Impact Test**
  - **Sandwich 4-Point Flexure After Impact Test**

➡ **Notch Sensitivity of Sandwich Composites**

  - **Investigation of Candidate Test Methods**
  - **Initial Testing and Analysis**

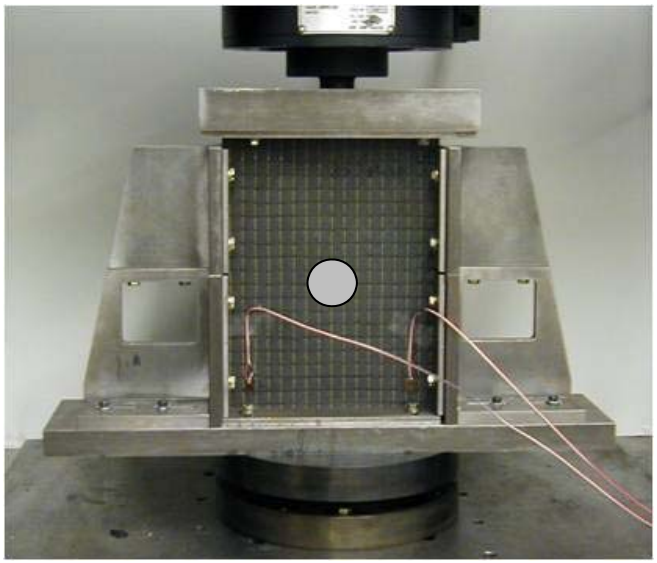
Background:
Notch Sensitivity of Sandwich Composites

- **In-plane 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
- **Less attention to notch sensitivity test 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

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

Candidate Test Configurations:
Notch Sensitivity of Sandwich Composites



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Edgewise Compression

- In-plane compression
- Circular hole
- Most popular test found in literature

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Four-Point Flexure

- Out-of-plane bending
- Circular hole
- Constant bending moment and zero shear in damaged section of panel

Wichita State University

In-Plane Tension

- Circular hole most common
- Complicated fixturing

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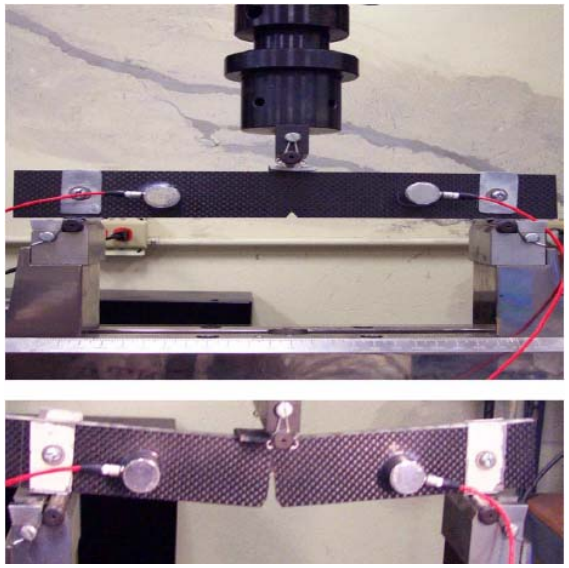
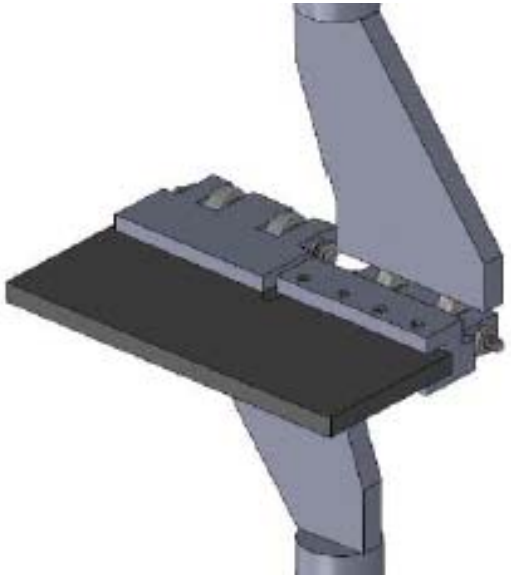
Candidate Test Configurations (Con'd):
Notch Sensitivity of Sandwich Composites



University of Puerto Rico

Flexure Edge Notch

- In-plane bending
- U or V shaped edge notch
- Four-point loading could increase applicability to more notch configurations



