DAMAGE TOLERANCE & 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:**
  Martin Raming
  Marcus Stanfield
  Brad Kuramoto
- **FAA Technical Monitor:** Dave Stanley

Primary Collaborators:

- Boeing (Charles Park)
- Hexcel (Lance Smith)
- ASTM Committee D30 on Composites

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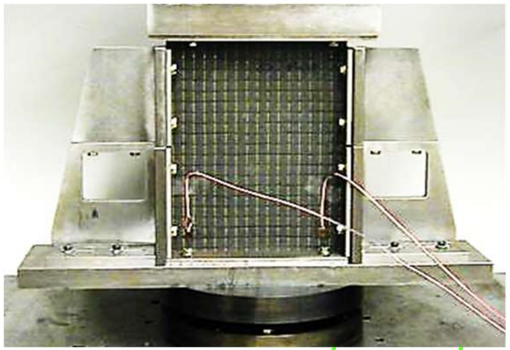
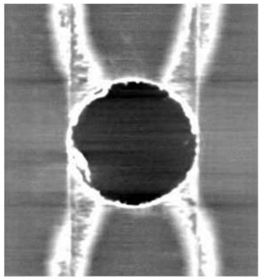
Project Overview:

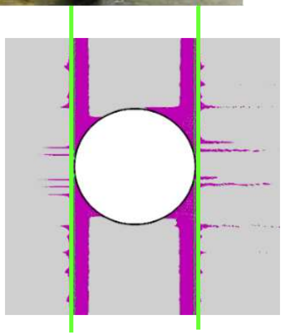
Primary Research Emphases

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





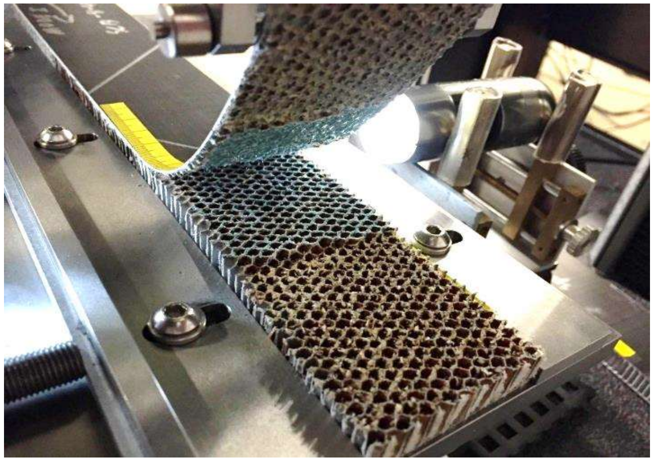
Sandwich Notch Sensitivity
- Assessment of predictive capabilities for sandwich composite notch sensitivity
- Development of standardized test methods for notch sensitivity

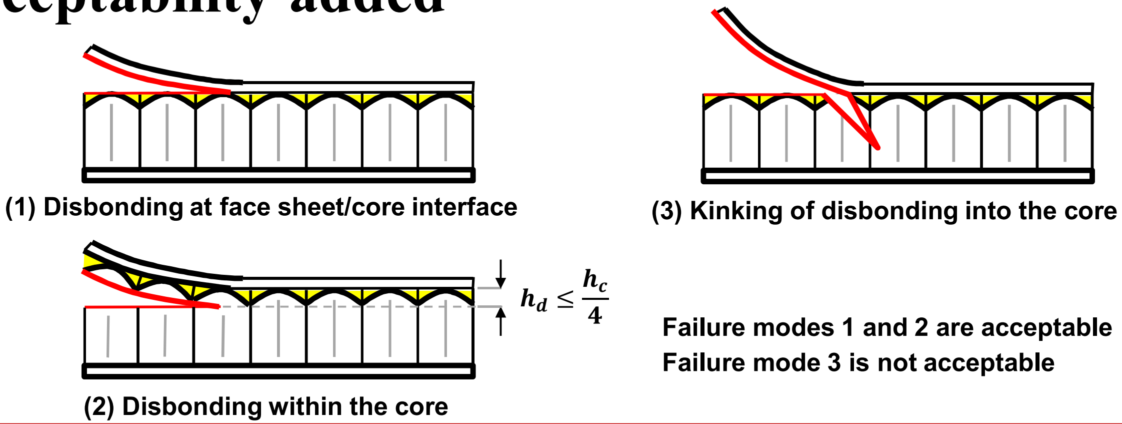
Status Update:

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 possible failure modes and their acceptability added





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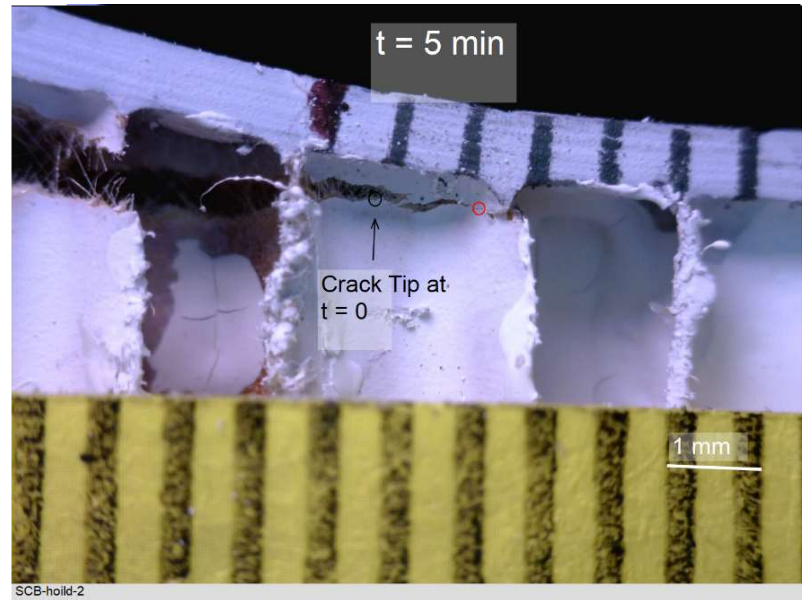
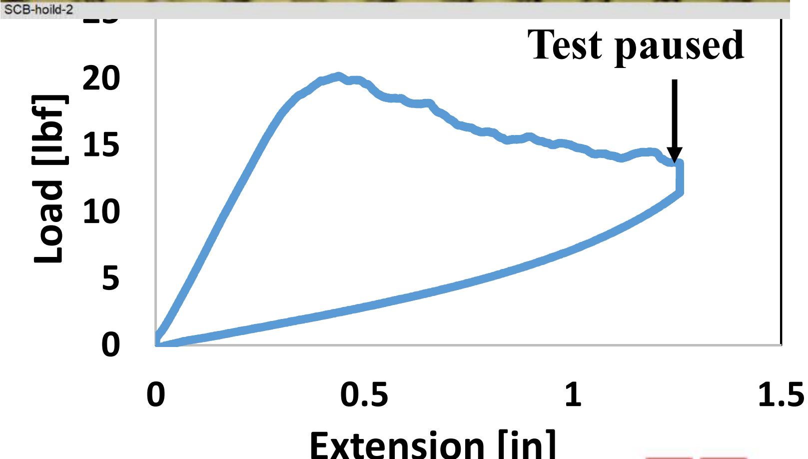
Current SCB Discussion Item:
Pausing Test for Crack Tip Measurement

