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JOINT ADVANCED MATERIALS & STRUCTURES
CENTER OF EXCELLENCE

Damage Tolerance and Notch Sensitivity of Composite Sandwich Structures

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Marcus Stanfield
Brad Kuramoto
Martin Raming
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JAMS 2019 Technical Review
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THE UNIVERSITY OF UTAH

FAA Sponsored Project Information

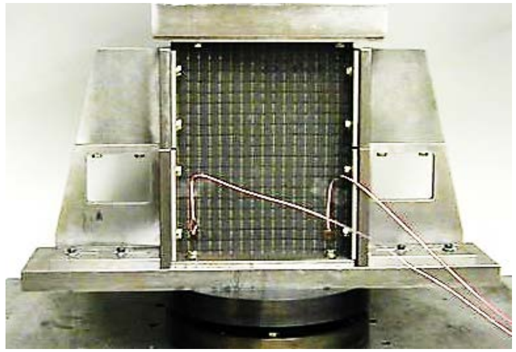
- **Principal Investigators:**
  - Dr. Dan Adams
  - Dr. Mike Czabaj
- **Graduate Student Researchers:**
  - Martin Raming
  - Brad Kuramoto
  - Marcus Stanfield
- **Primary Collaborators:**
  - Boeing (Charles Park), Hexcel (Lance Smith)
  - Materials Sciences Corporation
  - ASTM D30 (Composites)

Project Overview:
Primary Research Emphases

Sandwich Fracture Mechanics

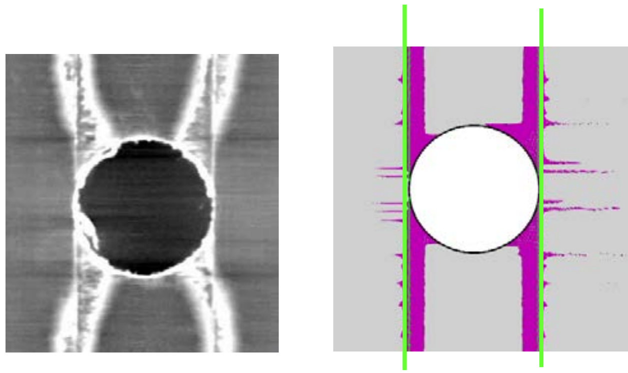
- Development of standardized test methods for facesheet/core disbond growth
- Building block approach for assessment of disbond growth in sandwich structures

Sandwich Damage Tolerance



- Assessment of predictive capabilities for damage formation and growth
- Development of standardized test methods for damage tolerance

Sandwich Notch Sensitivity

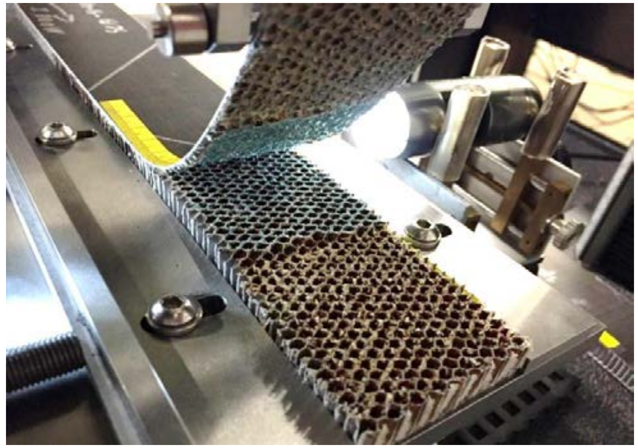


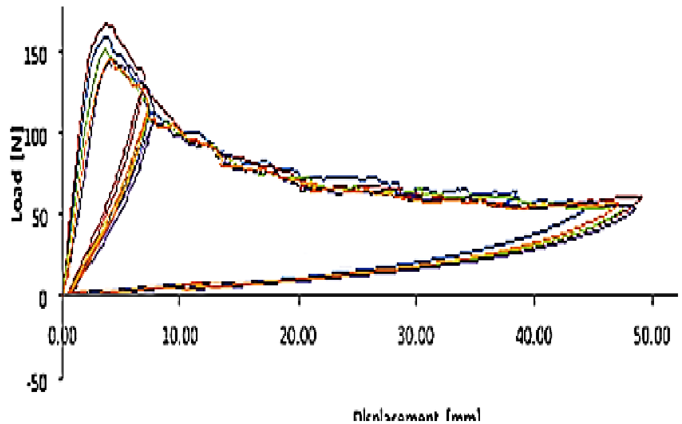
- Assessment of predictive capabilities for sandwich composite notch sensitivity
- Development of standardized test methods for notch sensitivity

Status Update: Mode I Sandwich Fracture Mechanics Test Method

Standardization of Single Cantilever Beam (SCB) Test

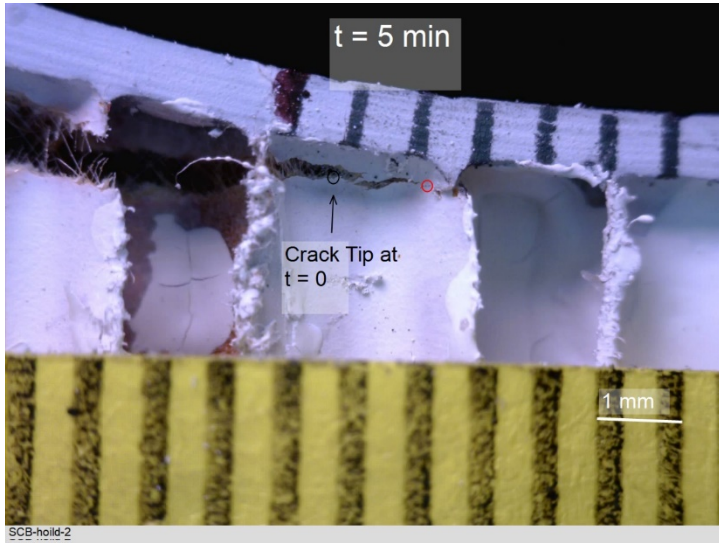
- **Completed three rounds of ASTM balloting; fourth upcoming**
- **Recent changes:**
  - **Mode mixity: “Mode I dominant”**
  - **Acceptable disbond location: within top one-fourth of core**
- **Discussion of remaining issues:**
  - **Procedure for disbond initiation toughness**
  - **Accelerated loading rate to produce acceptable disbond growth rate and test time**

