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An Engineering Approach for Damage Growth Analysis of Sandwich Structures Subjected to Combined Compression and Pressure Loading

Waruna Seneviratne, John Tomblin, Shenal Perera
Pirashandan Varatharaj, Vishnu Saseendran

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NIAR
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National Institute for Aviation Research

Research Team

- **National Institute for Aviation Research**
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  - Shenal Perera
  - Pirashandan Varatharaj
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- **FAA**
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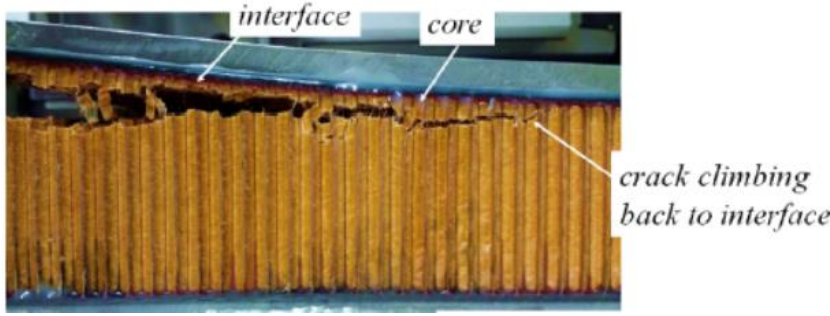
  - Larry Ilcewicz, PhD

Kansas Aviation Research & Technology Growth Initiative

An Engineering Approach for Damage Growth Analysis of Sandwich Structures Subjected to Combined Compression and Pressure Loading

- **Motivation and Key Issues**
  - Thermo-mechanical loads during ground-air-ground (GAG) cycling result in localized mode I stresses that cause further delamination/disbond/core fracture growth.
- **Objective**
  - Develop an engineering approach for damage tolerance analysis of sandwich structures subjected to combined mechanical and pressure loads.
- **Approach [Shown in the next slide]**
  - Engineering Approach [Discussed in next slide]
    - SCB Testing (Obtain G_{IC} facture toughness values)
    - FEA Analysis on SCB Test and Validate modeling techniques
    - Develop a test method for GAG (Edgewise Compression) specimens.
    - Develop High Fidelity FEA models for GAG Specimens
    - Blind Predictions Comparing GAG FEA Data with Test Data



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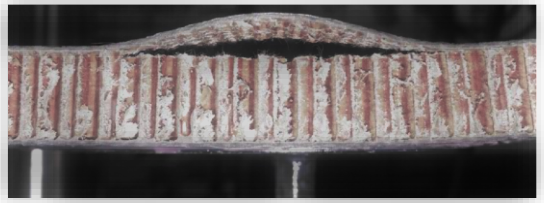
Accomplishments

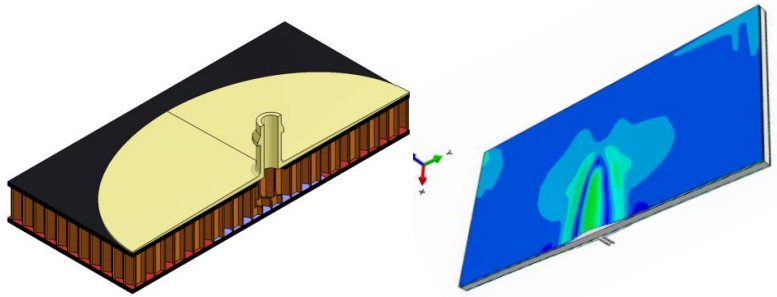
Mode I (G1c) Fracture Toughness of Composite Sandwich Structures for Use in Damage Tolerance Design and Analysis

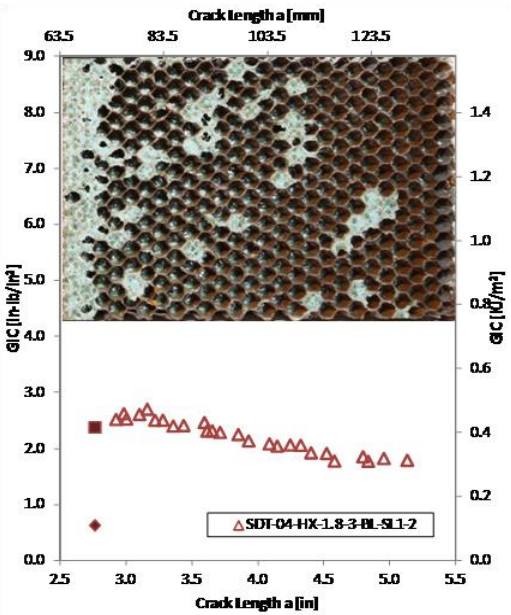


- Volume 1: ***Static Testing Including Effects of Fluid Ingression*** **(DOT/FAA/TC-16/23)**
- Volume 2: ***Fatigue Testing Including Effects of Fluid Ingression*** **(DOT/FAA/TC-17/06)**
- Volume 3: ***Damage Growth in Sandwich Structures*** **(DOT/FAA/TC-17/7)**
- Volume 4: ***Investigation of Face/Core Interface Debonding in Aircraft Sandwich Composites Subjected to Combined Pressure and In-plane Loading: An Engineering Approach*** ***(On Going)***

Other Contributions to ASTM D30 & CMH-17

- CMH-17 Rev. H chapters/sections (***completed review***)
- SCB Fracture test standard development ASTM D30





Other Publications

- Damage Initiation and Fracture Analysis of Honeycomb Core Single Cantilever Beam (SCB) Sandwich Specimen *(submitted to JSSM)*
- Damage Growth Analysis of Sandwich Structures Subjected to Combined Compression and Pressure Loading *(Accepted for ASC 34th Technical Conference)*

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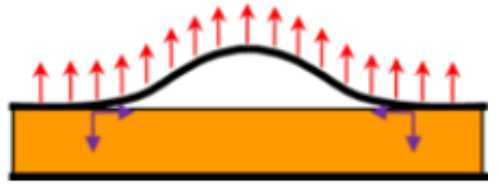
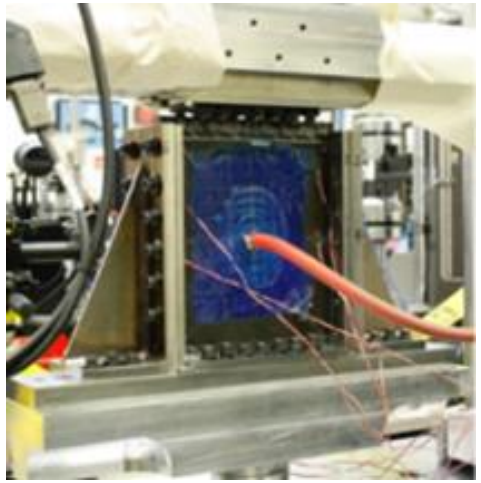
Analysis – Engineering Approach