- **Current procedure leads to long tests**
  - **5-30 minutes <u>without</u> initiation toughness measurements**
  - **10-60 minutes <u>with</u> initiation toughness measurements**
- **Accelerated loading rate requires pausing for crack length measurement**
- **Minimal effect on measured G_c**
- **Minimal crack growth observed while paused under load**
- **Modified procedure under review by Sandwich Disbond Task Group**





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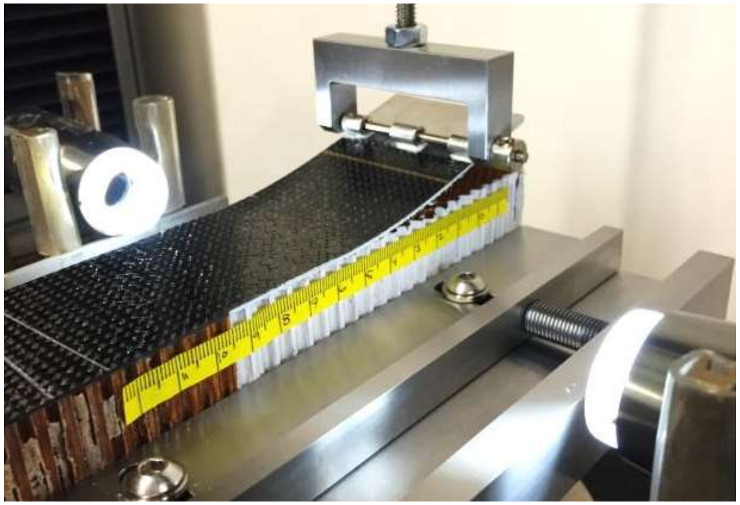
Recent Focus:
Single Cantilever Beam (SCB) Fatigue Test

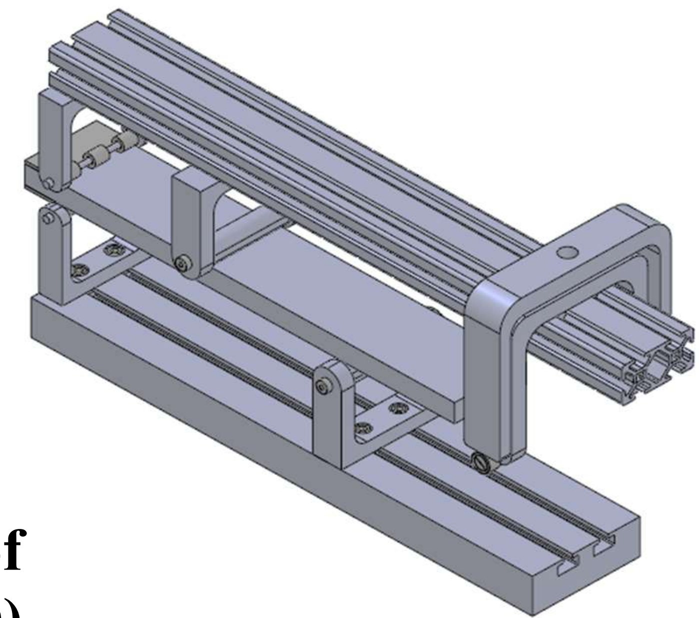
- **Follow-on *Standard Practice* to existing SCB test**
- **Several previous individual efforts within CMH-17 Sandwich Disbond Task Group**
- **Draft test procedure identified for upcoming round robin testing**

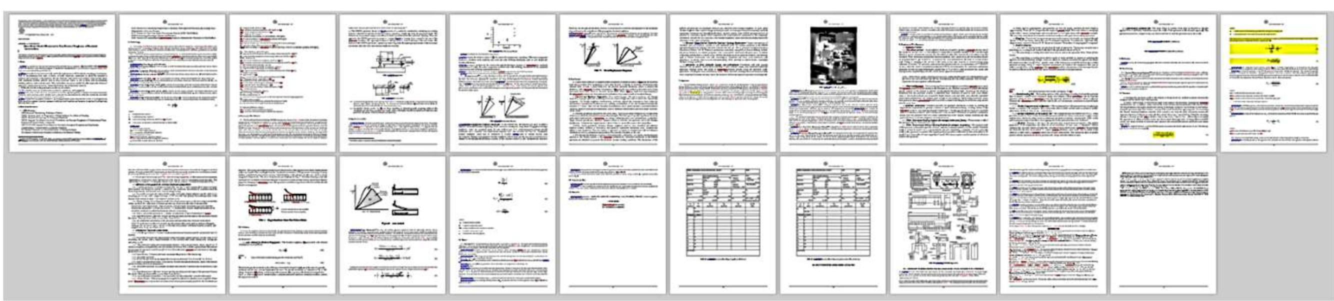


- **Sandwich specimens to be fabricated at University of Utah and distributed to round robin participants**
  - **IM7/8552 woven fabric prepreg facesheets**
  - **Nomex honeycomb core**
  - **Metlbond 1515-4 film adhesive**