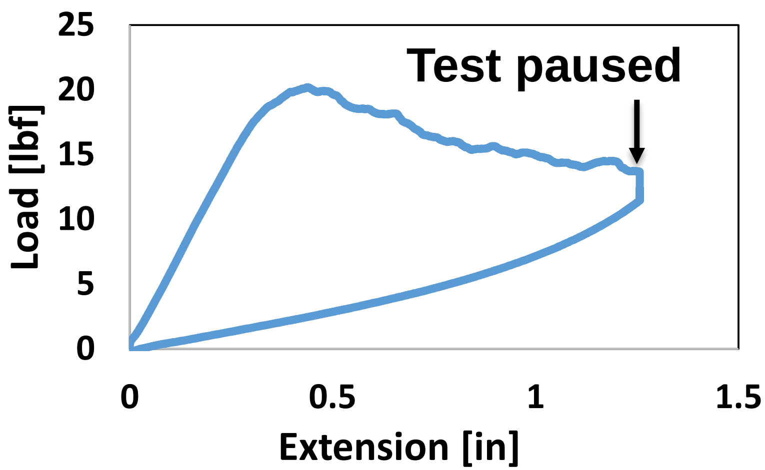




Current SCB Discussion Item:
Pausing Test for Crack Tip Measurement

- Current procedure leads to long test times
  - 5-30 minutes without initiation toughness measurements
  - 10-60 minutes with initiation toughness measurements
- Accelerated loading rate requires pausing for crack length measurement
- Minimal crack growth observed while paused under load
- Modified procedure under review by Sandwich Disbond Task Group

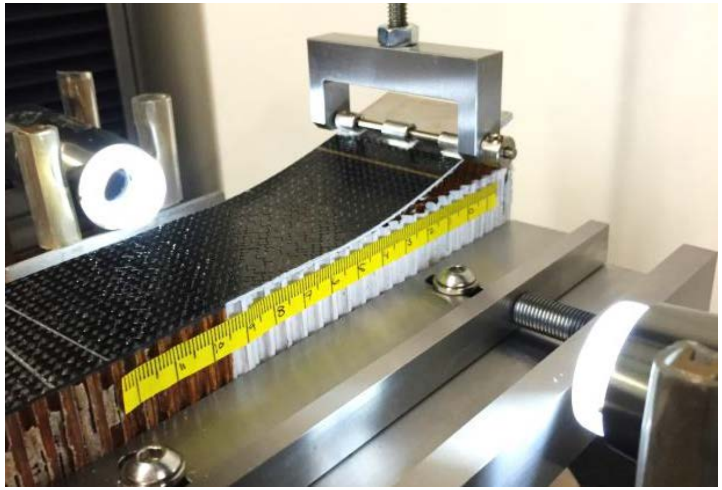




Recent Focus:

Single Cantilever Beam (SCB) Fatigue Test

- **Follow-on *Standard Practice* to existing SCB test**
- **Several previous individual efforts within CMH-17 Sandwich Disbond Task Group**
- **Draft test procedure identified for upcoming round robin testing**



- **Sandwich specimens to be fabricated at University of Utah and distributed to round robin participants**
  - **IM7/8552 woven fabric prepreg facesheets**
  - **Nomex honeycomb core**
  - **Metlbond 1515-4 film adhesive**

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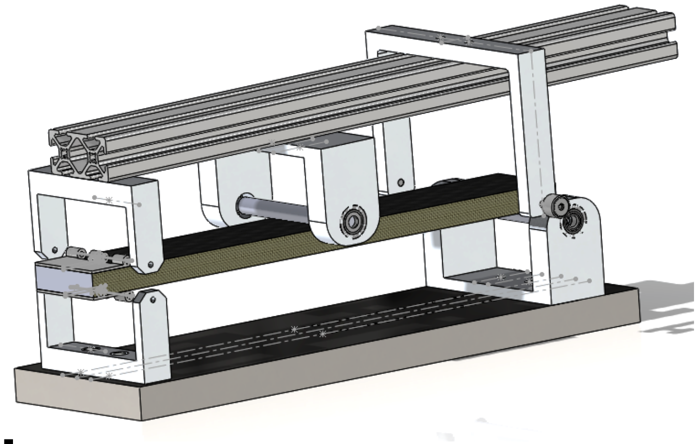
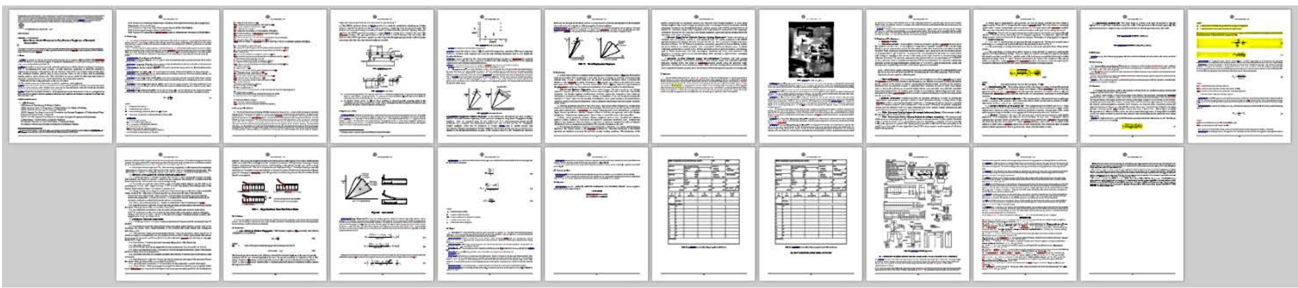
Recent Focus:
Sandwich Mixed Mode Bend (MMB) Test

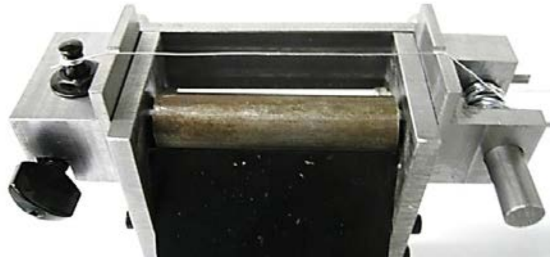
- **Enlarged/simplified version of test fixture used for composite laminates (ASTM D6671)**
- **High percentage Mode II possible (up to ~80%)**
- **Round-robin testing exercise planned**
- **Draft ASTM standard in progress**
- **Collaboration with DTU (C. Berggreen)**