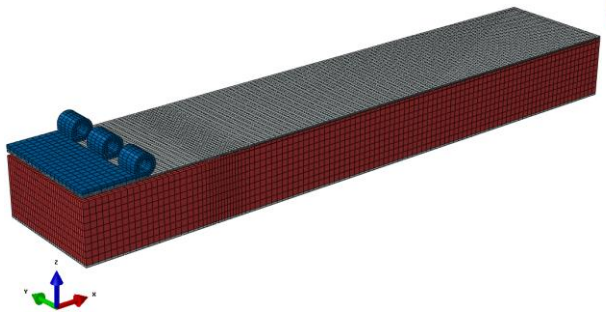
- SCB ➔ GAG

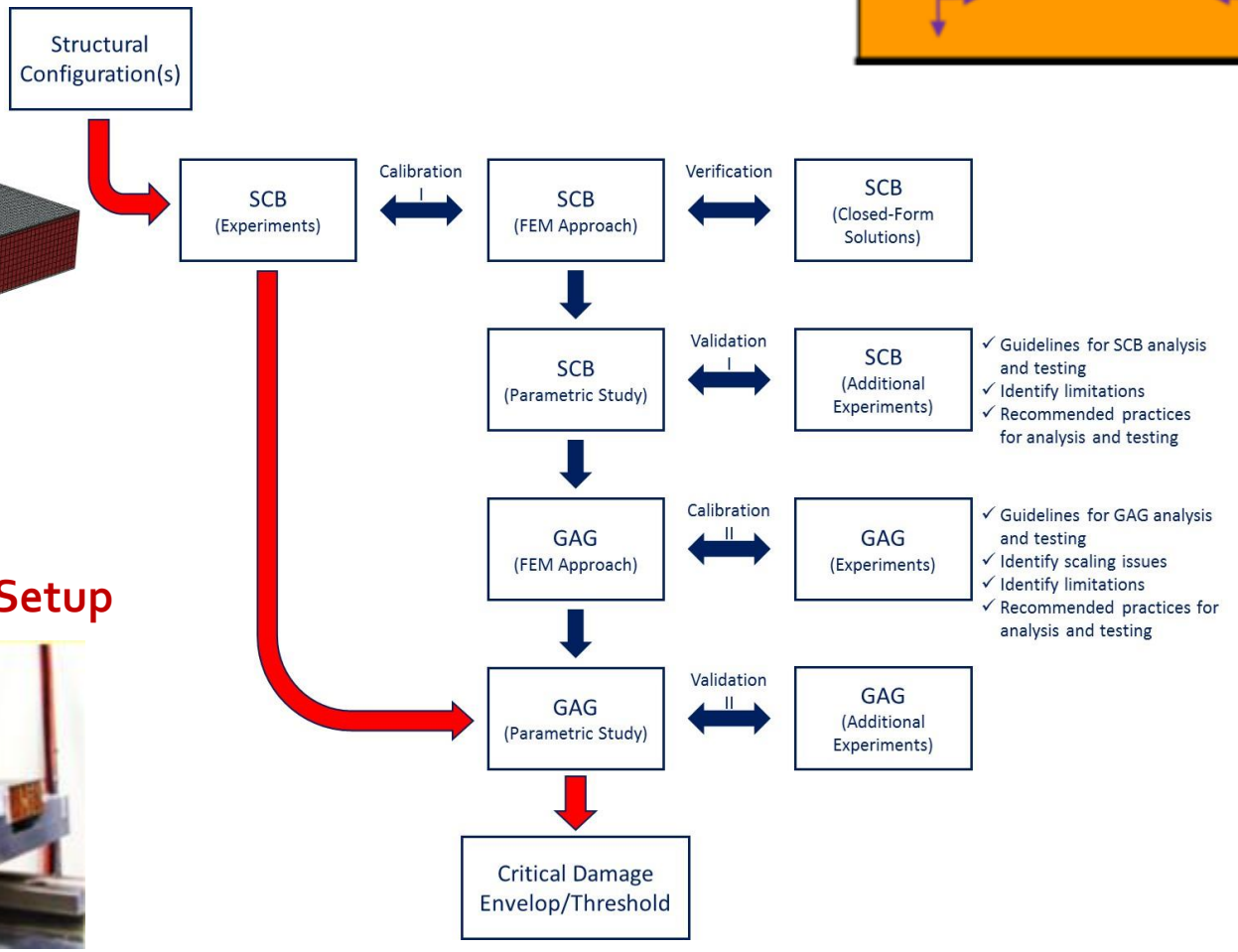


GAG Experimental Setup



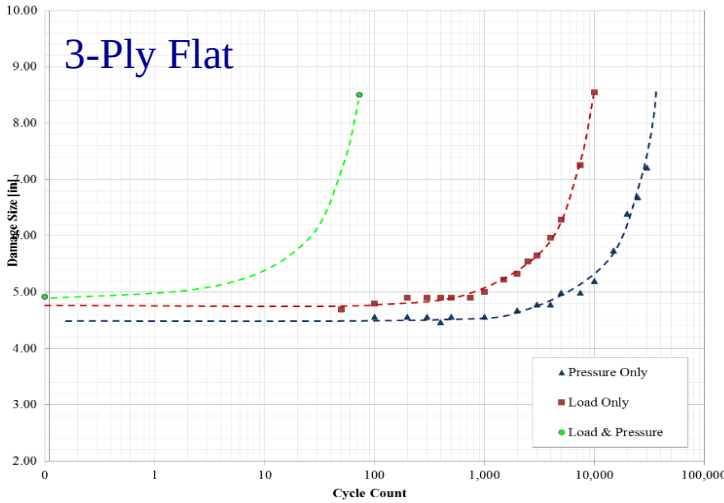
SCB FE Model





SCB Experimental Setup

GAG Loading Cycles

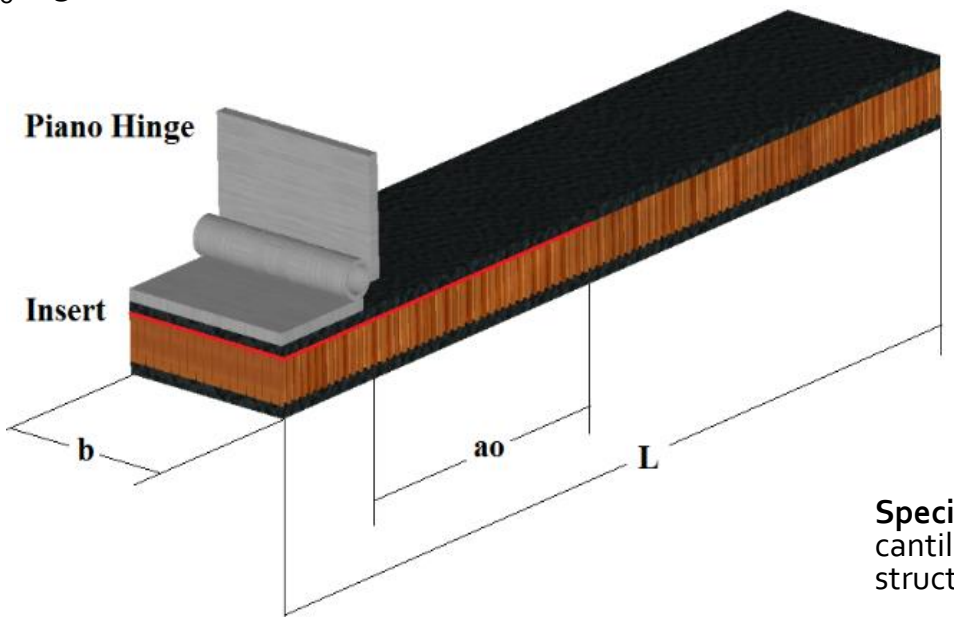


Outline

- **SCB Test Configuration**
  - **Materials & Test Setup (translatable base)**
- Foundation Model Approach & Validation
  - Comparison of Analytical, FEA & Exp. Results
- Finite Element Model Description of SCB Specimens
  - Cohesive-based modeling approach
- GAG - Edgewise Compression (EWC) Test Configuration w/t Pressure Loading
  - Test Setup & Loading
  - Static and fatigue testing
- Finite Element Model description for GAG Specimens
  - Modeling approach
  - Comparison to test data
- Summary & Future Work

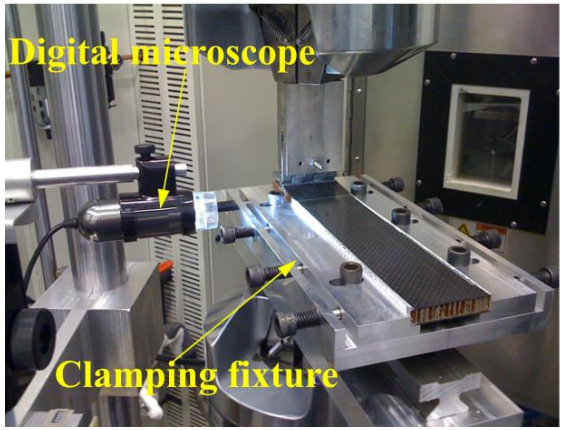
SCB Test Configuration

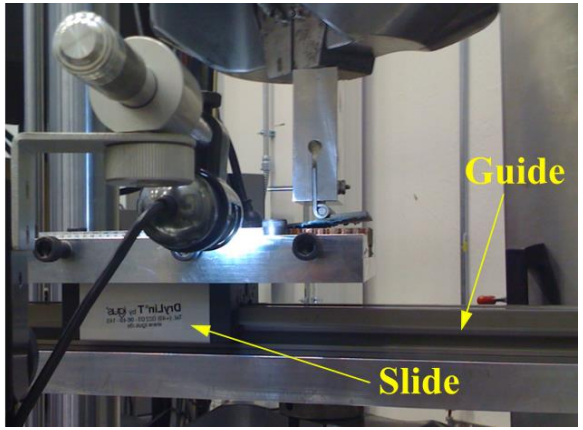
- Materials
  - Facesheet: T650 – 5320 PW
  - Core: Hexcel HRH-10
  - Adhesive: FM300 - 2
- Prescribed Crack
  - Teflon® inserts
  - a_0 = 50.8mm
- Dimensions
  - L = 254mm
  - b=50.8mm
- Piano Hinge
  - Bonded using EA9394



Test Matrix

Case	Facesheet Material	Plies	Cell Size (mm)	Core Density (kg/m³)	Core Thickness (mm)
1	T650/5320-PW	4	3.2	48.0	25.4
2	T650/5320-PW	4	3.2	96.0	12.7
3	T650/5320-PW	4	9.5	48.0	12.7
4	T650/5320-PW	8	3.2	96.0	12.7





Specimen sizing conforms w/t: Ratcliffe, James G., and James R. Reeder. "Sizing a single cantilever beam specimen for characterizing facesheet–core debonding in sandwich structure." *Journal of Composite Materials* 45.25 (2011): 2669-2684.

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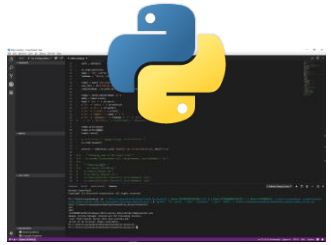
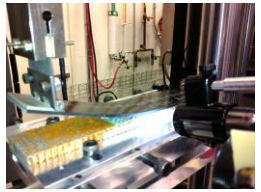
Foundation Model Approach & Validation

Python Based Suite

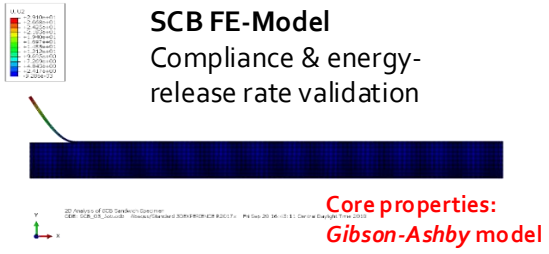
Python Suite



SCB Fracture Tests
Compliance, C = δ/P
crack length, a

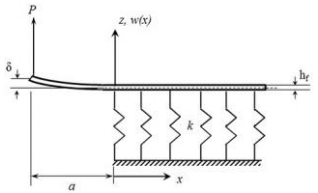


SCB FE-Model
Compliance & energy-release rate validation



Core properties:
Gibson-Ashby model

Foundation model
Compliance & energy-release rate validation



Closed – Form Expressions

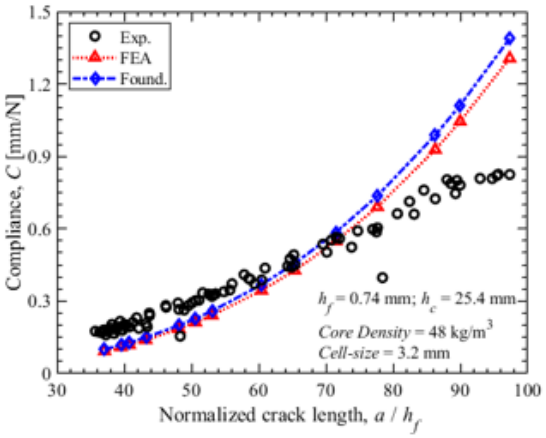
$$C = \frac{\delta(x=-a)}{P} = \frac{4\lambda}{k}\left[\frac{\lambda^3 a^3}{3} + \lambda^2 a^2 + \lambda a + \frac{1}{2}\right]$$

$$G = \frac{2P^2\lambda^2}{bk}\left[\lambda^2 a^2 + 2\lambda a + 1\right]$$

$$\lambda = \sqrt[4]{\frac{k}{4E_f I}} \qquad k = \frac{E_c b}{h_c/4}$$

Winkler-based foundation model

Compliance vs. crack length



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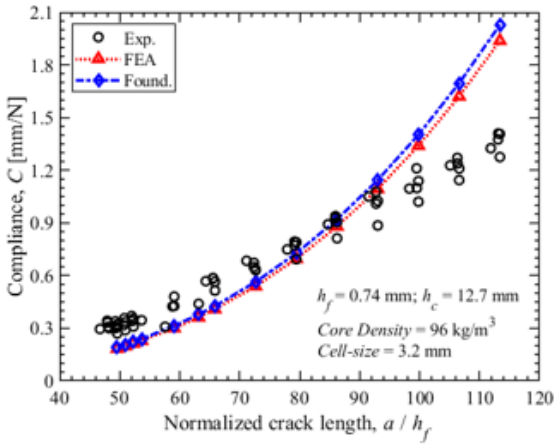