Recent Focus:
Sandwich Mixed Mode Bend (MMB) Test

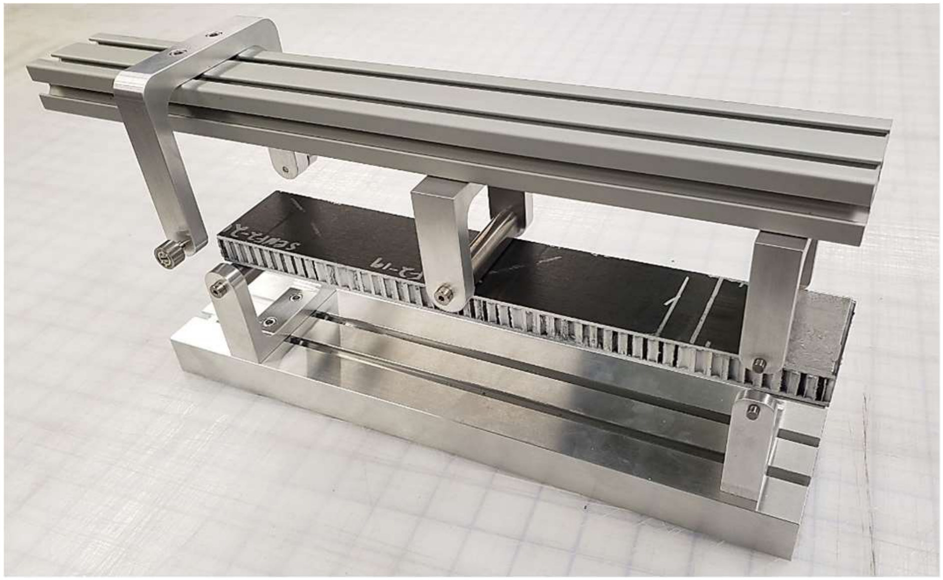
- **Enlarged/simplified version of test fixture used for composite laminates (ASTM D6671)**
- **High percentage Mode II possible (up to ~80%)**
- **Round-robin testing exercise planned**
- **Draft ASTM standard in progress**
- **Collaboration with Technical University of Denmark (DTU, Dr. Christian Berggreen))**



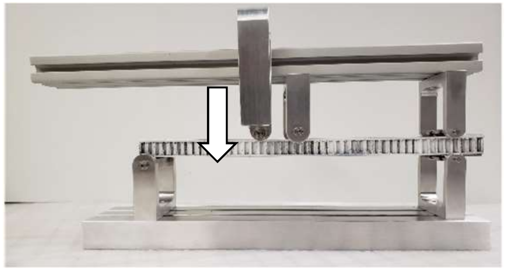


Prototype Test Fixture:
Sandwich Mixed Mode Bend Test

- **Accommodates 50 mm x 300 mm specimens used in SCB testing**
- **Adjustable loading span lengths**
- **Specimen connections at disbond using bonded hinge halves**
- **Adjustable position of loading yoke to produce desired mixed-mode loading condition**



High % Mode I

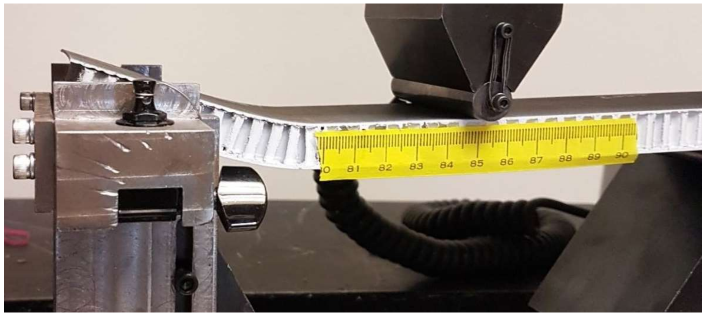


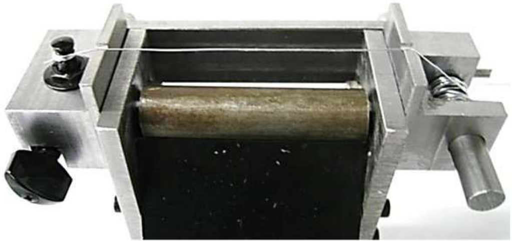
High % Mode II

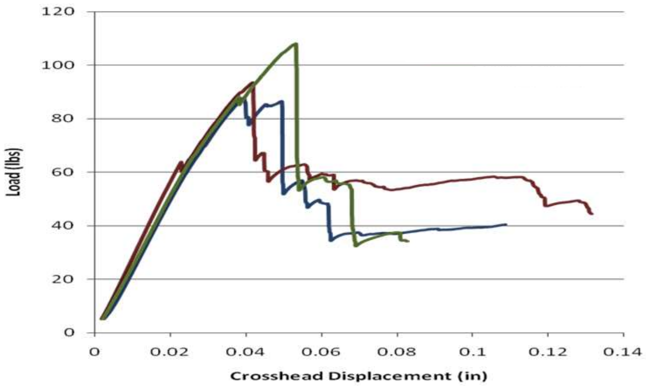
Status Update:

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 (Dr. Leif Carlsson)**



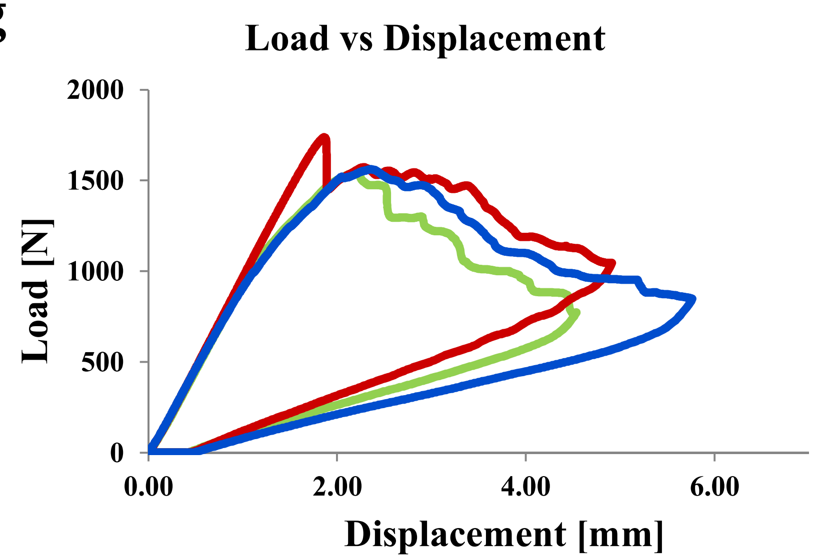


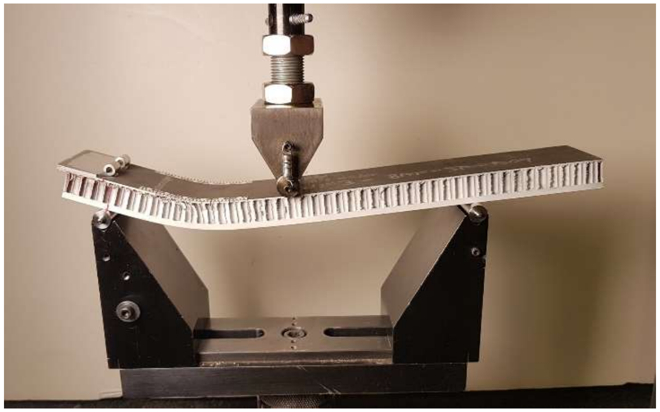


Recent Results:
Sandwich ENF Test Results

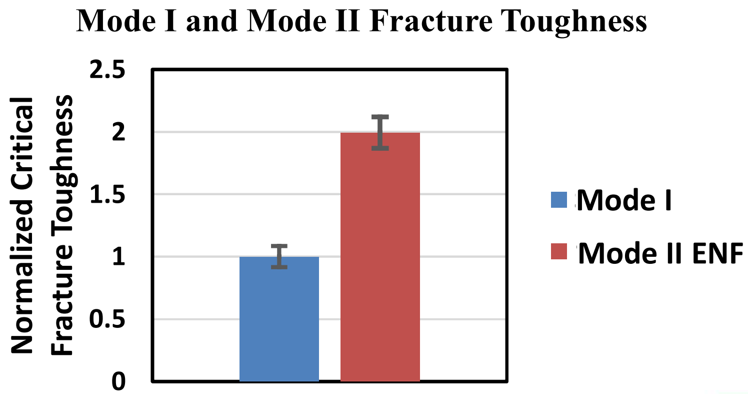
Mode II Disbond growth, no core crushing

- Facesheet thickness; $t_f = 0.045\ in.$
- Nomex Honeycomb core
  - $0.5\ in.$ thick
  - $8\ \mathrm{lb}/ft^3$ density
- Pre-cracked with SCB test method
- Area method used for calculation



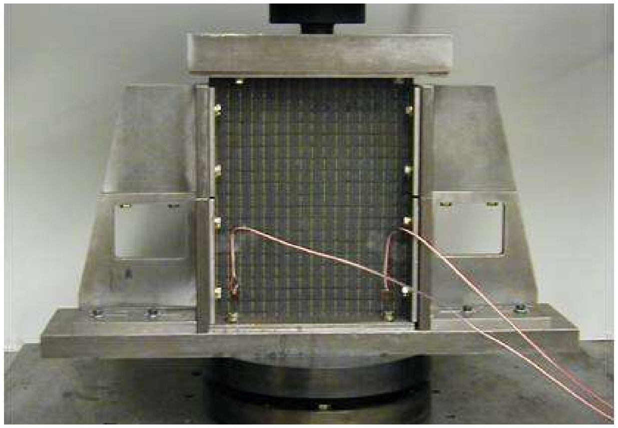


End Notch Flexure Test



Damage Tolerance Test Methods For Sandwich Composites

Edgewise Compression After Impact (SCAI)



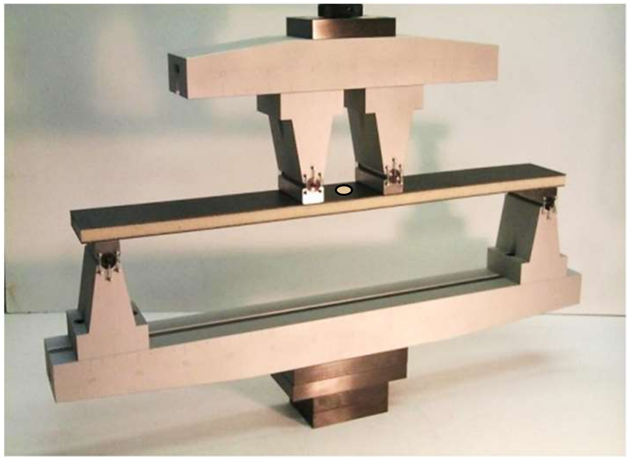
- Preferred damage tolerance test method for laminates
- High interest level for sandwich composites
- Second balloting completed this summer 2019
- Updates in progress

Four-Point Flexure After Impact (4-FAI)

- Constant bending moment and zero shear in damaged section
- Damaged facesheet can be loaded in compression or tension
- Initial draft practice completed
- Initial ASTM ballot submission pending

Notch Sensitivity Test Methods For Sandwich Composites

Sandwich Open Hole Flexure



- Initial draft practice completed
- Ready for ASTM ballot submission

Standard Configuration

- Width: 3 in.
- Hole diameter : 0.5 in.
- Span: 24 in.

Sandwich Open Hole Compression

- Initial draft standard in progress

Standard Configuration

- Width: 4 in.
- Height: 8 in.
- Hole Diameter: 0.67 in.

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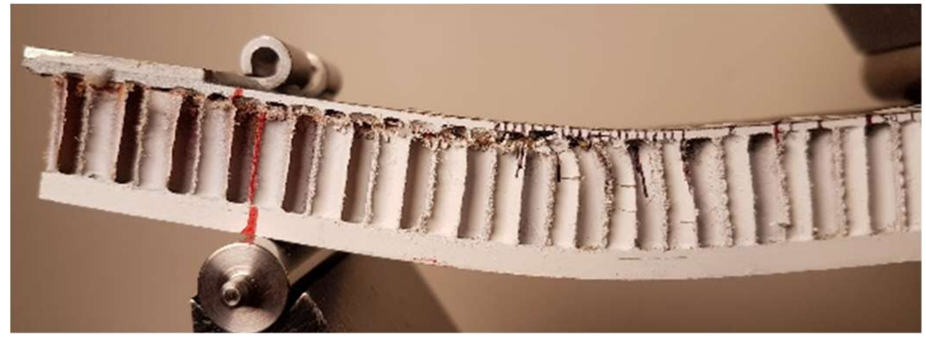
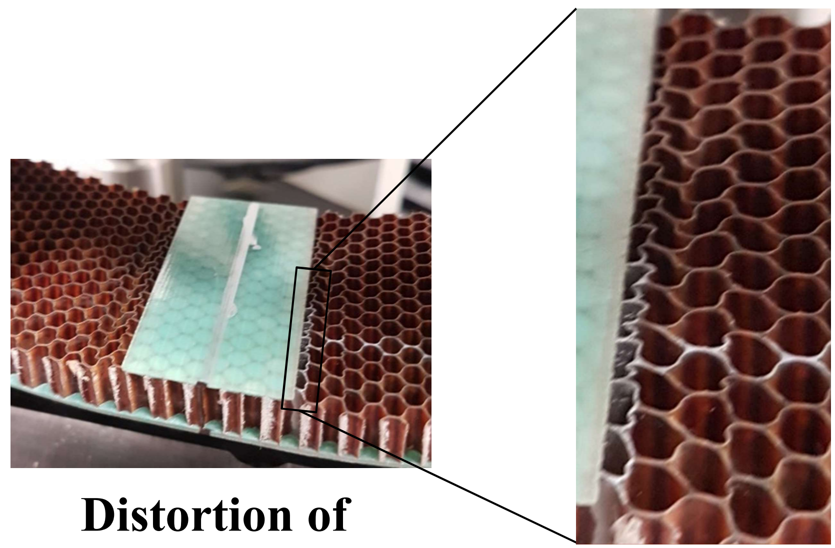
Sandwich Fracture Mechanics:
Mode II and Mixed-Mode Testing Challenges