Oregon State University

Out-Of-Plane Shear

- Mode III type loading
- Edge notch
- Currently in development at OSU for monolithic composites

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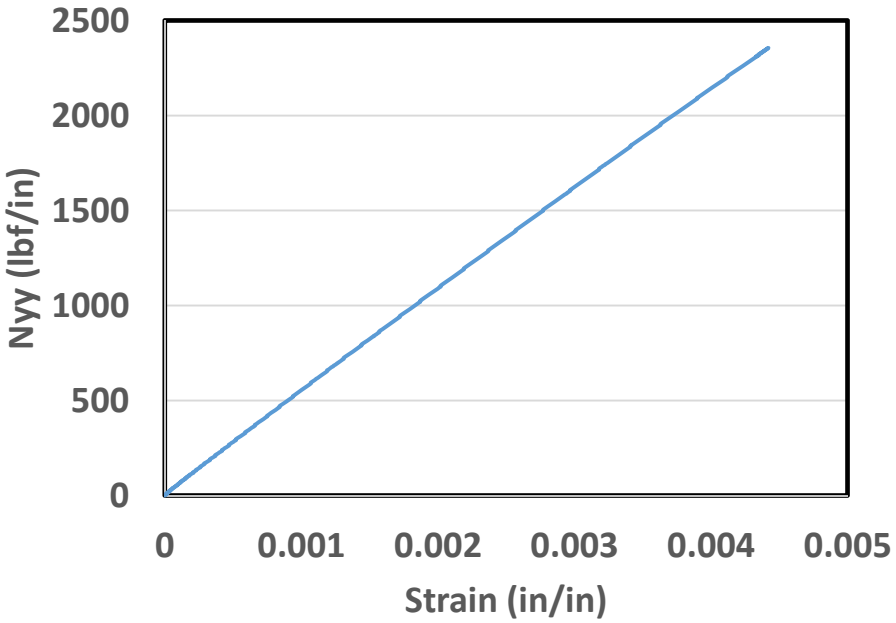
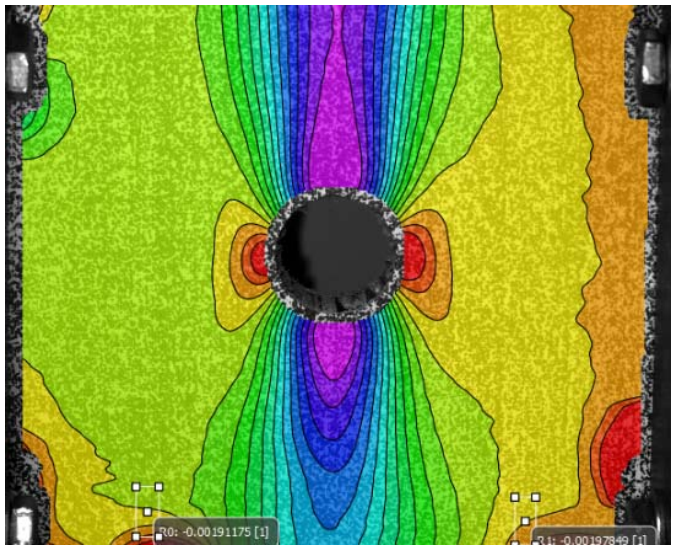
Initial Evaluation:
Edgewise Compression Notch Sensitivity

- Carbon/epoxy facesheets, 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

32% strength reduction relative to unnotched specimen

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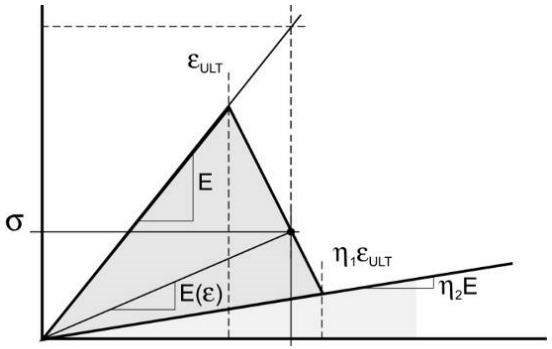
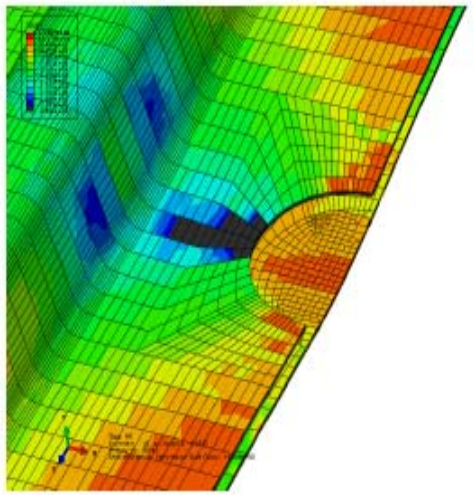
Failure Analysis of Notched Sandwich Specimens