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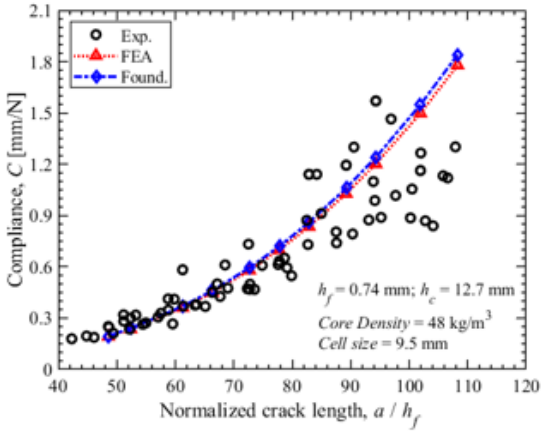

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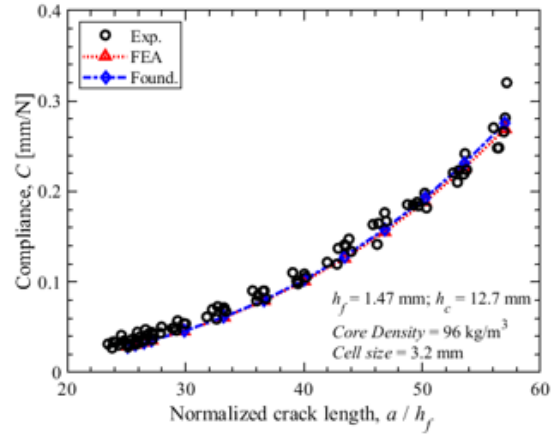
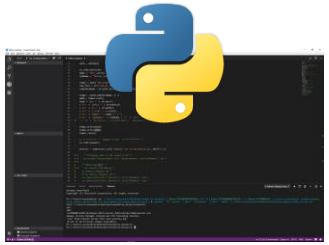


(d)

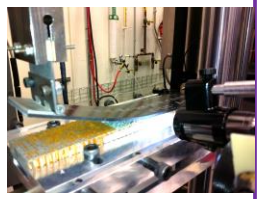
Foundation Model Approach & Validation

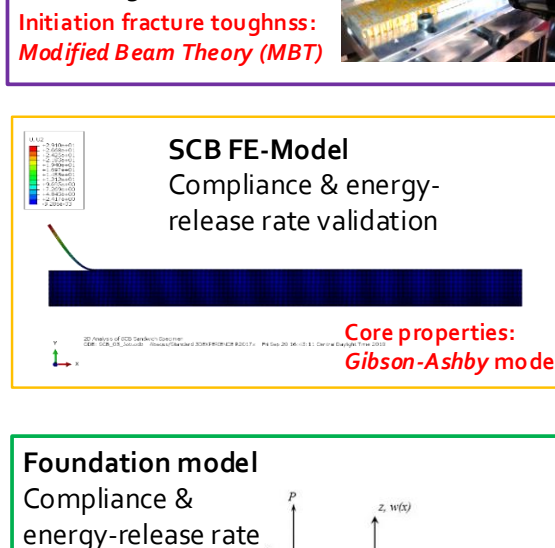
Python Based Suite

Python Suite



SCB Fracture Tests
Compliance, C = δ/P
crack length, a
Initiation fracture toughnss:
Modified Beam Theory (MBT)





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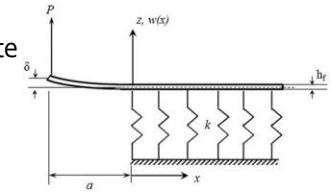
Foundation model
Compliance & energy-release rate validation



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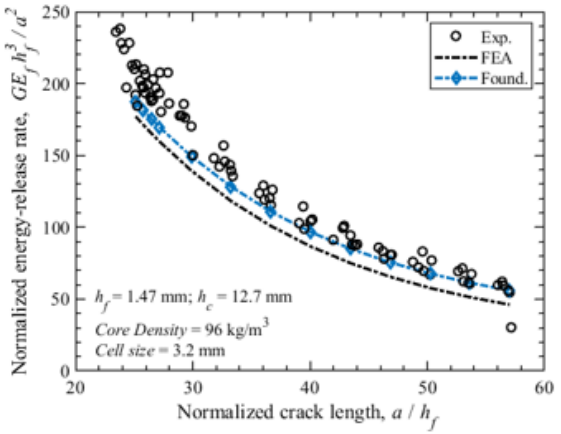
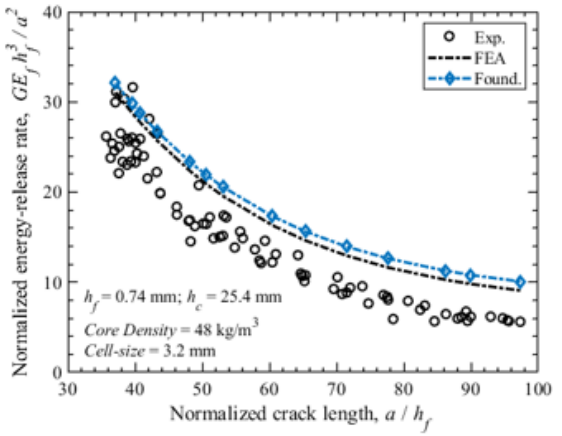
$$\lambda = \sqrt[4]{\frac{k}{4E_f I}} \qquad k = \frac{E_c b}{h_c/4}$$

Winkler-based foundation model

Energy-release rate vs. crack length



(a)



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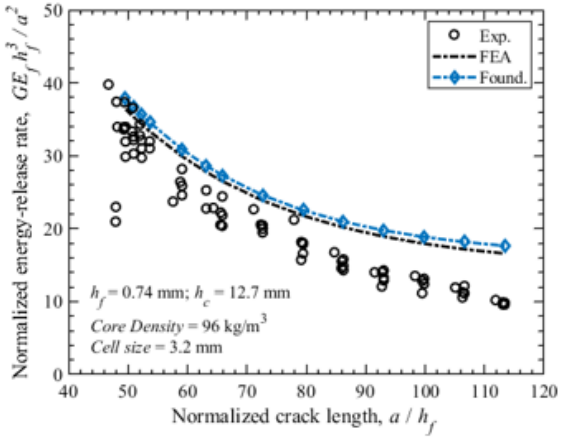

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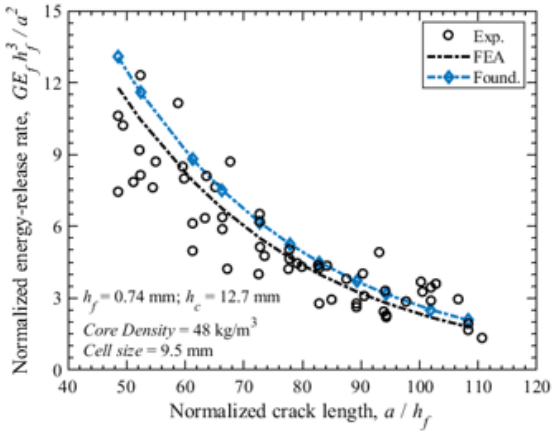

(d)

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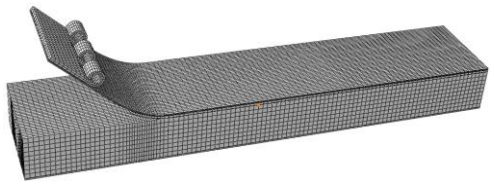
FEA – SCB Model Description and Approach

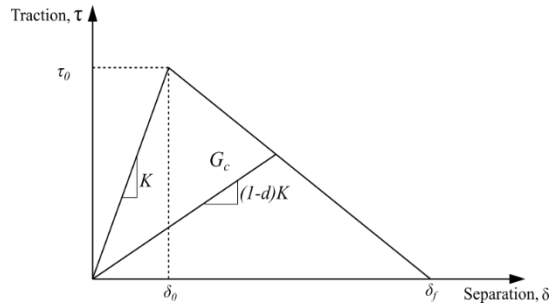
El-Sayed, S., & Sridharan, S. (2002). Cohesive layer models for predicting delamination growth and crack kinking in sandwich structures. *International Journal of Fracture*, *117*(1), 63-84.

- ***Cohesive zone*** to model the damage in the core.
- Four configurations considered:
  - Core density (48 96 kg/m^3) & Thickness (12.7, 25.4 mm)
  - Cell size (3.2, 9.5 mm)
  - Face-sheet thicknesses (4, 8-ply)
- Failure modeled in core using cohesive elements (located beneath meniscus layer)

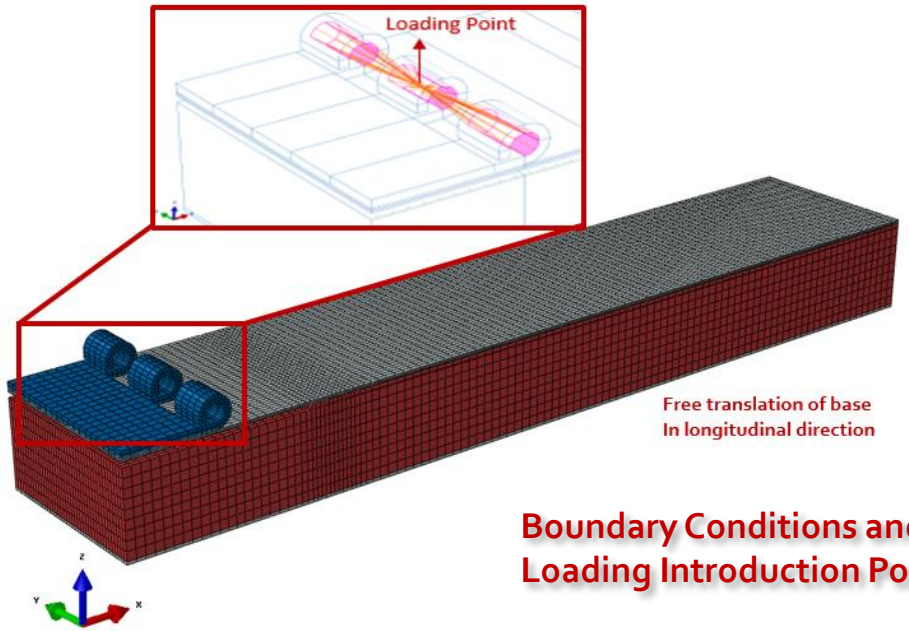
G1c

$$\tau_0 = \frac{4}{27}\sqrt{\frac{12E_cG_{1c}}{h_{eff}}} \qquad K_n = \frac{E_c}{h_{eff}}$$