For sandwich composites with Nomex Honeycomb Core…

- **Cell buckling near crack tip with no disbond growth**
- **Analytical and numerical models don't account for core constraint**
- **Effective core stiffness increase due to constraint effect**



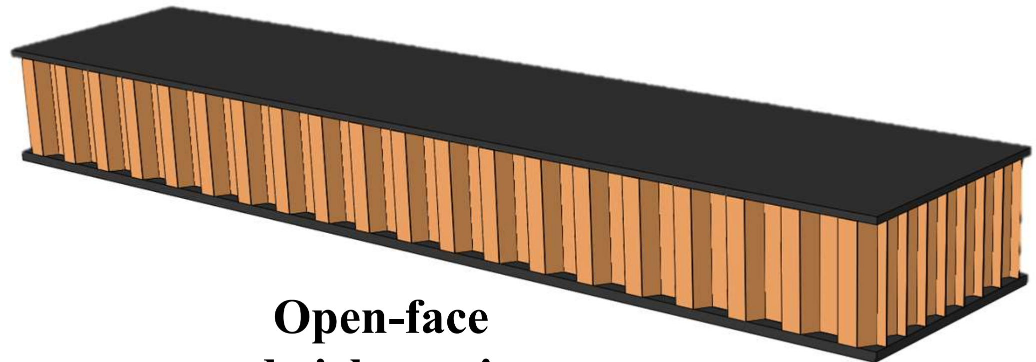
Core buckling in ENF test



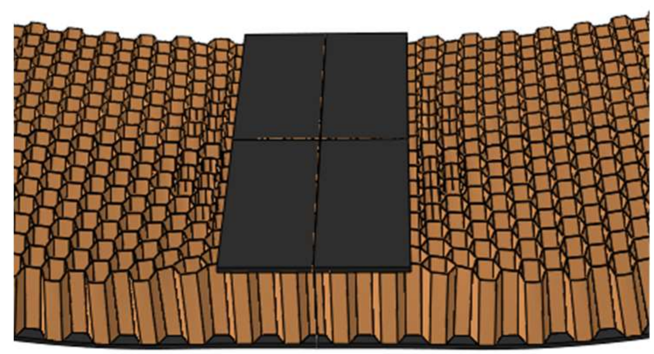
Distortion of cells at crack tip

Sandwich Fracture Mechanics:
Open-Face Sandwich Specimen

- Facesheet only on bottom of flexure specimen
- Investigate response of core in disbond region and near crack tip
- Investigate constraint effects
- Validation of numerical models



Open-face sandwich specimen



Tabbed open-face sandwich specimen

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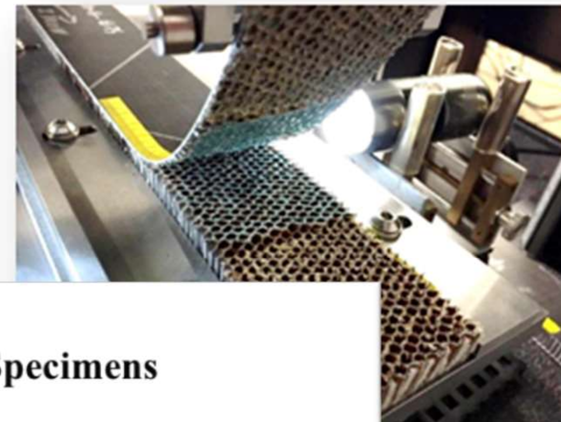
Sandwich Fracture Mechanics:
Modeling and Analysis Approach