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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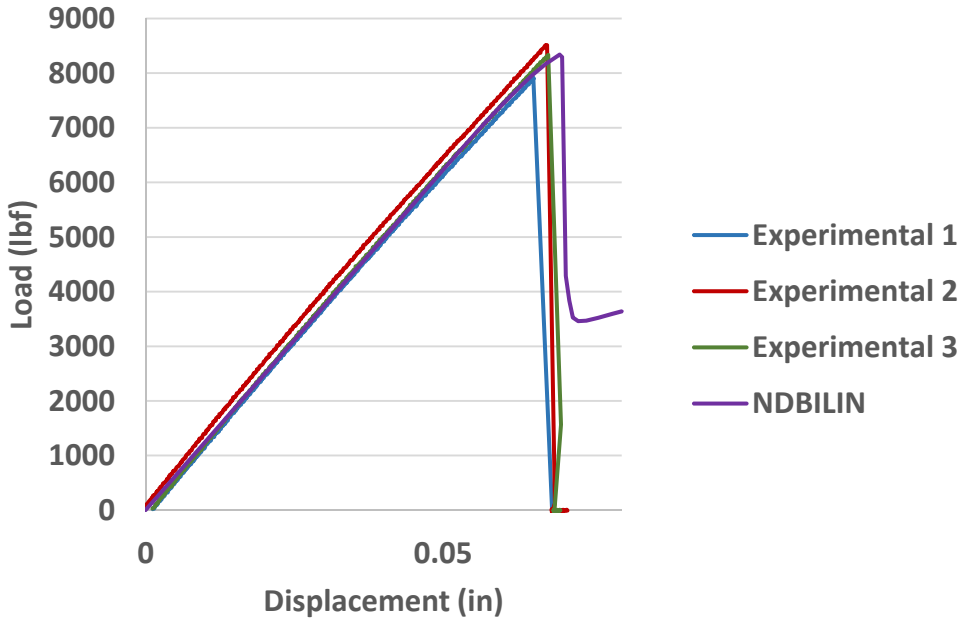
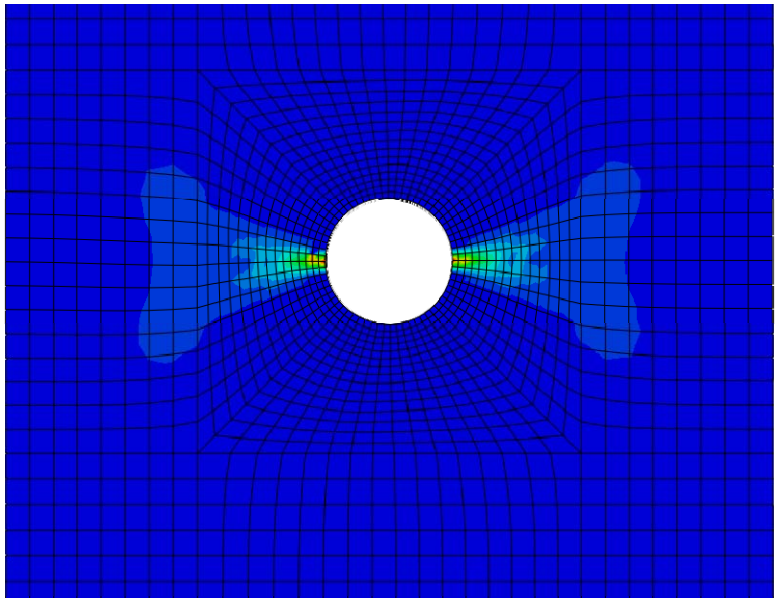
Failure Analysis of Notched Sandwich Specimens