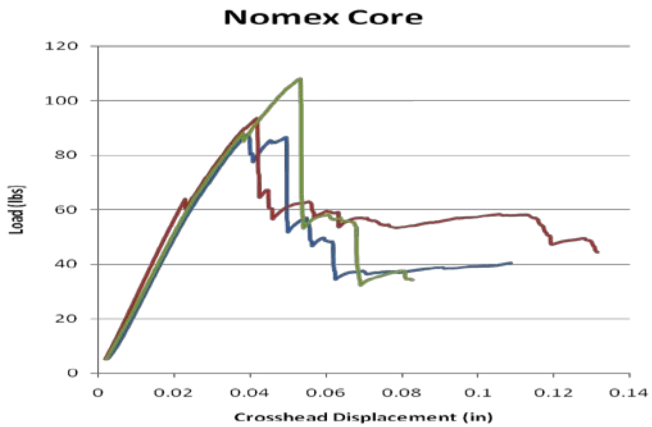




Status Update:
Mode II Separated End-Notched Flexure (S-ENF) Test

- **Modified three-point flexure test**
- **Use of tensioned wire to achieve facesheet/core separation**
- **No core removal required**
- **Adjustable wire height and span**
- **High % Mode II (>80%) for all sandwich configurations studied**
- **Cell buckling at crack tip with no crack growth for some honeycomb core configurations**
- **Under further investigation with FAU collaborators (L. Carlsson)**





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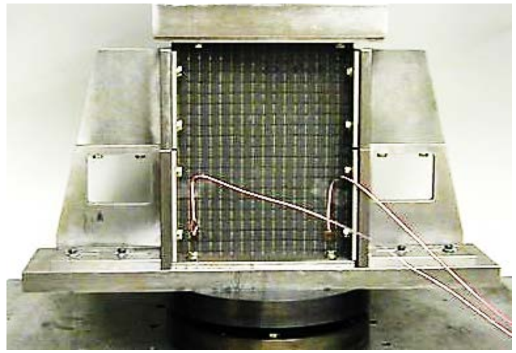
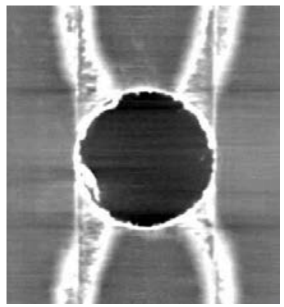
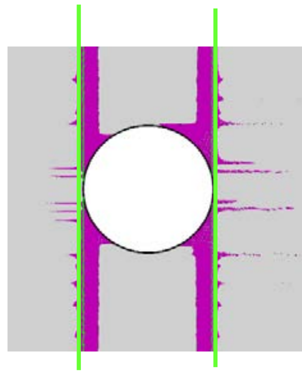
Sandwich Damage Tolerance
- Assessment of predictive capabilities for damage formation and growth
- Development of standardized test methods for damage tolerance



Sandwich Notch Sensitivity
- Assessment of predictive capabilities for sandwich composite notch sensitivity
- Development of standardized test methods for notch sensitivity





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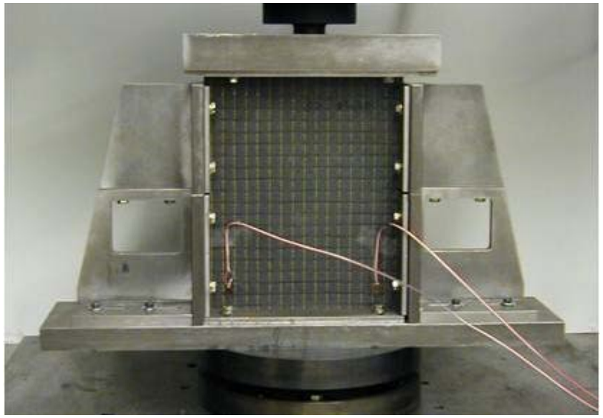
Damage Tolerance Test Methods For Sandwich Composites

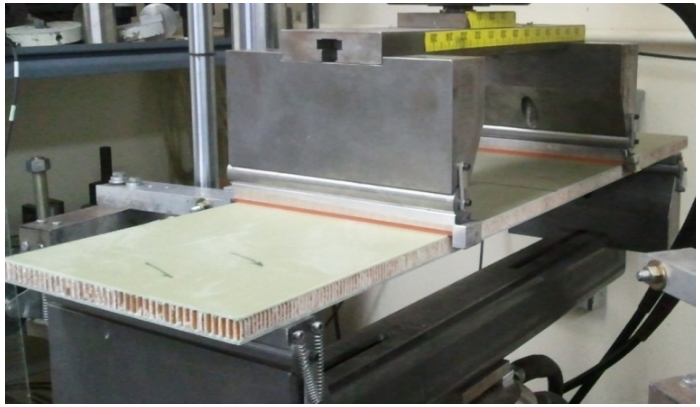
In the initial stages of ASTM standardization

Edgewise Compression After Impact



- **Preferred damage tolerance test method for laminates**
- **High interest level for sandwich composites**
- **Second ASTM balloting in Summer 2019**

Four-Point Flexure After Impact

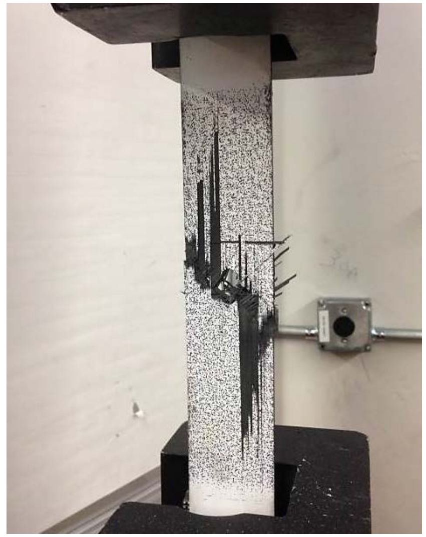


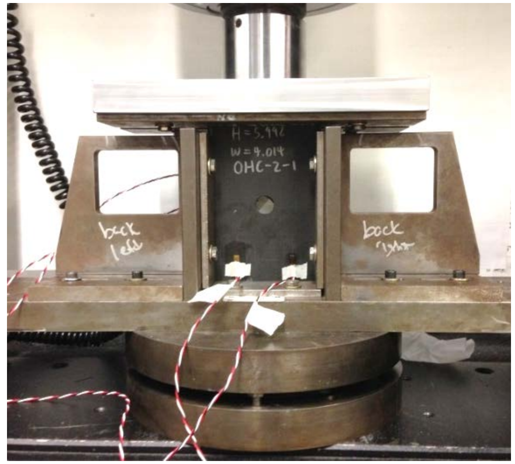
- **Constant bending moment and zero shear in damaged section**
- **Damaged facesheet can be loaded in compression or tension**
- **Initial ASTM ballot submission in Summer 2019**