Testing Considerations

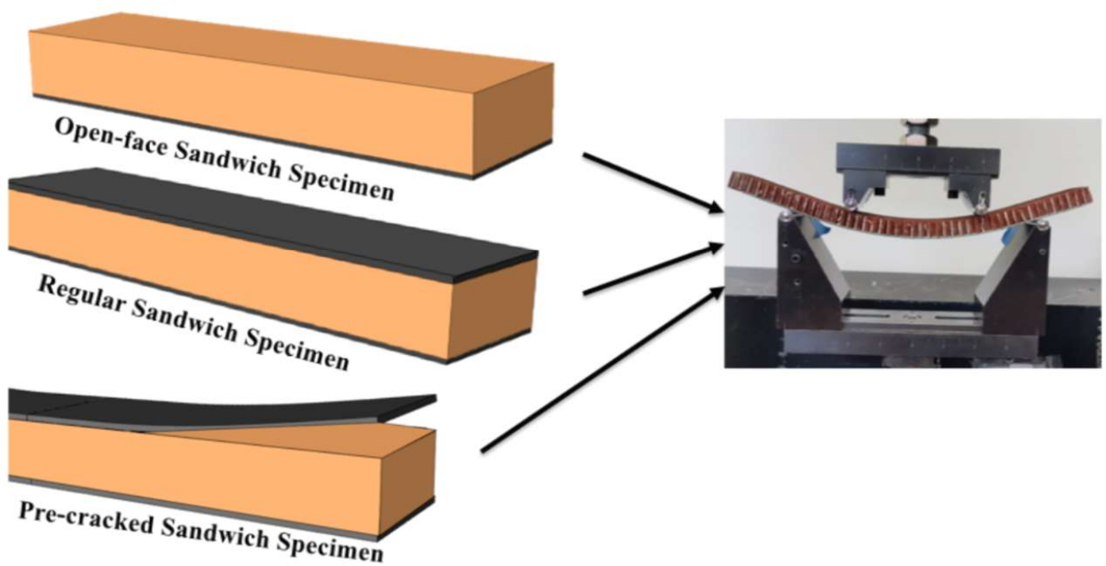
End Notch Flexure Test



eam Test

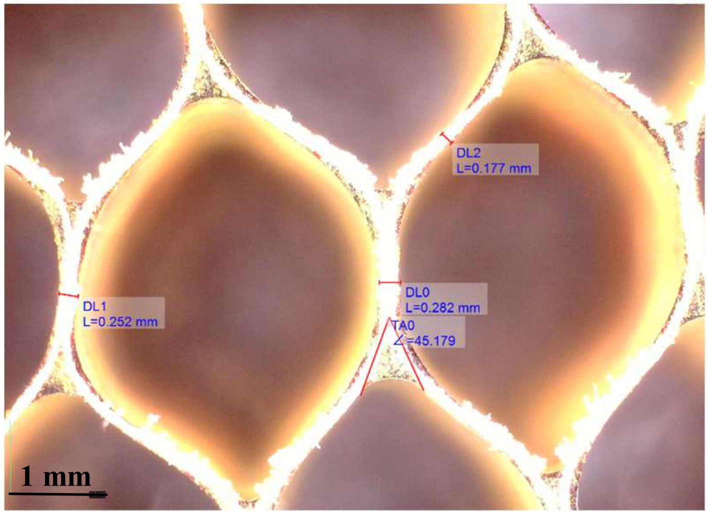
on Test

Homogeneous Core Validation Test Specimens

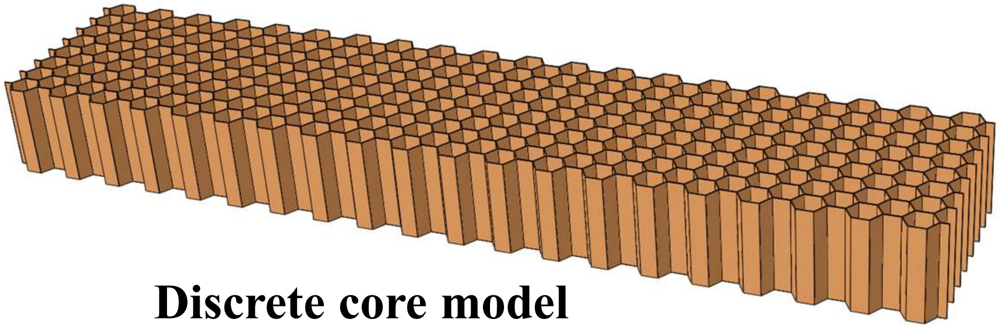


Sandwich Fracture Mechanics:
Discrete Modeling of Honeycomb Core

- Investigate constraint effects observed in experiments
- Extract effective modulus increase due to constraint effects in honeycomb core
- Validate homogenized core model
- Determine stress levels at which core failure/buckling occurs
- Predict mode-mixity using VCCT
  - Single Cantilever Beam test
  - Mixed Mode Bend test
  - End Notched Flexure test



Cell measurement using digital microscope



Discrete core model

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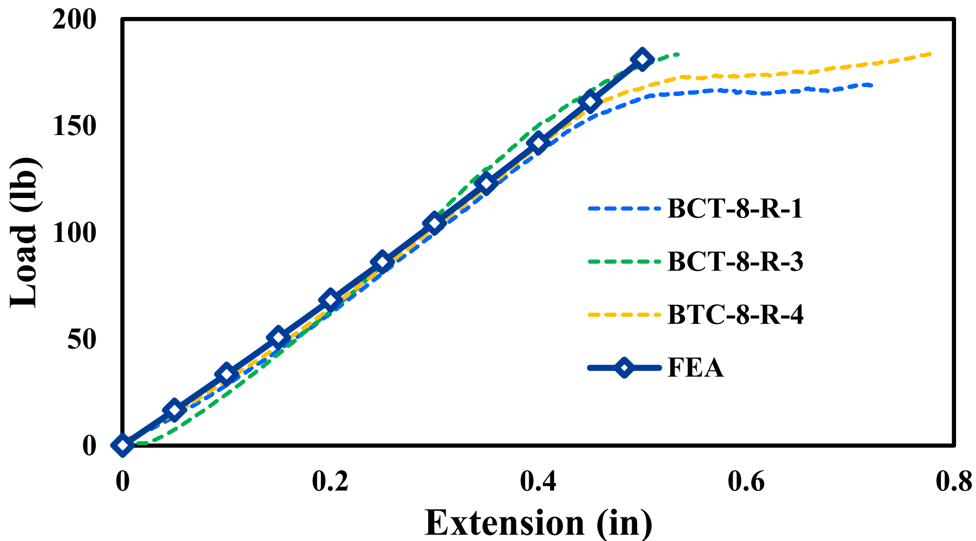
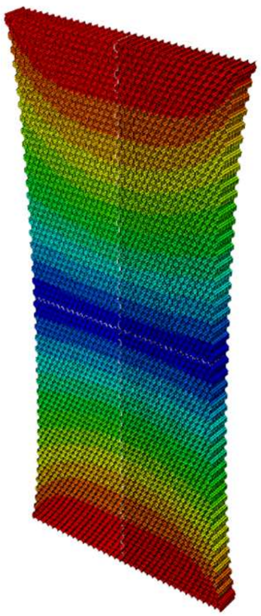
Discrete Modeling of Honeycomb Core:
Initial Model Development