Initial Verification of NDBILIN

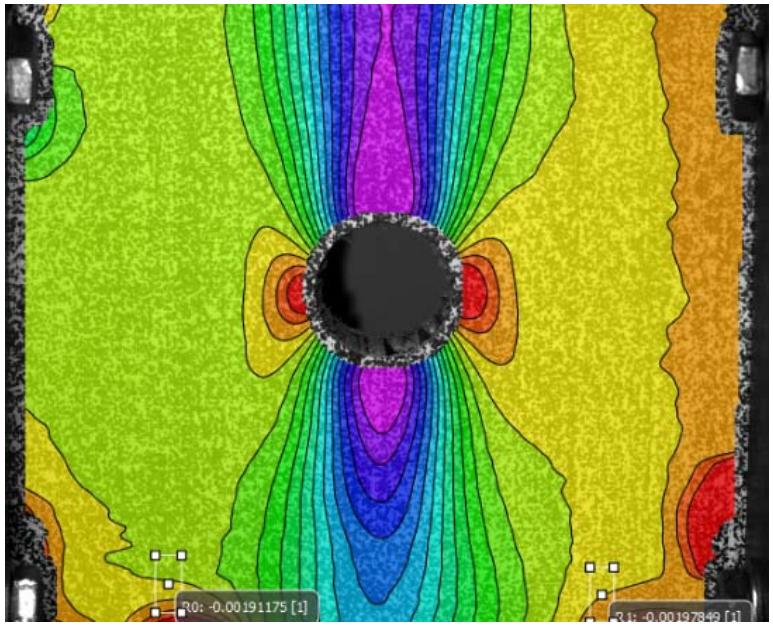
- **Simulation of open hole tension test of IM7/8552 carbon/epoxy composite laminate**
- **Comparison with experimental results**
- **Accurate prediction of stiffness and failure load**