Damage Progression in Sandwich Composites:

Testing to Evaluate of Predictive Capabilities

- **Damage progression in facesheets**
  - Interlaminar delamination (Mode I and II)
  - Laminate tension (±45 layup)
  - Open-hole tension
  - Open-hole compression
- **Damage progression in core**
  - Flatwise compression
  - Flatwise shear
- **Damage progression in sandwich composites**
  - Sandwich interface disbond (Mode I and II)
  - Sandwich open-hole shear
  - Sandwich open-hole flexure
  - Sandwich open-hole compression





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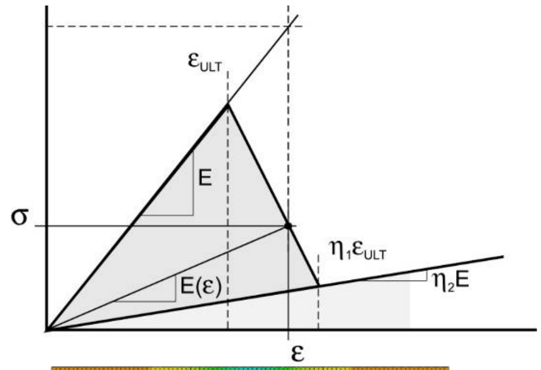
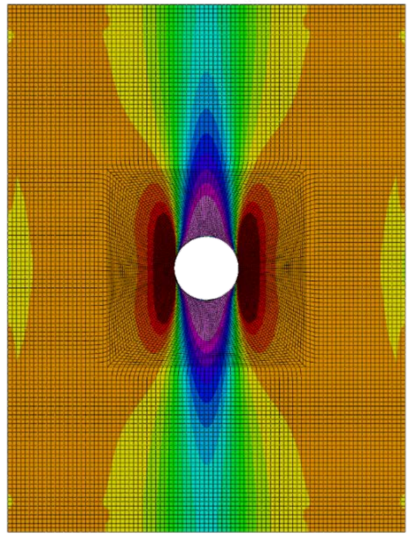
Progressive Damage Analysis of Sandwich Composites
ABAQUS with NDBILIN

- User-defined nonlinear material model (UMAT) for ABAQUS
- Developed by Materials Sciences Corp.
- Stiffness degradation based progressive damage model
  - Bilinear stiffness response used to model material damaged state
  - “Built in” laminated plate theory for elements
  - Lamina level stiffness degradation
  - Max. stress, max. strain or Hashin failure criteria for damage onset





Materials Sciences Corporation

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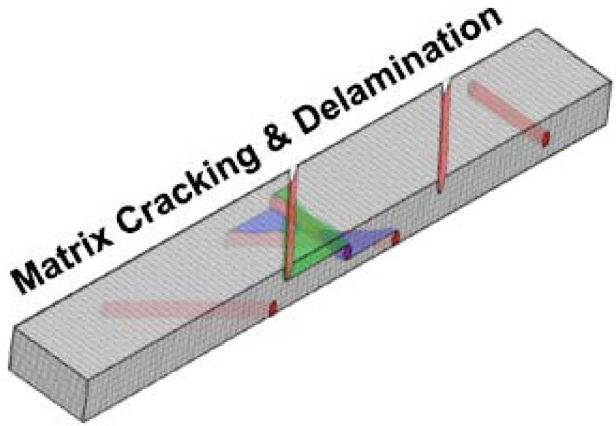
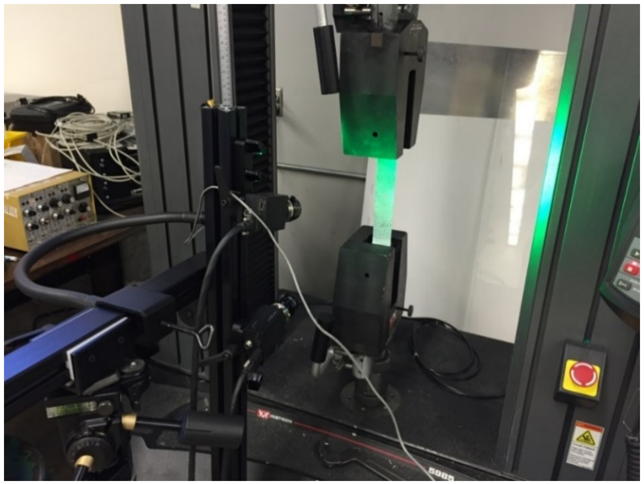
Progressive Damage Analysis of Sandwich Composites
B-Spline Method (BSAM):

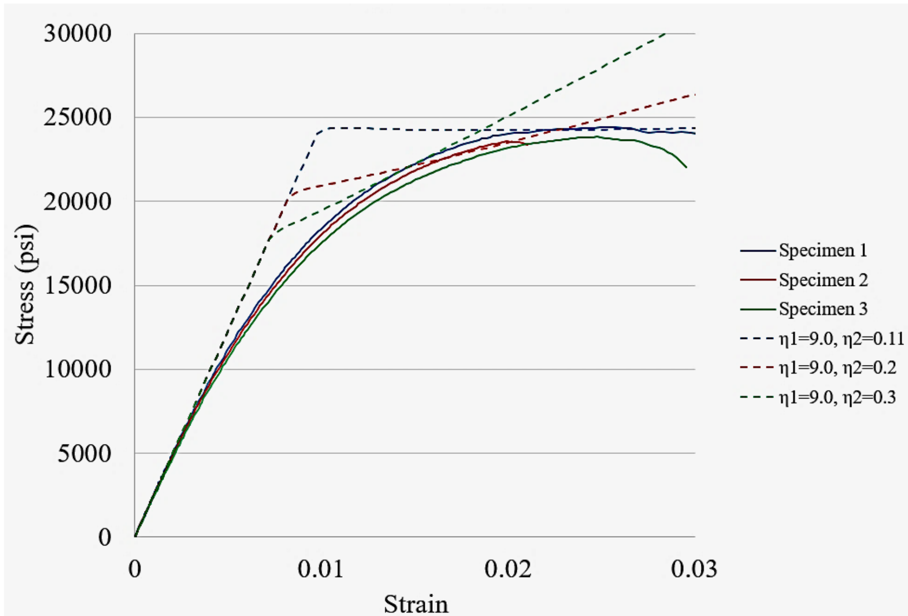
- **Stand-alone software**
- **Developed by AFRL, UDRI, UTA**
- **Discrete damage modeled using Regularized Extended Finite Element Method (Rx-FEM)**
  - **Matrix Cracking**
    - **Multiple failure criteria for damage onset**
    - **Damage propagation using cohesive zone method**
  - **Delamination using cohesive zone method**
  - **Fiber failure using Critical Failure Volume or CDM**