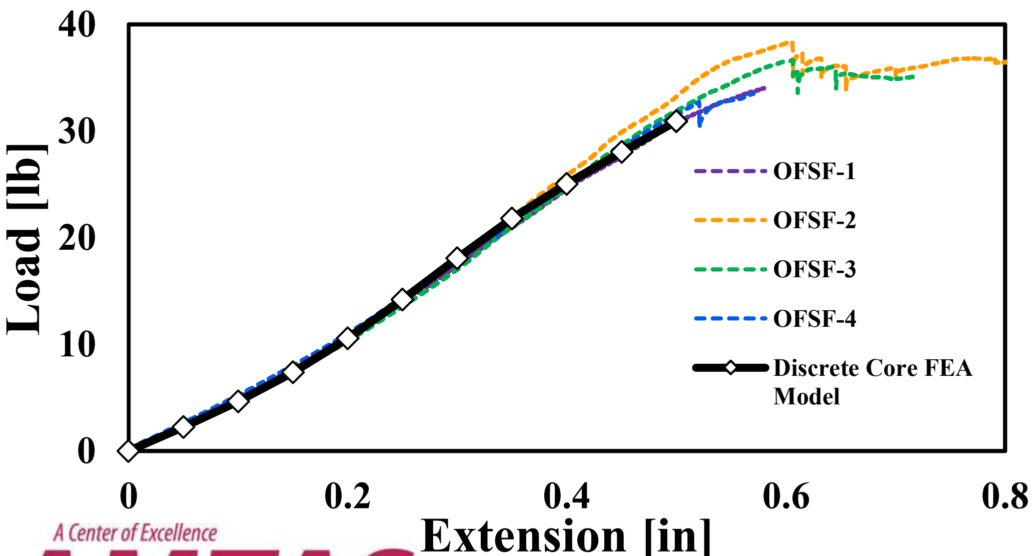
- **Initial "bare core" tension testing**
- **Tuning of material properties using flatwise compression and flatwise shear testing**
  - **Validation testing**
  - **Predict elastic response**

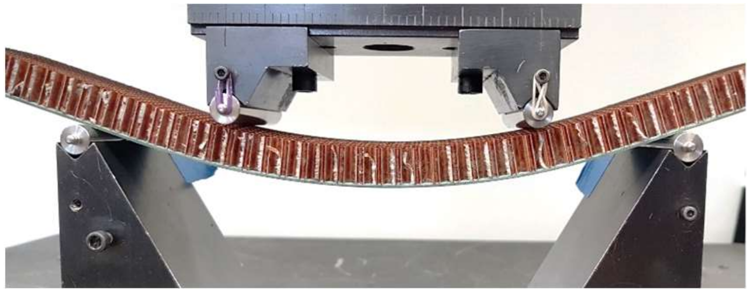




Discrete Modeling of Honeycomb Core:
Validation in Flexural Loading

- **“Open-face” four point flexure testing (no upper facesheet)**
- **Constrained and unconstrained regions of core**
- **Discreet core model matches initial portion of test**
- **Used to develop homogenized core model in disbond region**





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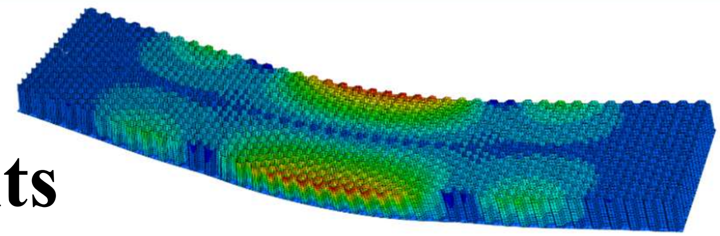
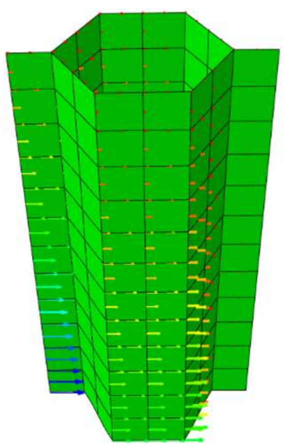
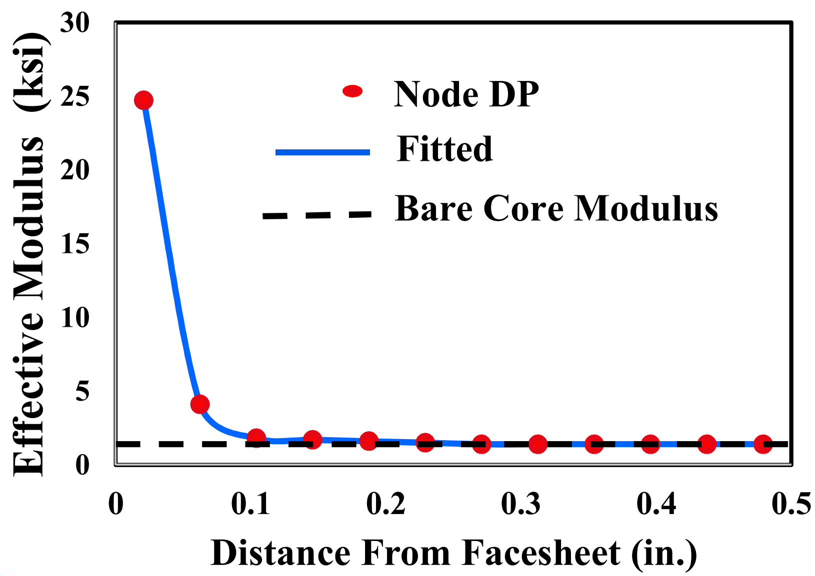
Discrete Modeling of Honeycomb Core:
Facesheet Constraint Effects

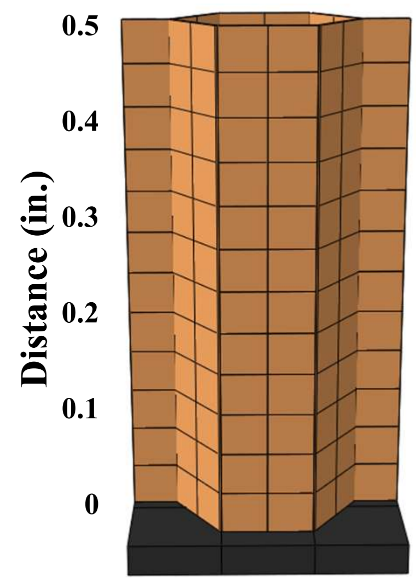


- Four-point flexure loading
- Use of nodal forces and displacements
- Calculation of effective modulus thru core thickness
- Unconstrained region matches "bare core" modulus