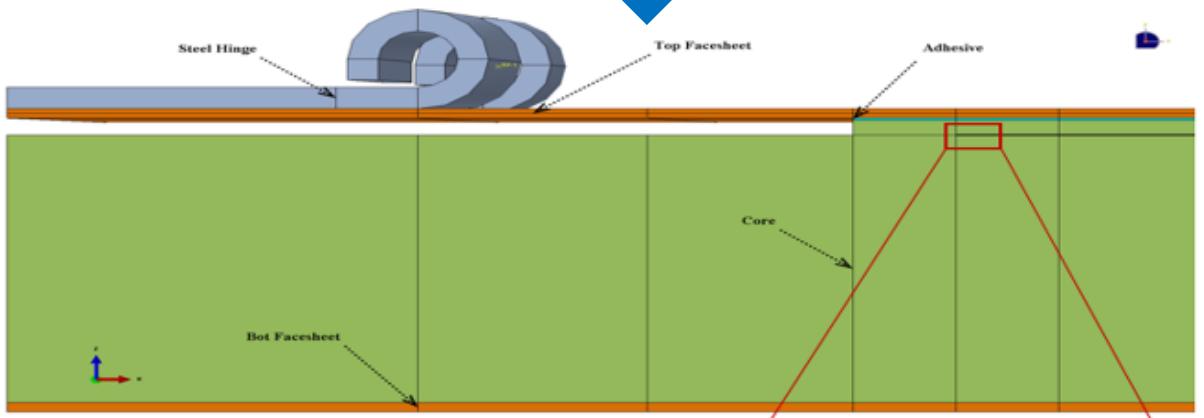




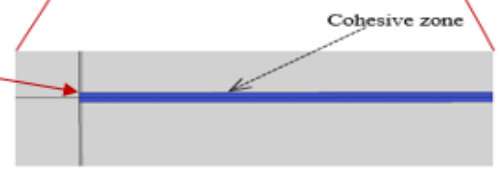
Core - Homogenous medium
(Gibson-Ashby Approach)



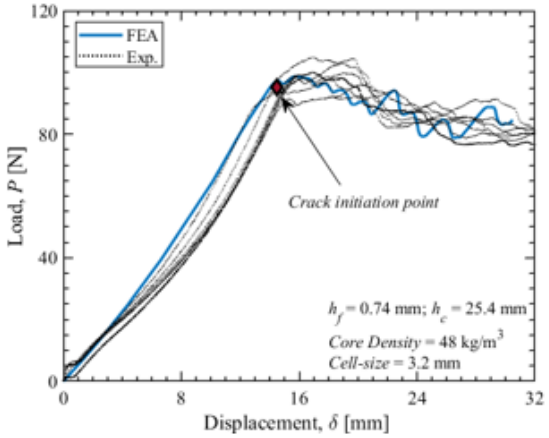
Boundary Conditions and Loading Introduction Point



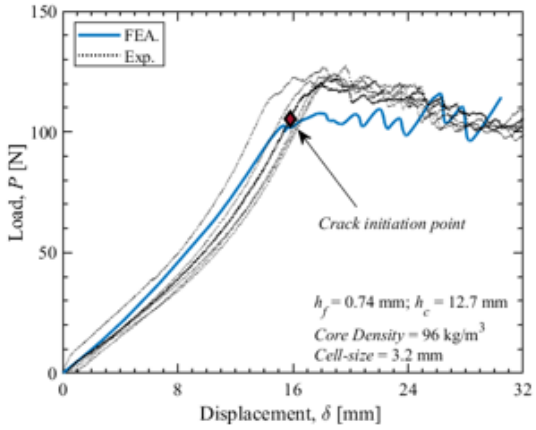
Damage in the core



Comparison of FE & Exp. Results



(a)



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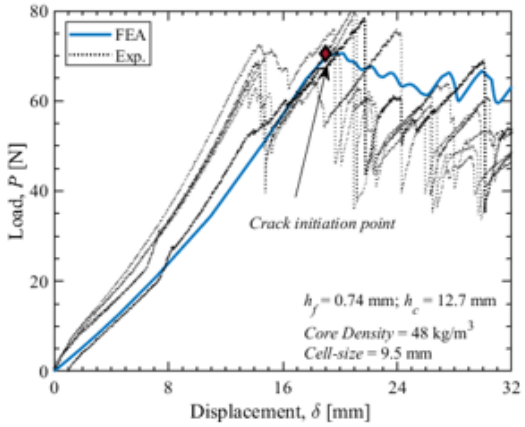

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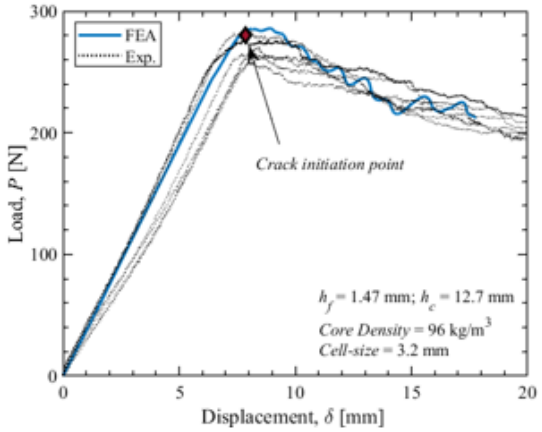
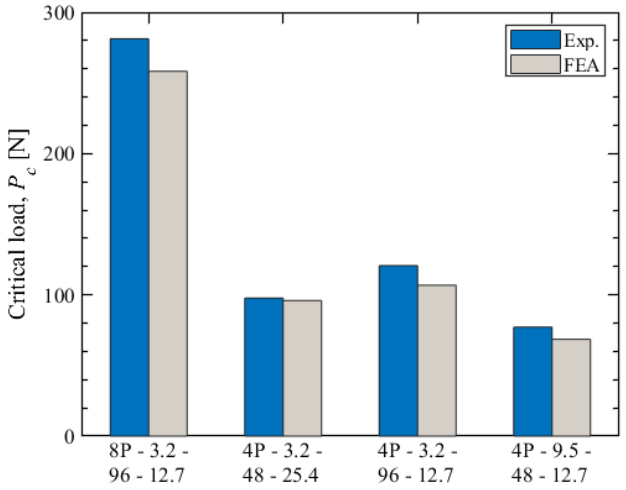
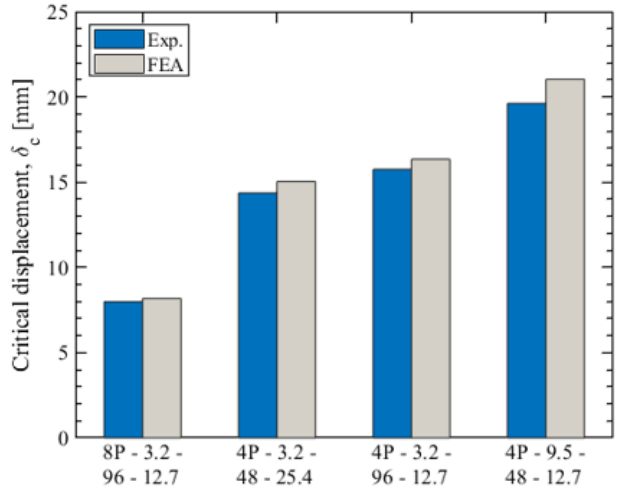


(d)

Critical Load and Displacement Comparison





Case	Facesheet Material	Plies	Cell Size (mm)	Core Density (kg/m³)	Core Thickness (mm)	Exp. Load (N)	Predicted Crack Initiation Load	
							FEA Load (N)	Error (%)
1	T650/5320-PW	4	3.2	48.0	25.4	97.7	96.0	-1.8
2	T650/5320-PW	4	3.2	96.0	12.7	120.7	106.8	-11.5
3	T650/5320-PW	4	9.5	48.0	12.7	77.2	68.5	-11.3
4	T650/5320-PW	8	3.2	96.0	12.7	258.2	281.3	8.9

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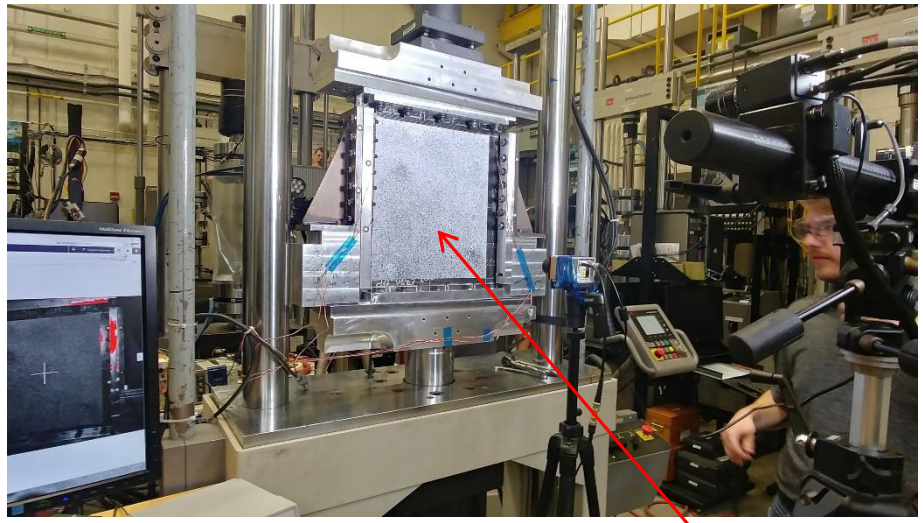
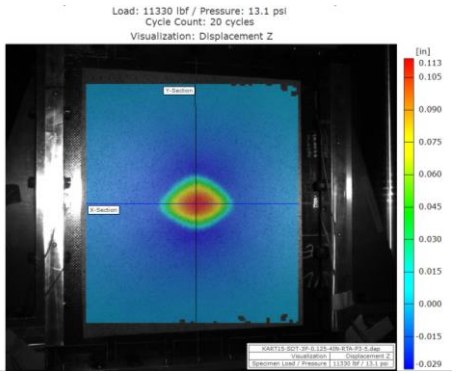
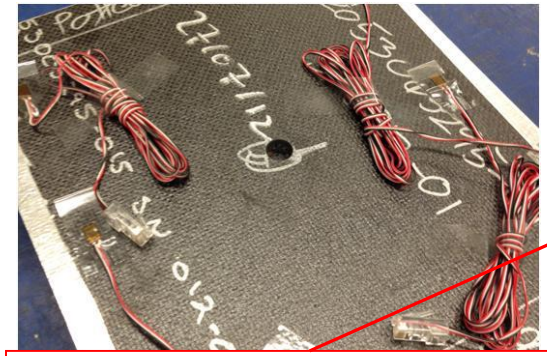
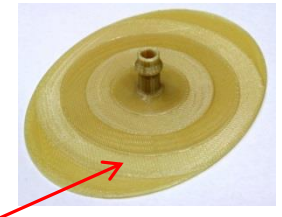
GAG - Edgewise Compression (EWC) Test Setup