Damage Progression in Facesheets:
Analysis of ±45 Laminates in Tension

- **Simulation of unnotched and open-hole tension testing**
- **IM7/8552 carbon/epoxy, $[45/-45]_{2S}$ laminates**
- **Matrix shear modulus, strength and damage parameters calibrated using measured stress-strain behavior**
  - **NDBILIN: bilinear response**
  - **BSAM: non-linear response**





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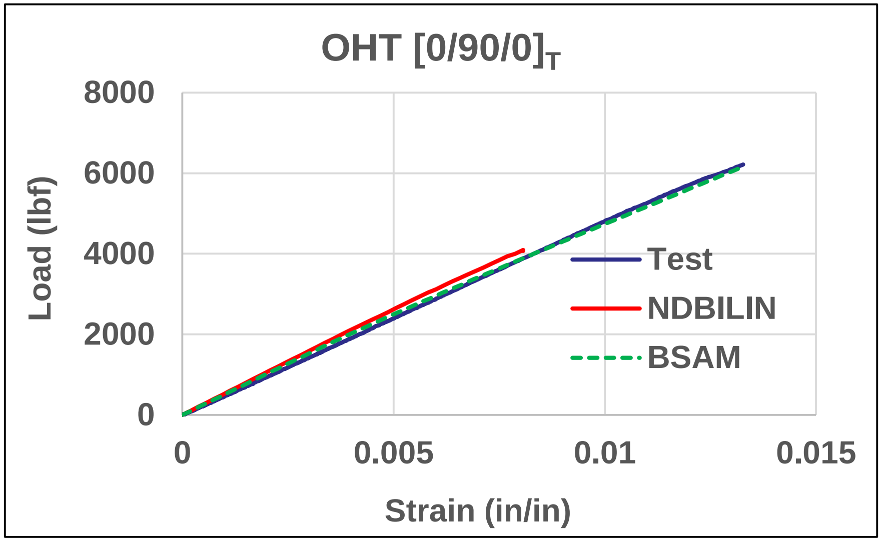
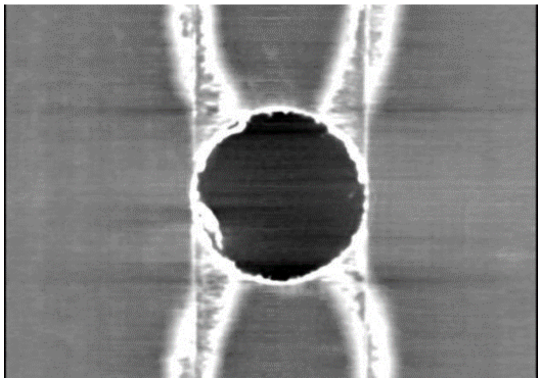
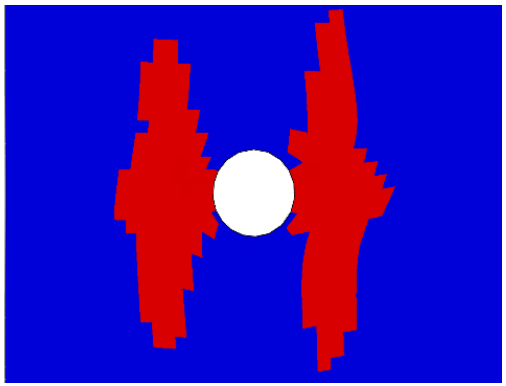
Damage Progression in Facesheets:
0/90 Cross-ply Open-Hole Tension

- **$[0/90/0]_T$ laminate representing sandwich facesheet**
- **NDBILIN predicts notch sensitivity**
- **BSAM predicts notch insensitive (Less than 4% error)**
- **BSAM requires fine mesh for a converged solution**

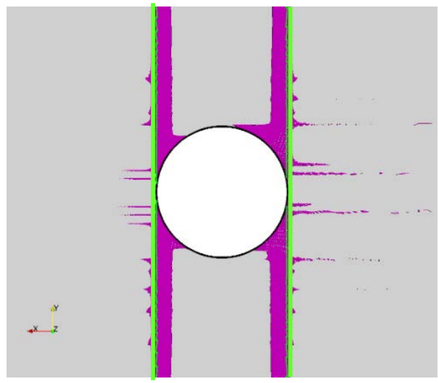




X-Ray CT



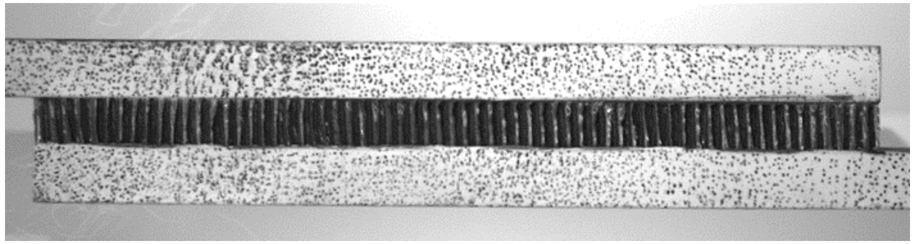
NDBILIN



BSAM

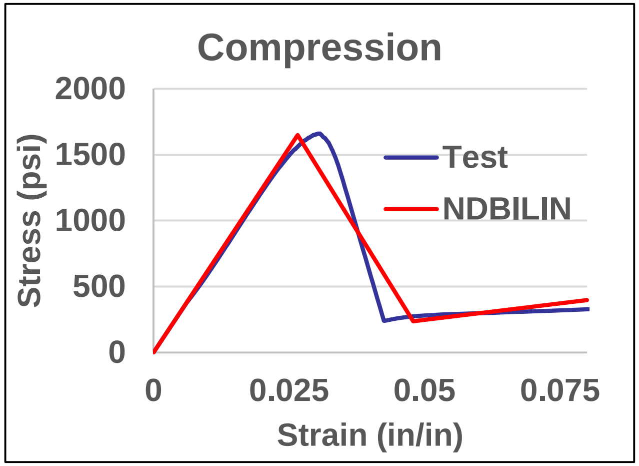
Damage Progression in Core:
Flatwise Compression/Shear