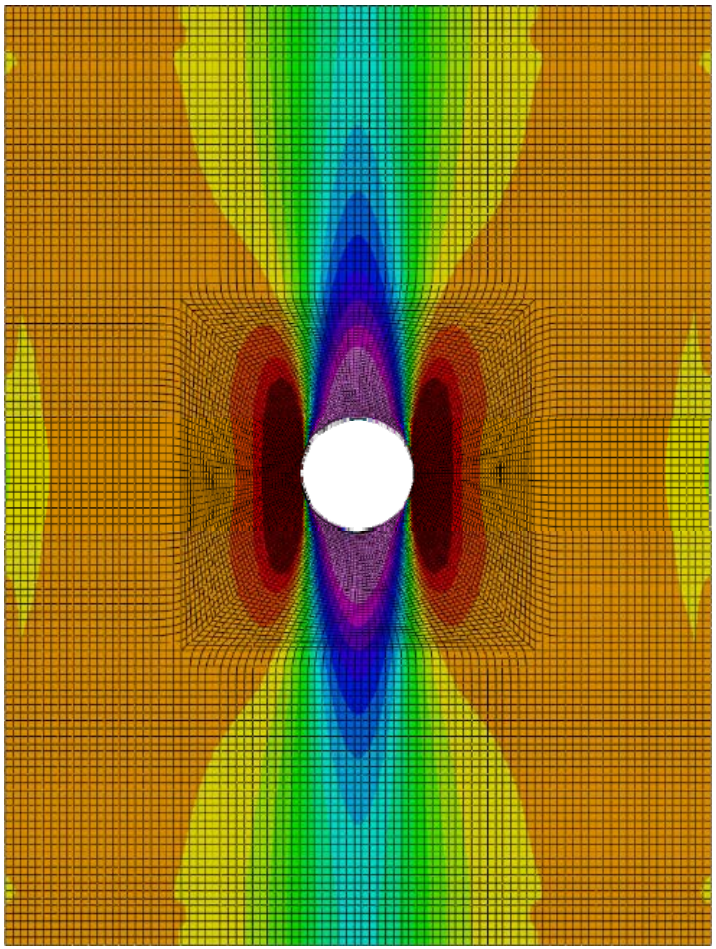


Initial Failure Analysis
Sandwich Open Hole Compression Test

Comparison of ε_y Strain Fields:
Digital Image Correlation versus ABAQUS/NDBILIN



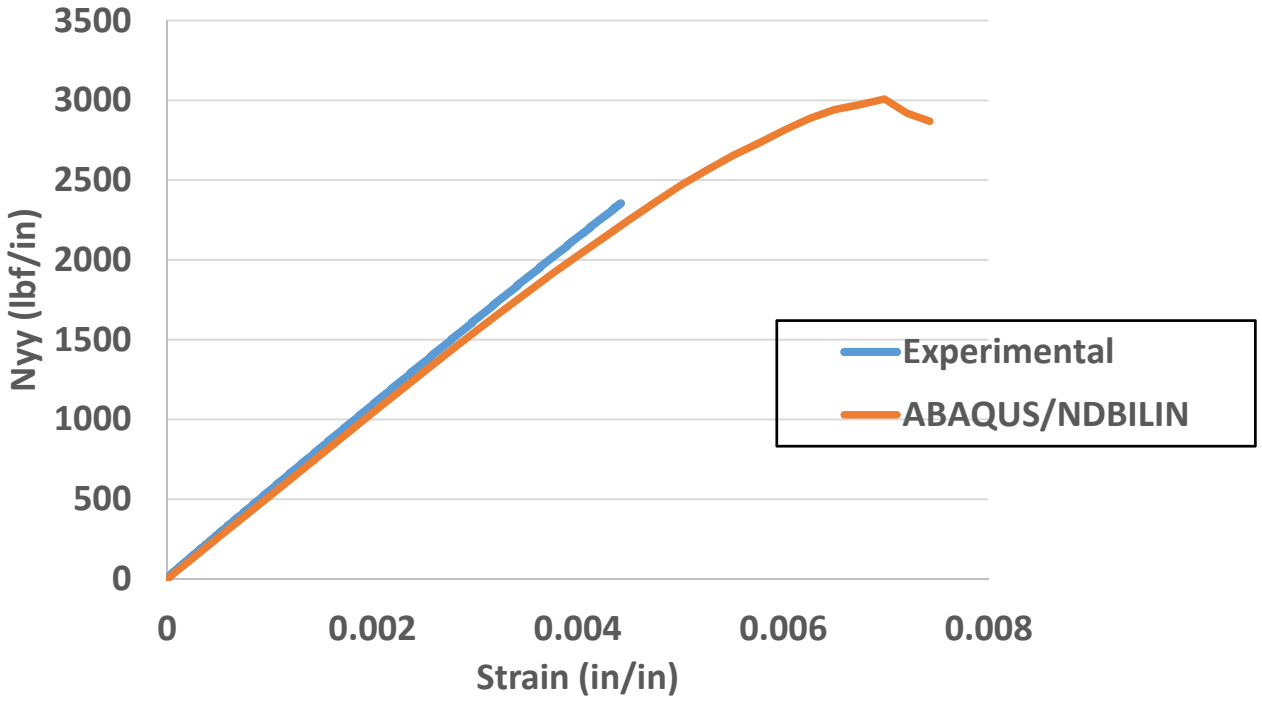
Digital Image Correlation Result



ABAQUS/NDBILIN Prediction

Initial Failure Analysis:
Sandwich Open Hole Compression Test

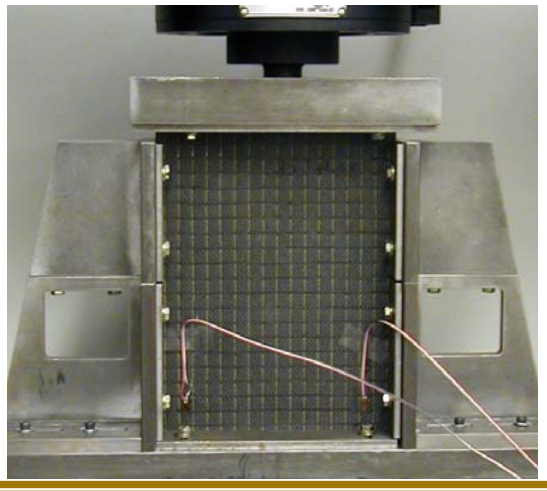
- Good agreement with measured stiffness
- Overprediction of notched compression strength
- Under further investigation

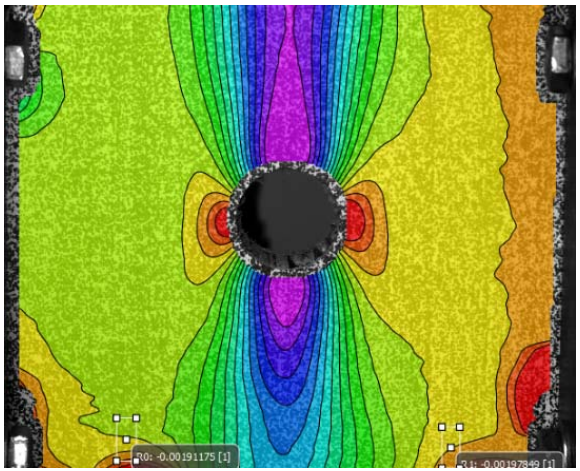


SUMMARY

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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