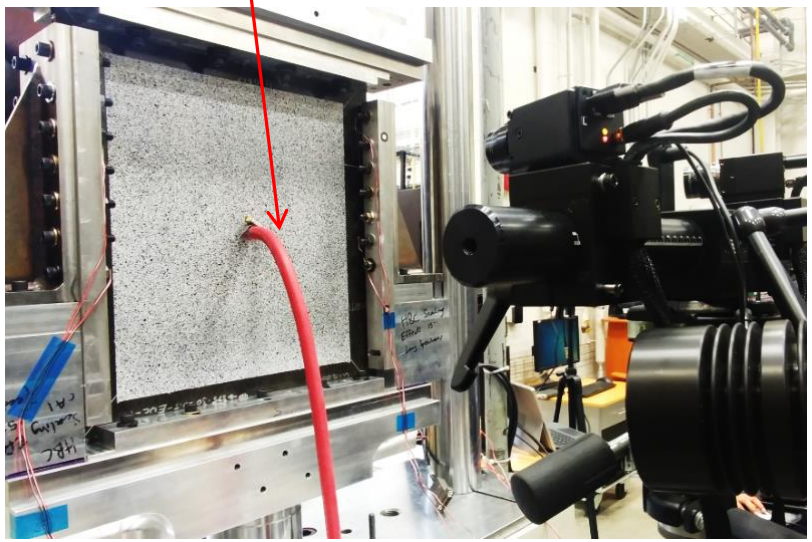
DIC speckle pattern on front and back sides





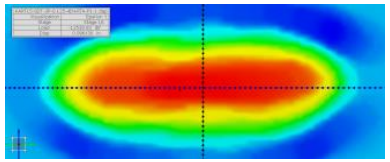
Hysol EA9309.3NA Epoxy

3D printed (Ultem) pressure port

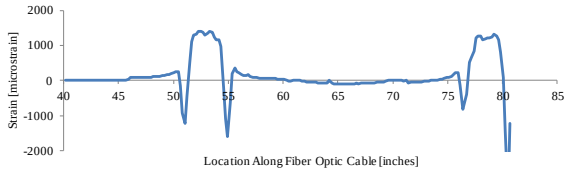


Ability to accommodate various specimen sizes
- 10x12 (shown) and 18x20 (test size)

Damage Growth monitoring

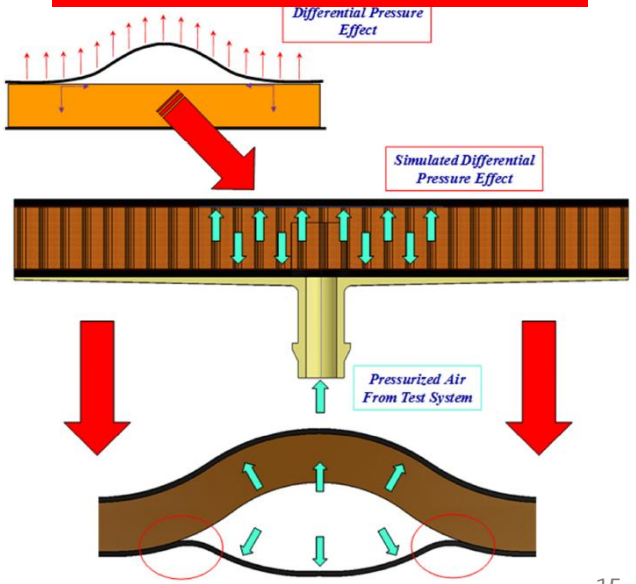


Digital Image Correlation (DIC)



Distributed fiber optic strain sensors

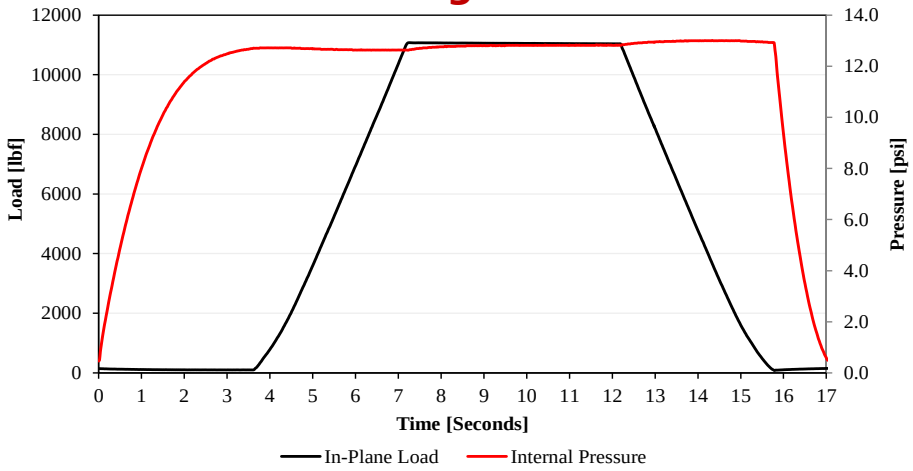
Pressure Simulation

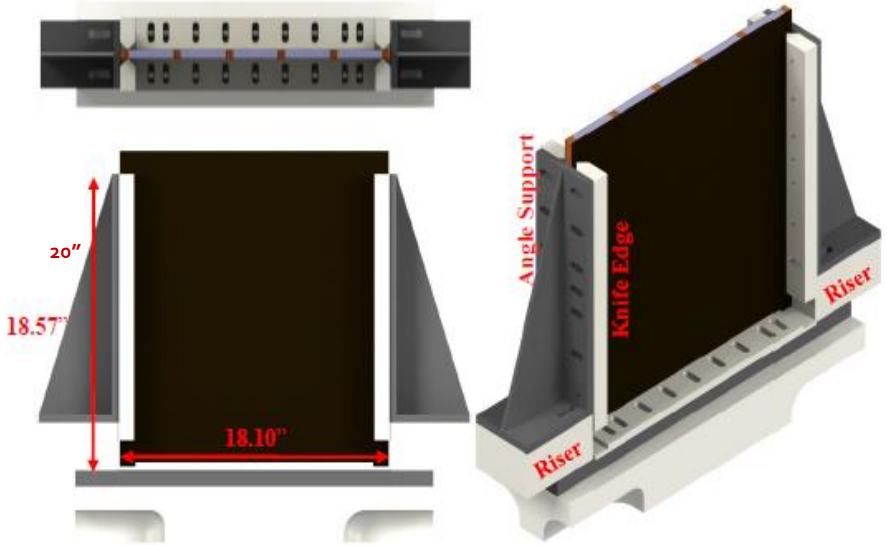


GAG (EWC) Quasi Static Testing w/t Pressure Loading

- Test rig developed for combined compression (in-plane) & pressure loading
- Face sheet & core parameters altered
- Ability to accommodate various specimen sizes