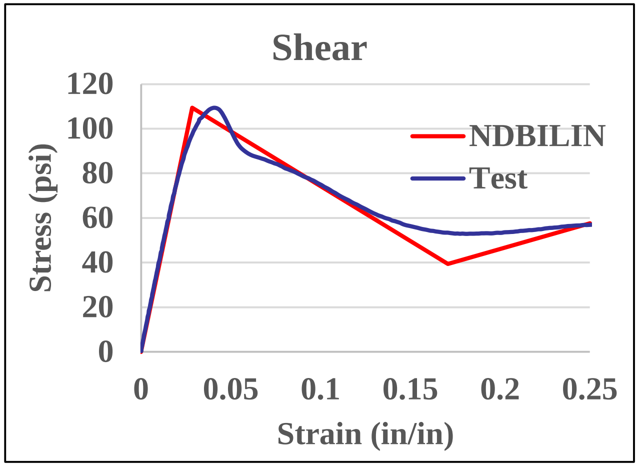
- **Honeycomb core loaded until core collapse in both compression and shear**
- **NDBILIN parameters fit to stress vs strain curves**
- **Used to predict open-hole shear test results**



Flatwise Shear Test

Compression Test





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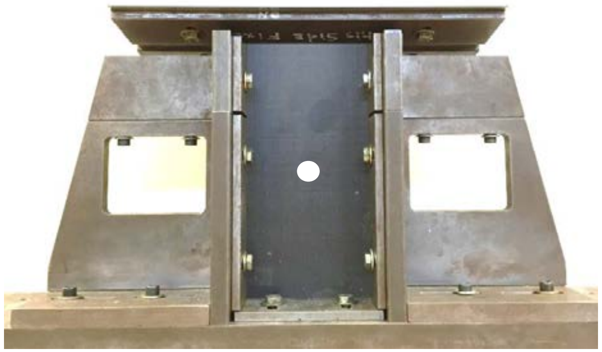
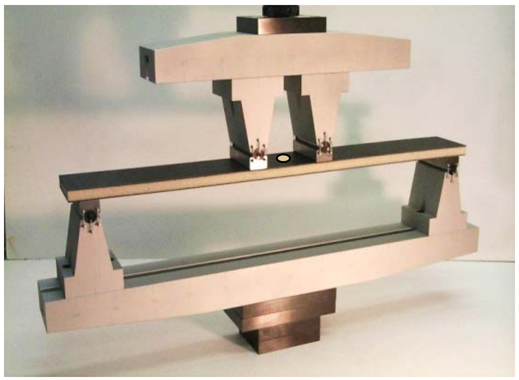
Test Method Development:
Notch Sensitivity of Sandwich Composites

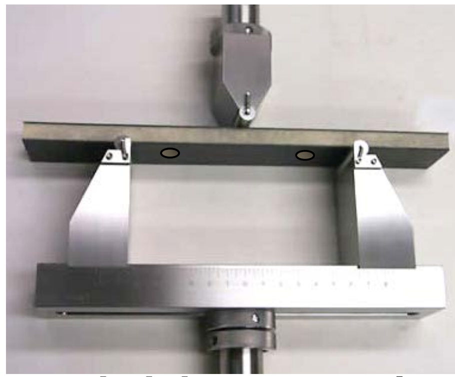
- **Open Hole Compression and Open Hole Flexure test method development for ASTM standardization (Draft standards in progress)**
- **Used for assessment of progressive damage analysis methods**
- **Open Hole Shear test designed to focus on progressive core damage during three-point flexure loading**



Sandwich Open Hole Compression



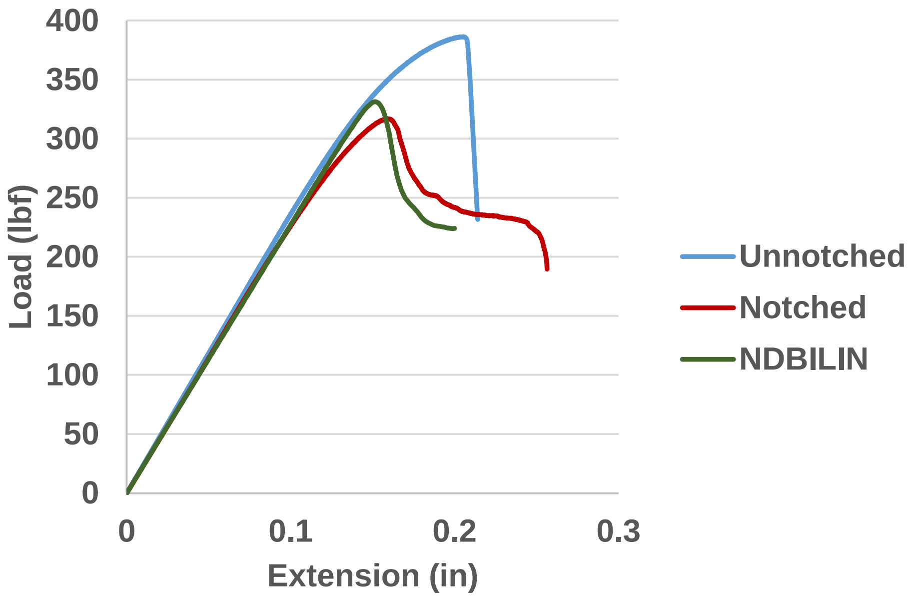
Sandwich Open Hole Flexure



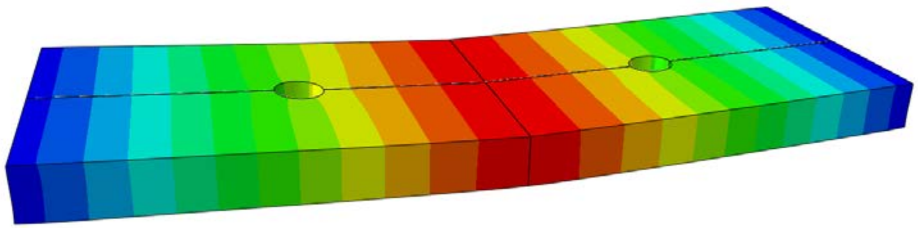
Sandwich Open Hole Shear

Damage Progression in Sandwich Composites:
Analysis of Open Hole Shear Tests

- **Unnotched and notched four-point flexure testing**
- **Core modeled with NDBILIN**
- **Slight over prediction of max load in open hole shear test**