Reaction forces at nodes





Free at open-face

Constrained at facesheet

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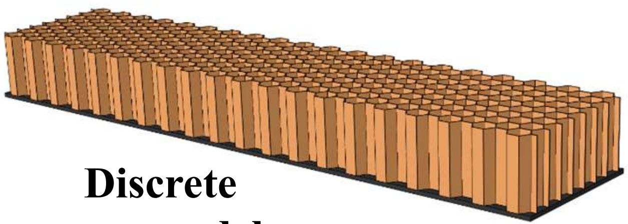
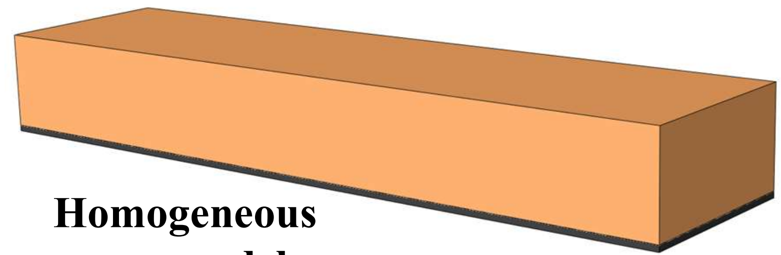
Development of Homogeneous Honeycomb Core Model

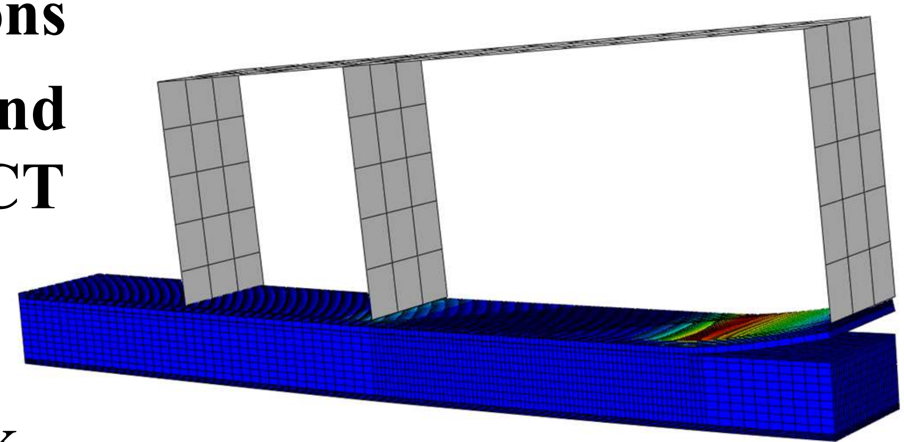


Discrete
core model



Homogeneous
core model

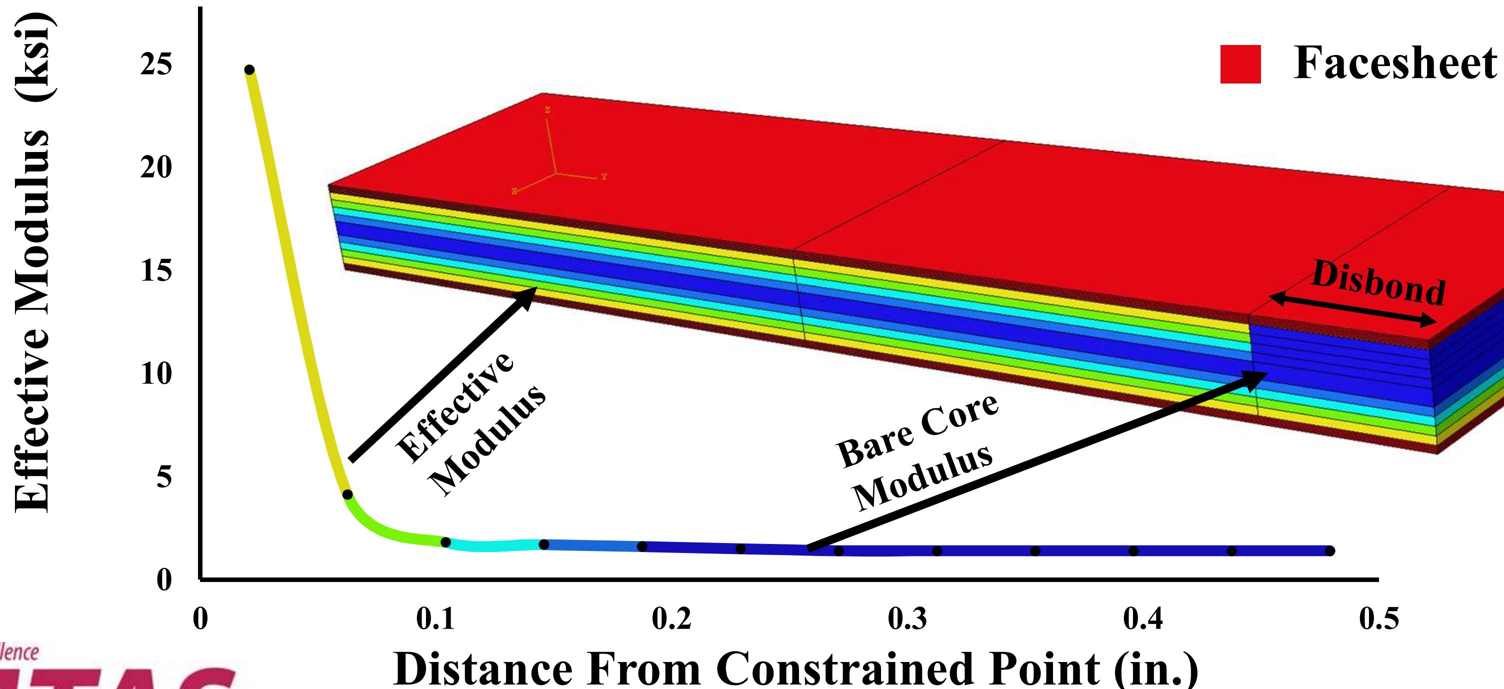
- **Simplified model incorporating constraint effects in disbond regions**
- **Investigate mode mixity for disbond growth in test methods using VCCT (SCB, MMB, ENF)**
- **Calibrate interfacial cohesive elements for higher building block analysis of sandwich disbond**



MMB test simulation with
homogenous core model

Development of Homogenous Core Model:
Facesheet Constraint Effects

- Core moduli values obtained from discrete core modeling
- Partitions created, different properties applied in thru-thickness regions
- No constraint effects in region of sandwich disbond



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Summary

- Several sandwich composite test methods currently in the ASTM standardization process

  (Fracture mechanics, damage tolerance, and notch sensitivity)

- Round-robin testing activities initiated to investigate three sandwich disbond test methods

- Investigating proper honeycomb core modeling in vicinity of sandwich disbonds with focus on use in building block approach

- Wrapping up assessment of predictive capabilities for sandwich composite notch sensitivity & damage tolerance

Thank you for your attention!

Questions?