Loading Condition

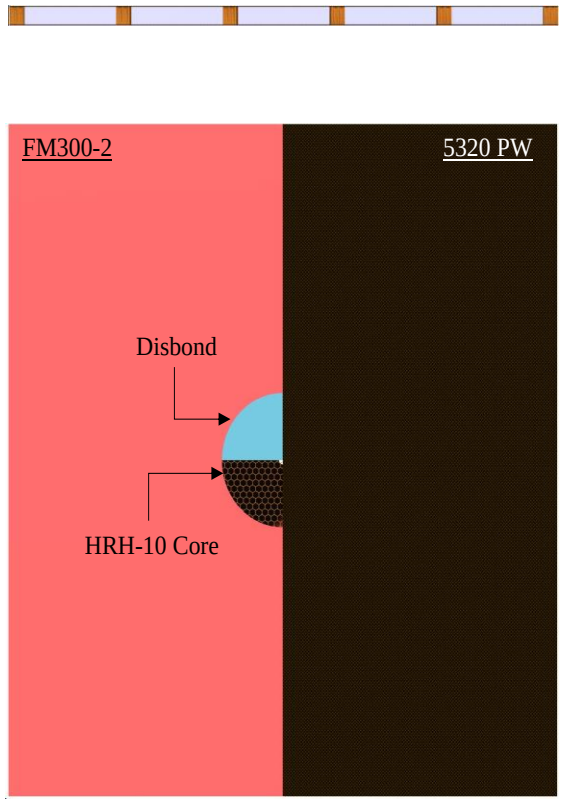


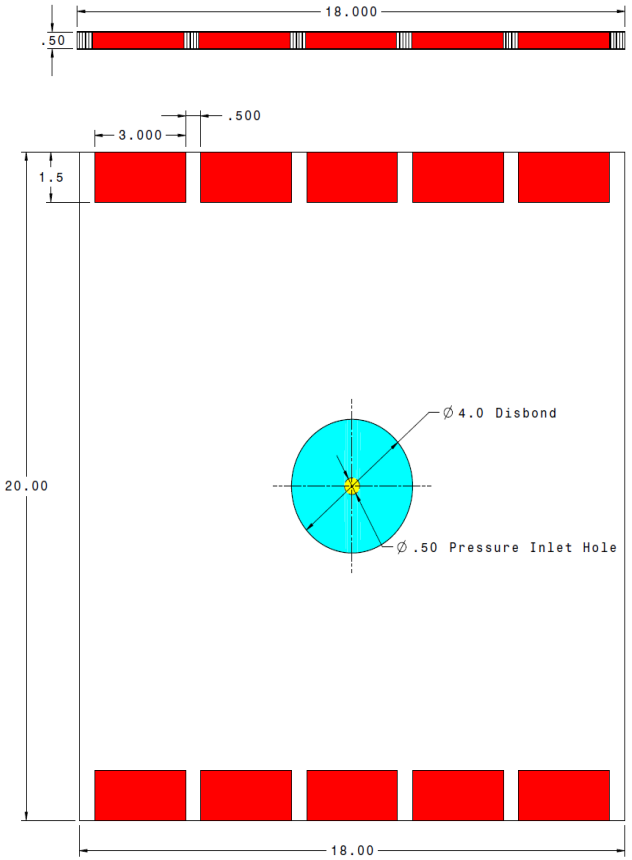


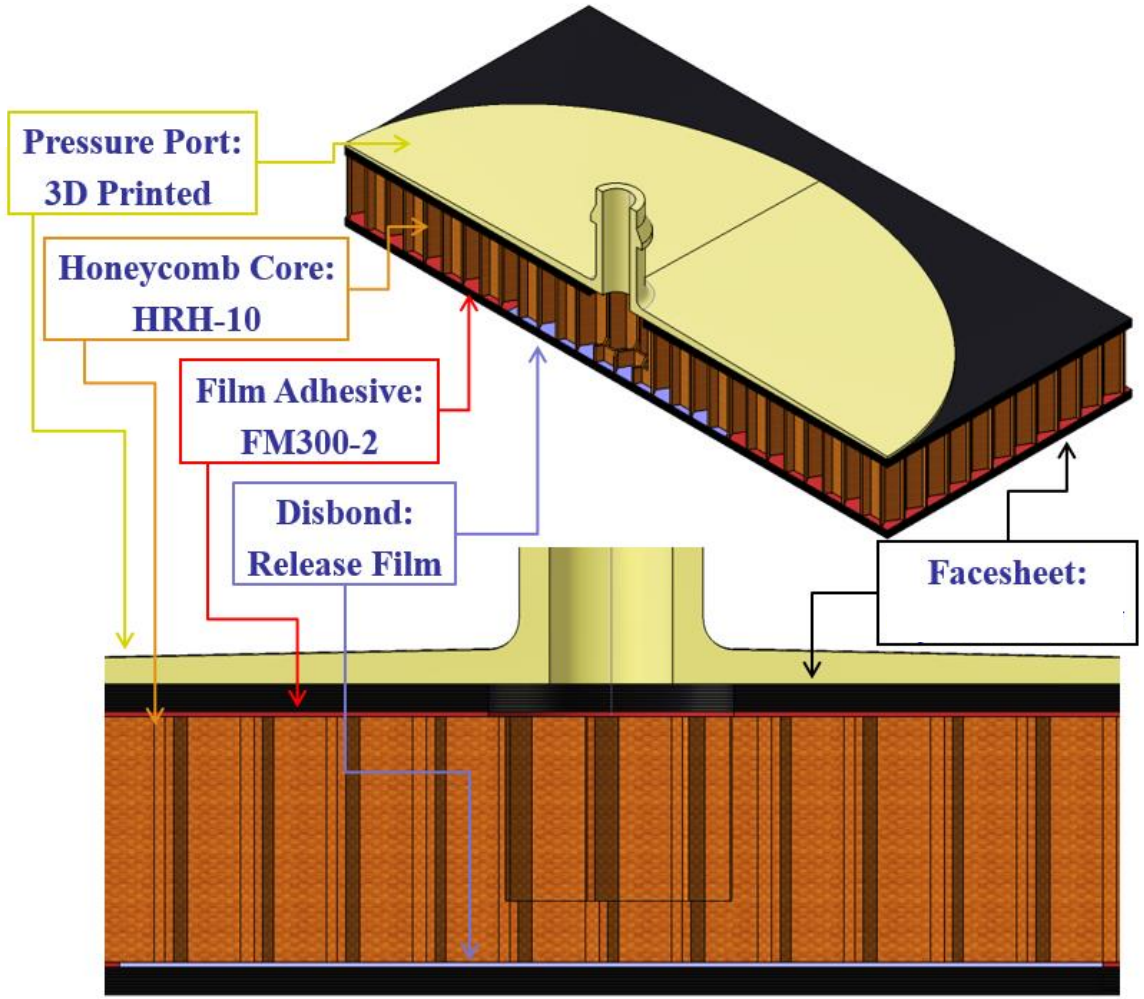
Test Matrix

Case	Facesheet Material	Plies	Cell Size (mm)	Core Density (kg/m³)	Core Thickness (mm)
1	T650/5320-PW	4	3.2	48.0	25.4
2	T650/5320-PW	4	3.2	96.0	12.7
3	T650/5320-PW	4	9.5	48.0	12.7
4	T650/5320-PW	8	3.2	96.0	12.7

GAG - Edgewise Compression (EWC) Specimen Configuration





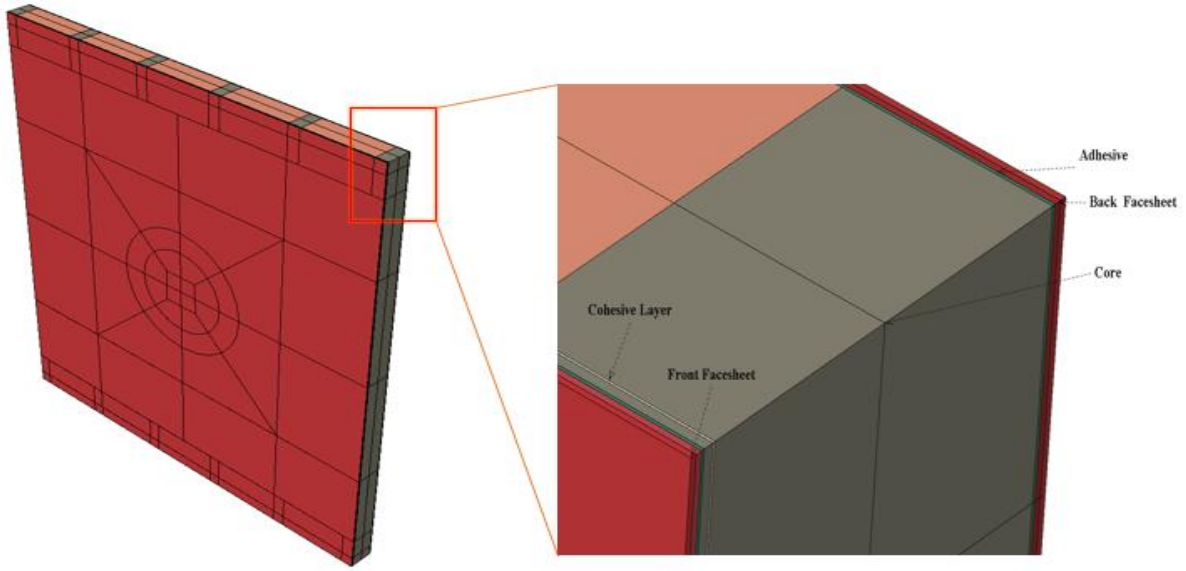


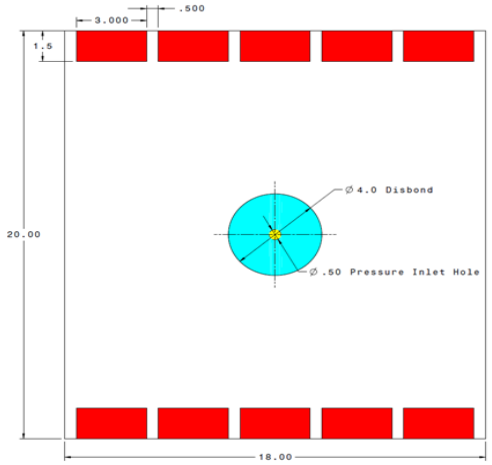
Outline – Moving Forward

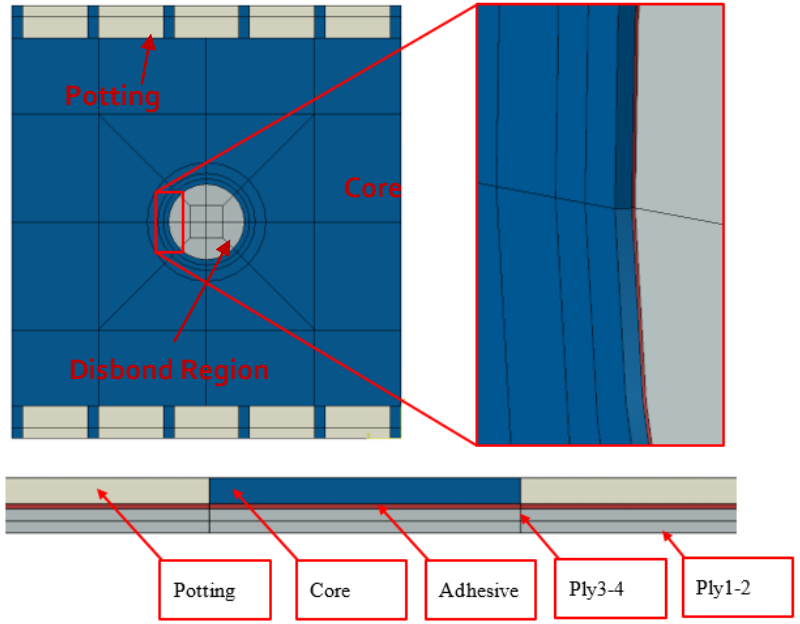
- SCB Test Configuration
  - Materials & Test Setup (translatable base)
- Foundation Model Approach & Validation
  - Comparison of Foundation, FE & Exp. Results
- Finite Element Model Description of SCB Specimens
  - Cohesive-based modeling approach
- GAG - Edgewise Compression (EWC) Test Configuration
  - Test Setup & Loading
  - Static and fatigue testing
- **Finite Element Model Description for GAG Specimens**
  - **Modeling approach**
  - **Comparison to test data**
- Summary & Future Work

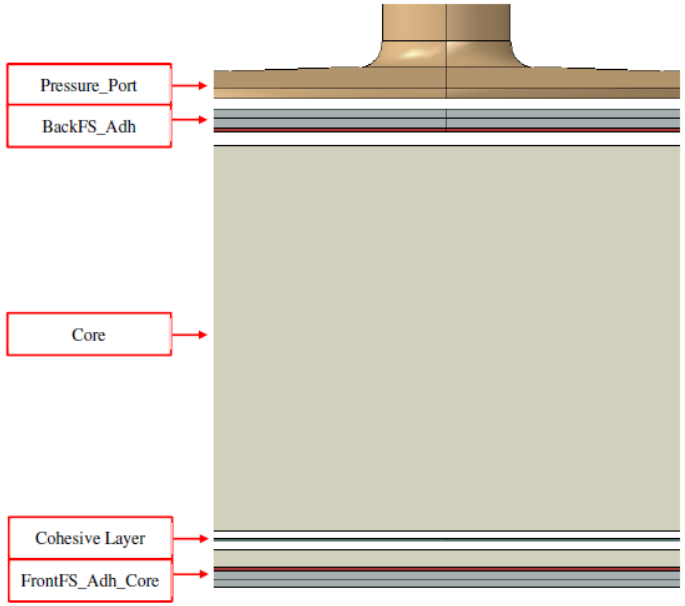
FEA – GAG (EWC) FE-Model Description and Approach