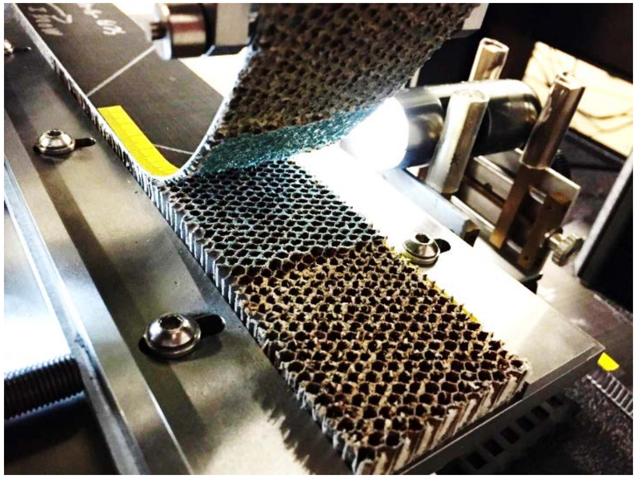
Sandwich Open-Hole Shear Failure



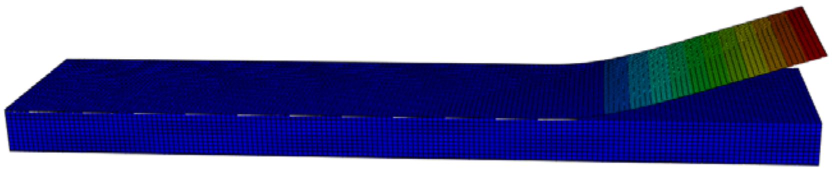
Model Deformation

Damage Progression in Sandwich Composites:
Analysis of Facesheet/Core Disbond

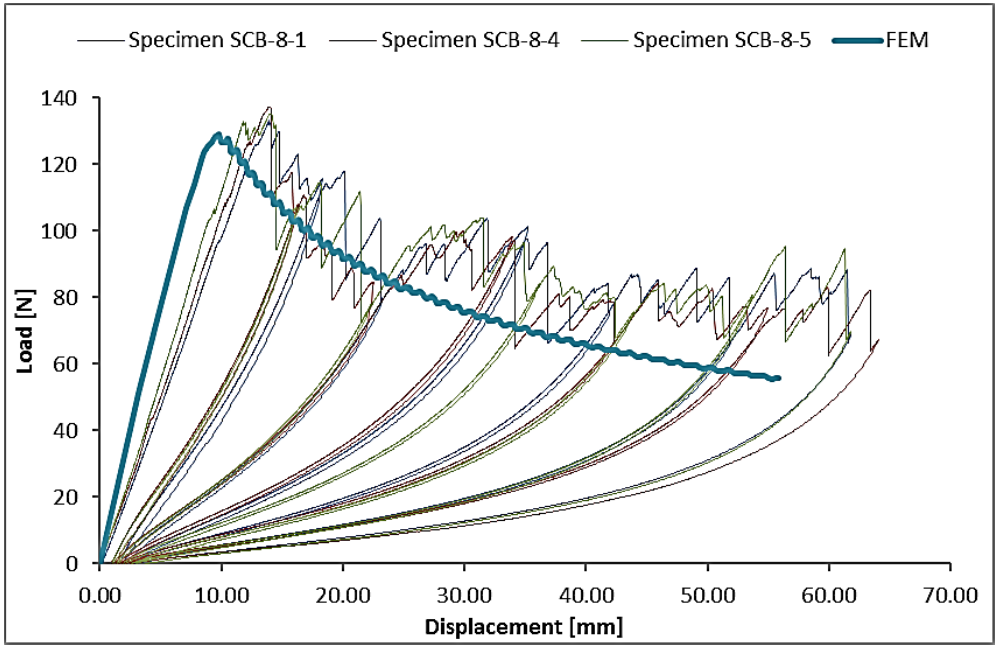
- **Calibration of interfacial cohesive zone**
  - **Mode I Sandwich SCB**



Single Cantilever Beam Test



SCB Model Displacements



Load vs Displacement Data

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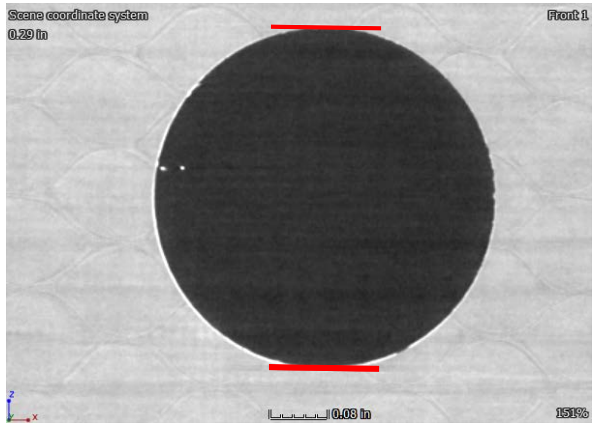
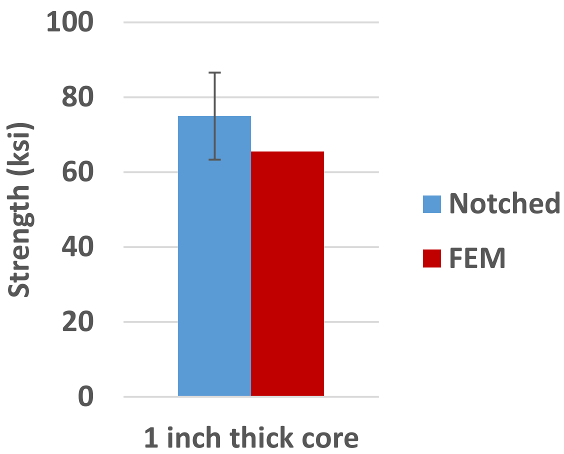
Damage Progression in Sandwich Composites:
Analysis of Open-Hole Flexure Test