- Cohesive based FE analysis – combined static & pressure loading.
- Cohesive parameters from SCB analysis.
  - *G1c*, Penalty parameters (stiffness, K_n & strength, τ_n)
- Damage modeled in the core (similar to SCB specimens)





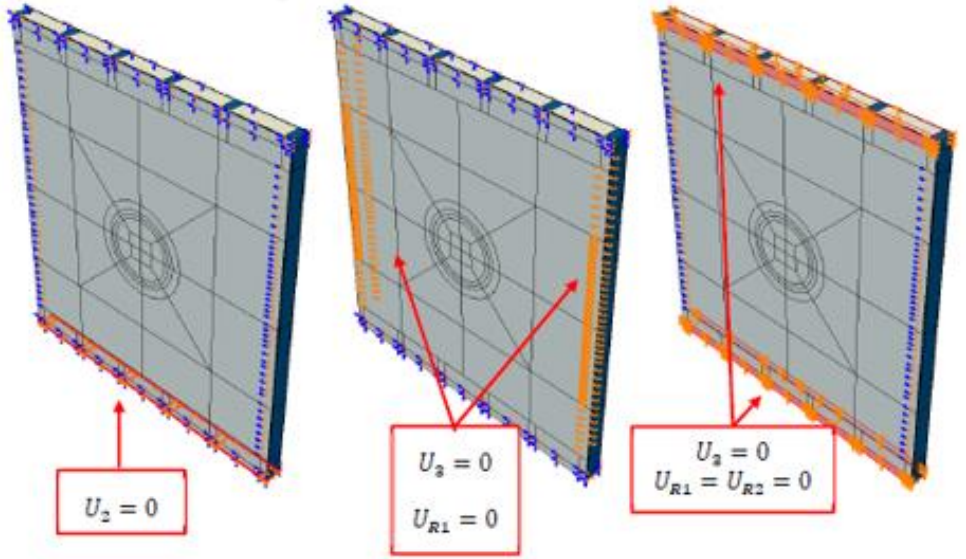




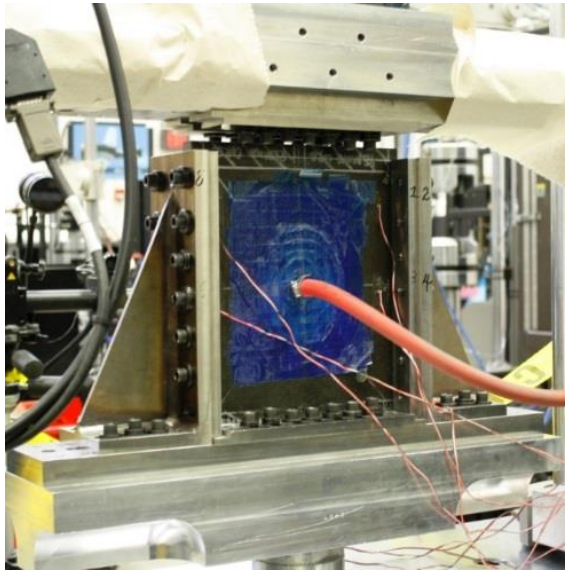
FEA – GAG (Model Description: Loading and Boundary Conditions)

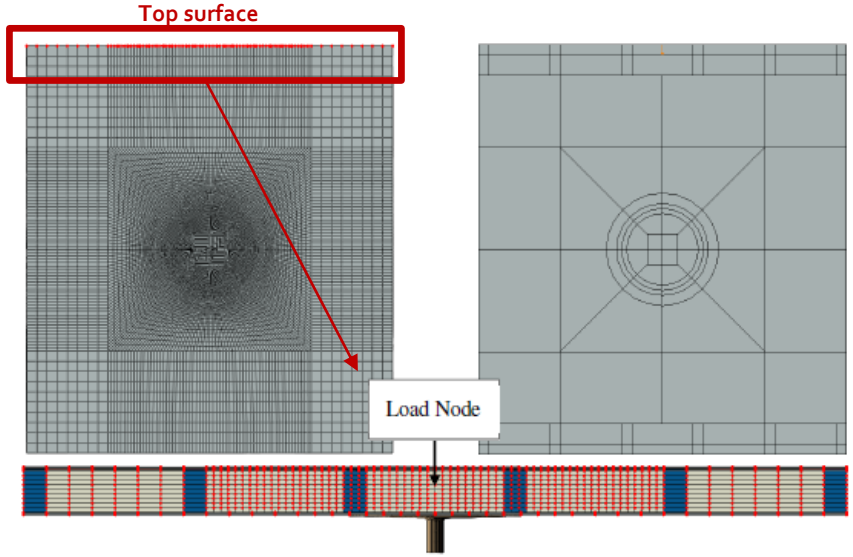
- Displacement applied at top surface
- Constant pressure (13.1 Psi) applied
- BCs applied on specimen edges to closely replicate the test setup

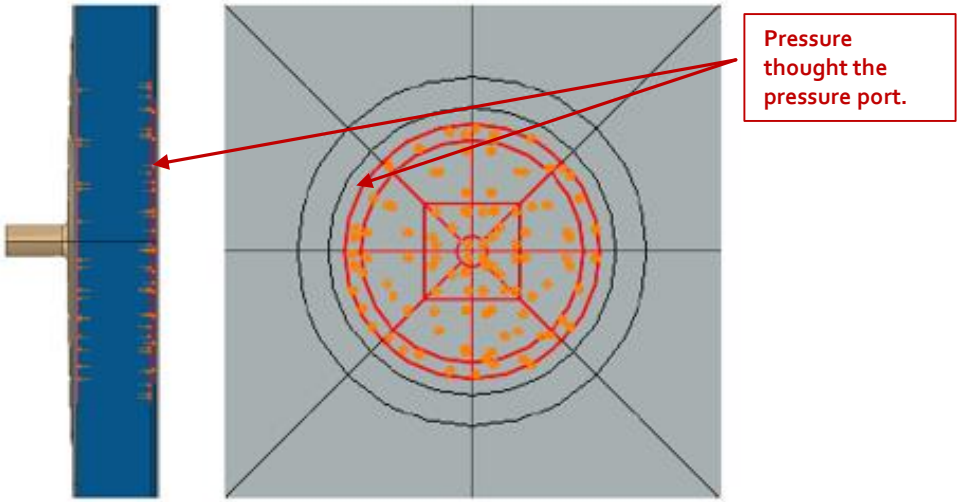
Boundary Conditions and Load Introduction



Test Setup



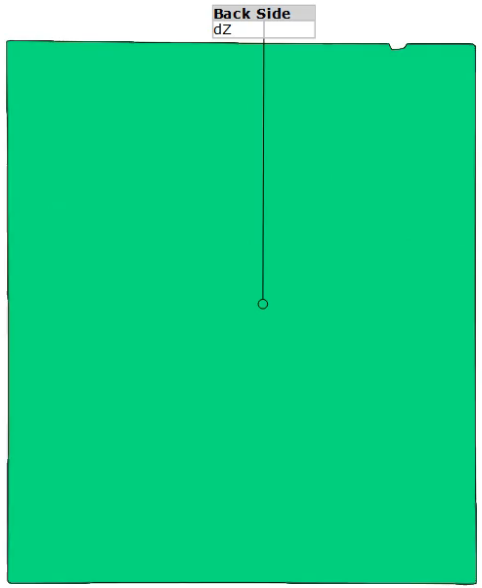


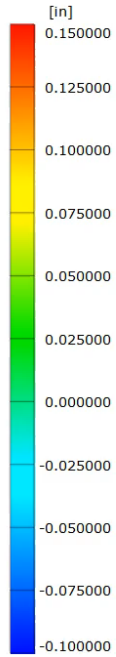


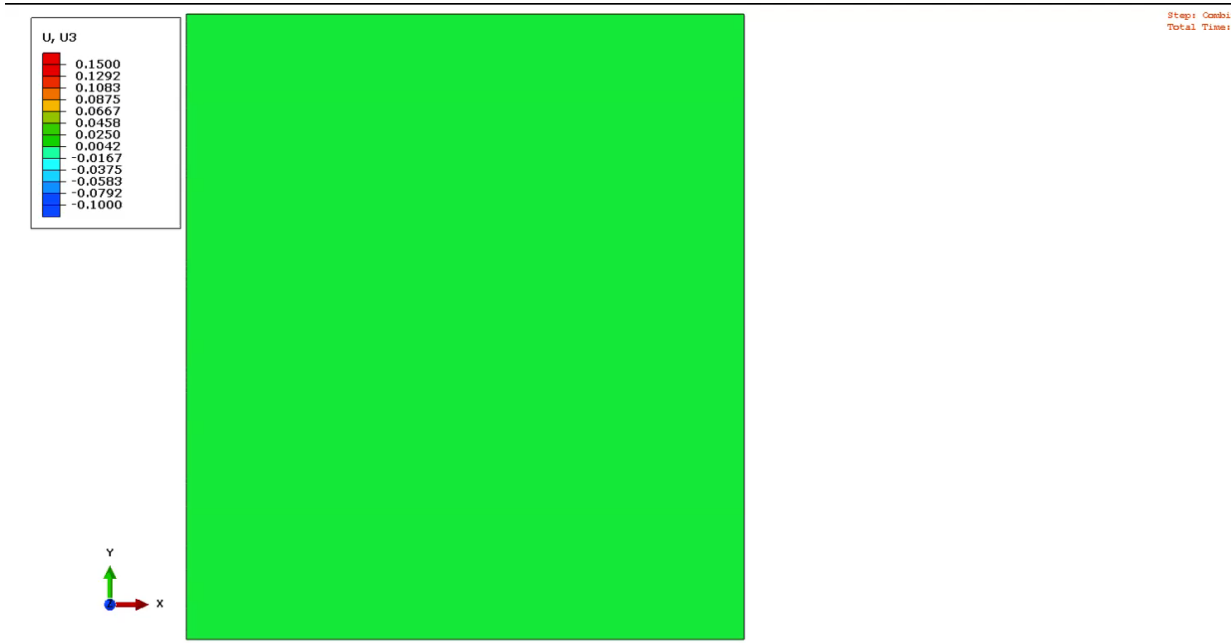
GAG Test Data Comparison Summary

- Out-of-plane displacement plots *(disp. inches, force in lbf)*
- Crack initiation monitored by deletion of Cohesive elements