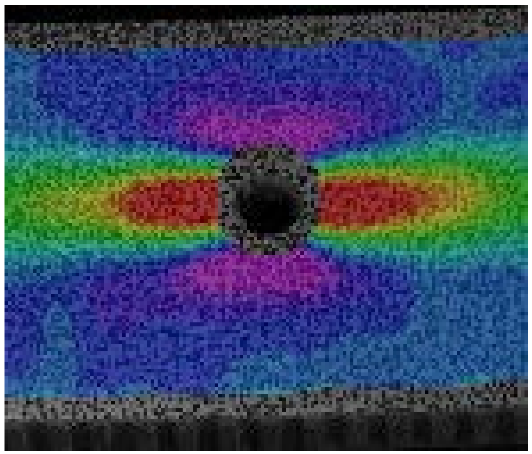
- **90% load X-ray CT shows minimal damage progression**
- **NDBILIN overpredicting damage and under predicting failure load**



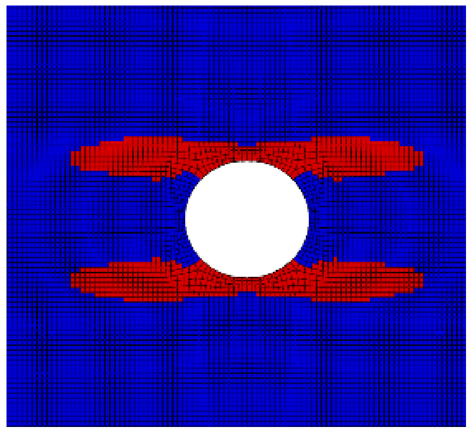
X-Ray CT
(Courtesy of Southwest Research Institute)



Compression Strength Comparison



DIC Strain



NDBILIN Damage Prediction

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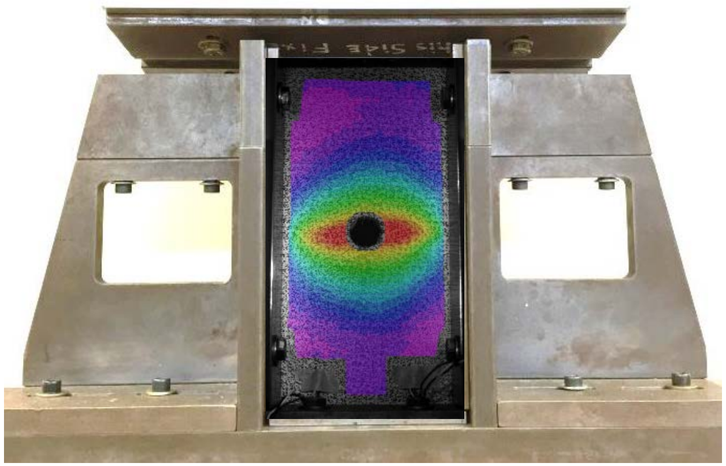
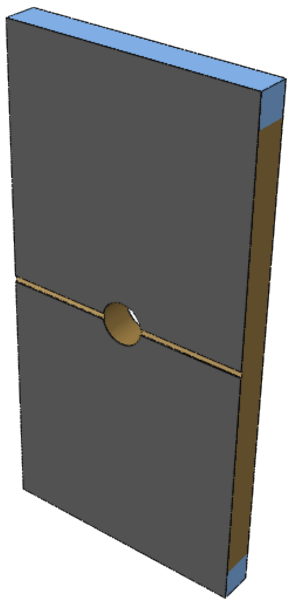
Damage Progression in Sandwich Composites:
Analysis of Open-Hole Compression

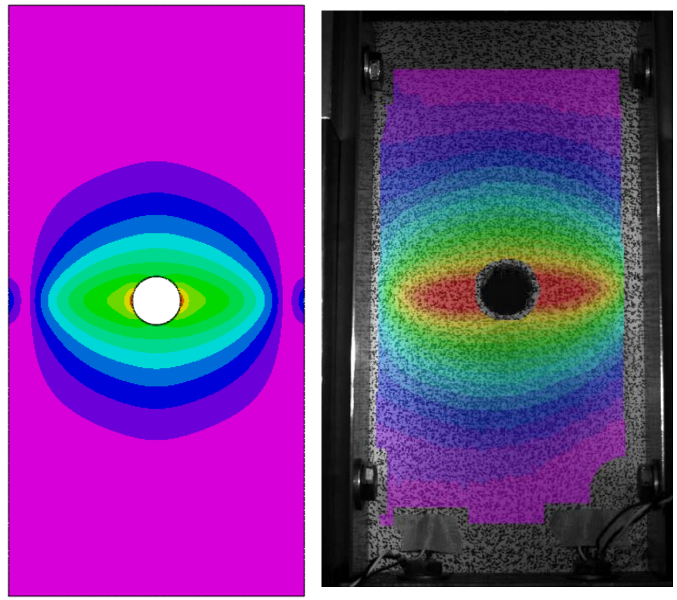
- **Out-of-plane displacements observed in DIC measurements**
- **First mode facesheet buckling observed**
- **Global buckling due to failure on non-DIC facesheet**
- **Deformation caused by post failure eccentric loading**



Measured out-of-plane deformation



Idealized Failure



Out-of-plane deformations

FEM **DIC**

BENEFITS TO AVIATION

- Standardized test methods to assess facesheet/core disbond growth in sandwich composites
- Evaluation of current numerical capabilities for predicting notch sensitivity and damage tolerance of sandwich composites
- Standardized test methods to assess notch sensitivity in sandwich composites
- Standardized test methods to assess damage tolerance in sandwich composites
- Dissemination of research results through FAA technical reports and conference/journal publications

Questions?

Don’t forget to fill out the feedback form in your packet or online at www.surveymonkey.com/r/jamsfeedback

Thank you.

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