8-ply facesheet; 0.5" core







GAG Test Data Comparison Summary

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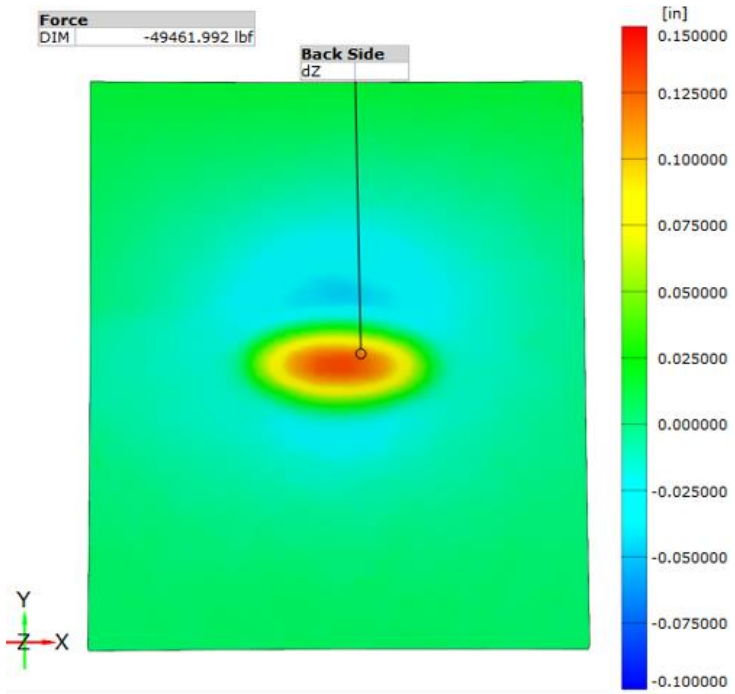
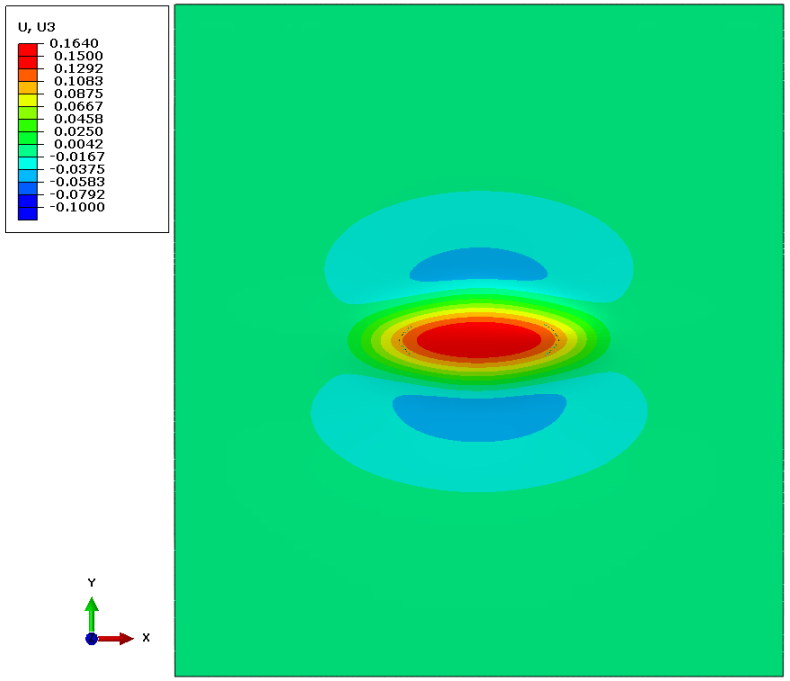
8-ply facesheet; 0.5" core

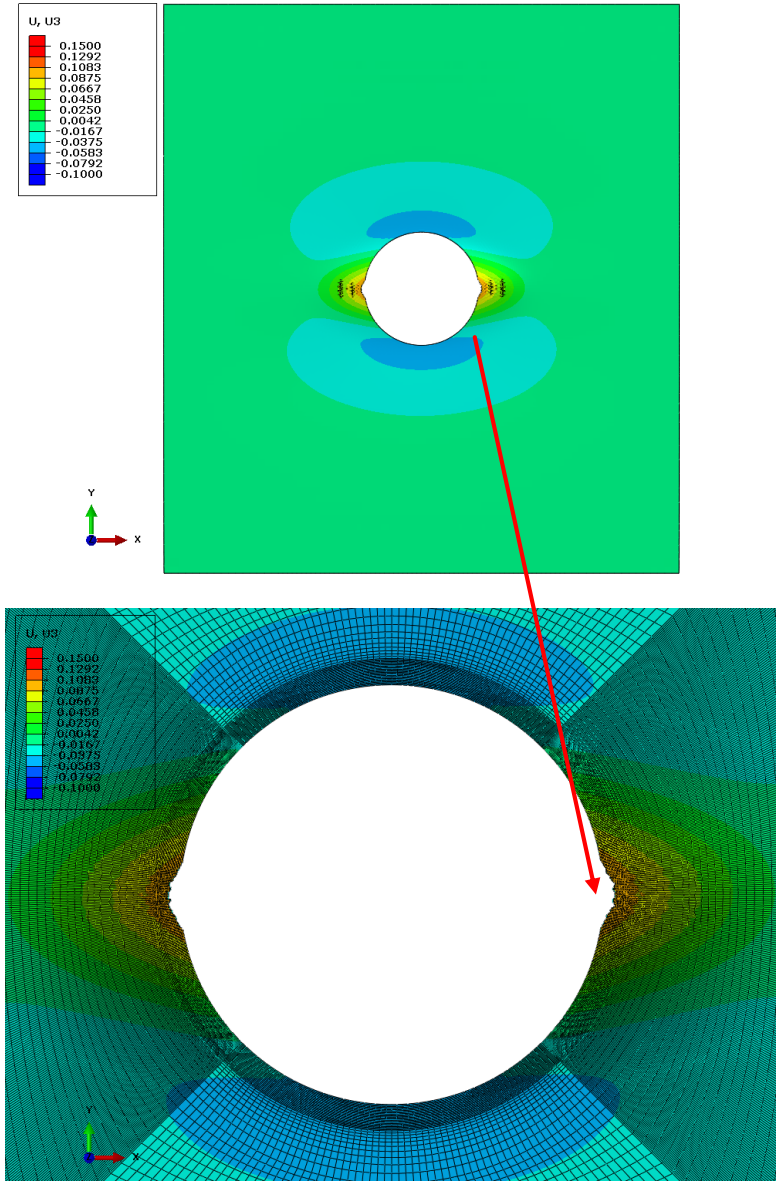
DIC



FEA



Cohesive elements



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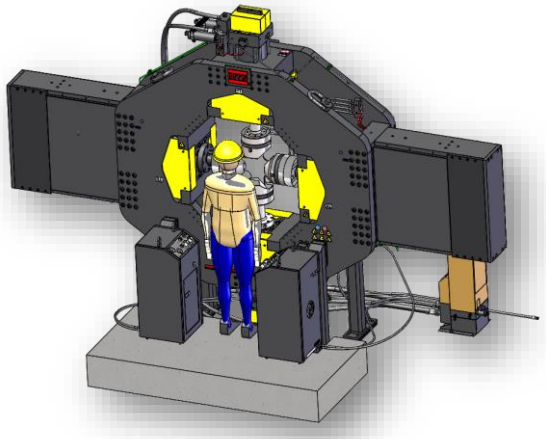
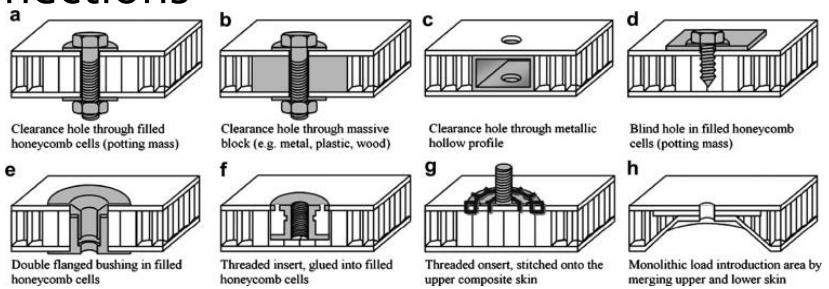
  - Modeling approach
  - Comparison to test data
- **Summary & Future Work**

Summary & Future Work

- An engineering approach to study debonding presented
  - SCB fracture tests on typical honeycomb core sandwich specimens validated & benchmarked against analytical expressions
  - A test setup capable of applying combined pressure and in-plane loading developed (GAG-cycle)
  - A cohesive zone based FE-model of GAG tests developed
    - FE-model over-predicted for the thicker core; thinner core prediction within the range 3-18%
  - The current approach could be expanded to study attachments/connections





Transport Category Approach

General Aviation Approach

CECAM center of excellence for composites and advanced materials

JAMS Joint Advanced Materials & Structures Center of Excellence

AMTAS Advanced Materials in Transport Aircraft Structures

Thank You

References

1. Tomblin JS, Seneviratne W, Denning S. *Mode I (G1c) Fracture Toughness of Composite Sandwich Structures for Use in Damage Tolerance Design and Analysis : Vol . I Static Testing Including Effects of Fluid Ingression DOT/FAA/TC-16/23*. New Jersey, 2017. DOT/FAA/TC-16/23

2. Tomblin JS, Seneviratne W, Denning S. Fatigue Damage Growth Rate of Sandwich Structures DOT/FAA/TC-17/6. New Jersey, 2018

3. Tomblin JS, Seneviratne W, Denning S. Damage Growth in Sandwich Structures: Supplement to Volume I Testing DOT/FAA/TC-17/7. New Jersey, 2018.

4. Ratcliffe JG, Reeder JR. Sizing a single cantilever beam specimen for characterizing facesheet-core debonding in sandwich structure. J Compos Mater 2011; 45: 2669–2684.

5. Gibson LJ, Ashby MF. Cellular Solids: Structure and Properties. Cambridge University Press, 1999

6. El-Sayed, S., & Sridharan, S. (2002). Cohesive layer models for predicting delamination growth and crack kinking in sandwich structures. International Journal of Fracture, 117(1), 63-84.

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