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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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May 22-23, 2019

CMH-17
COMPOSITE MATERIALS HANDBOOK

FEDERAL AVIATION ADMINISTRATION

NIAR
Wichita State University
National Institute for Aviation Research

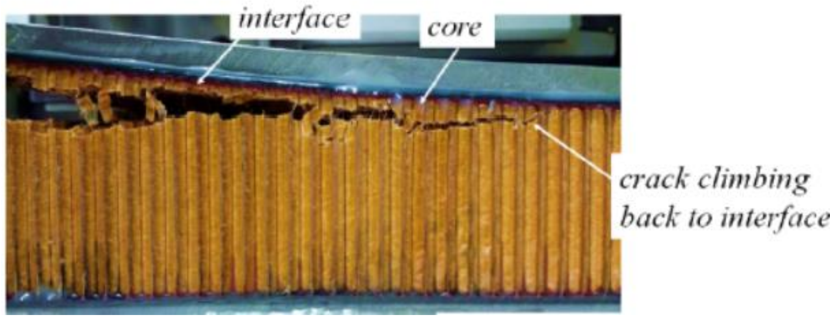
Research Team

- **National Institute for Aviation Research**
  - PI: Waruna Seneviratne, PhD
  - PI: John Tomblin, PhD
  - Shenal Perera
  - Pirashandan Varatharaj
  - Vishnu Saseendran, PhD
- **FAA**
  - Zhi-Ming Chen, PhD (Current TM)
  - 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

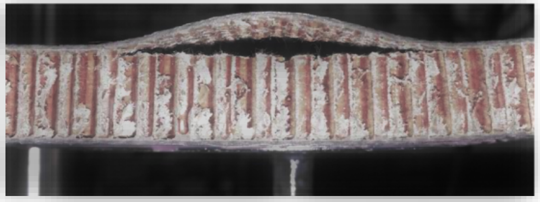
- **Motivation and Key Issues**
  - Thermo-mechanical loads during ground-air-ground (GAG) cycling result in localized mode I stresses that cause further delamination/disbond/core fracture growth.
- **Objective**
  - Develop an engineering approach for damage tolerance analysis of sandwich structures 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



Accomplishments

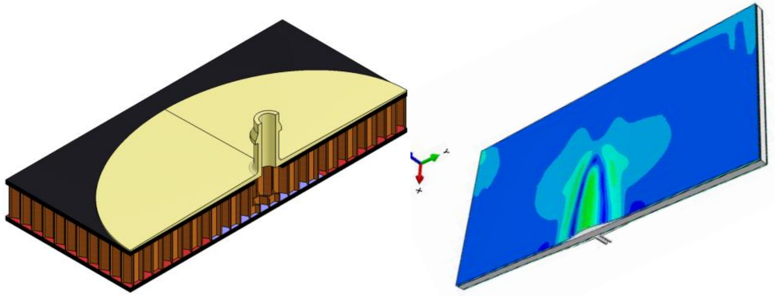
Mode I (G1c) Fracture Toughness of Composite Sandwich Structures for Use in Damage Tolerance Design and Analysis

- 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)***



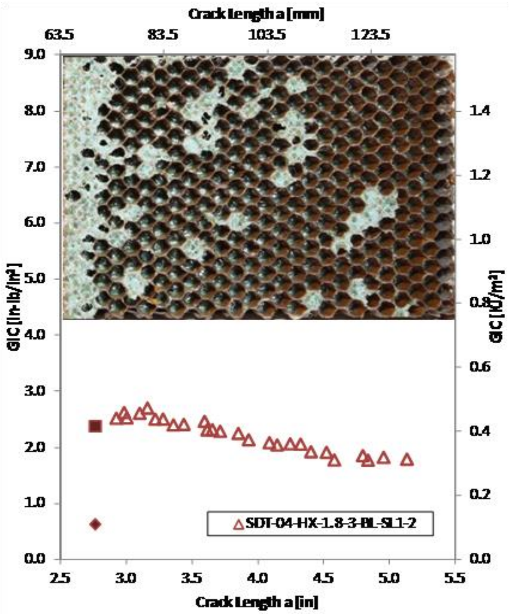
Other Contributions to ASTM D30 & CMH-17

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



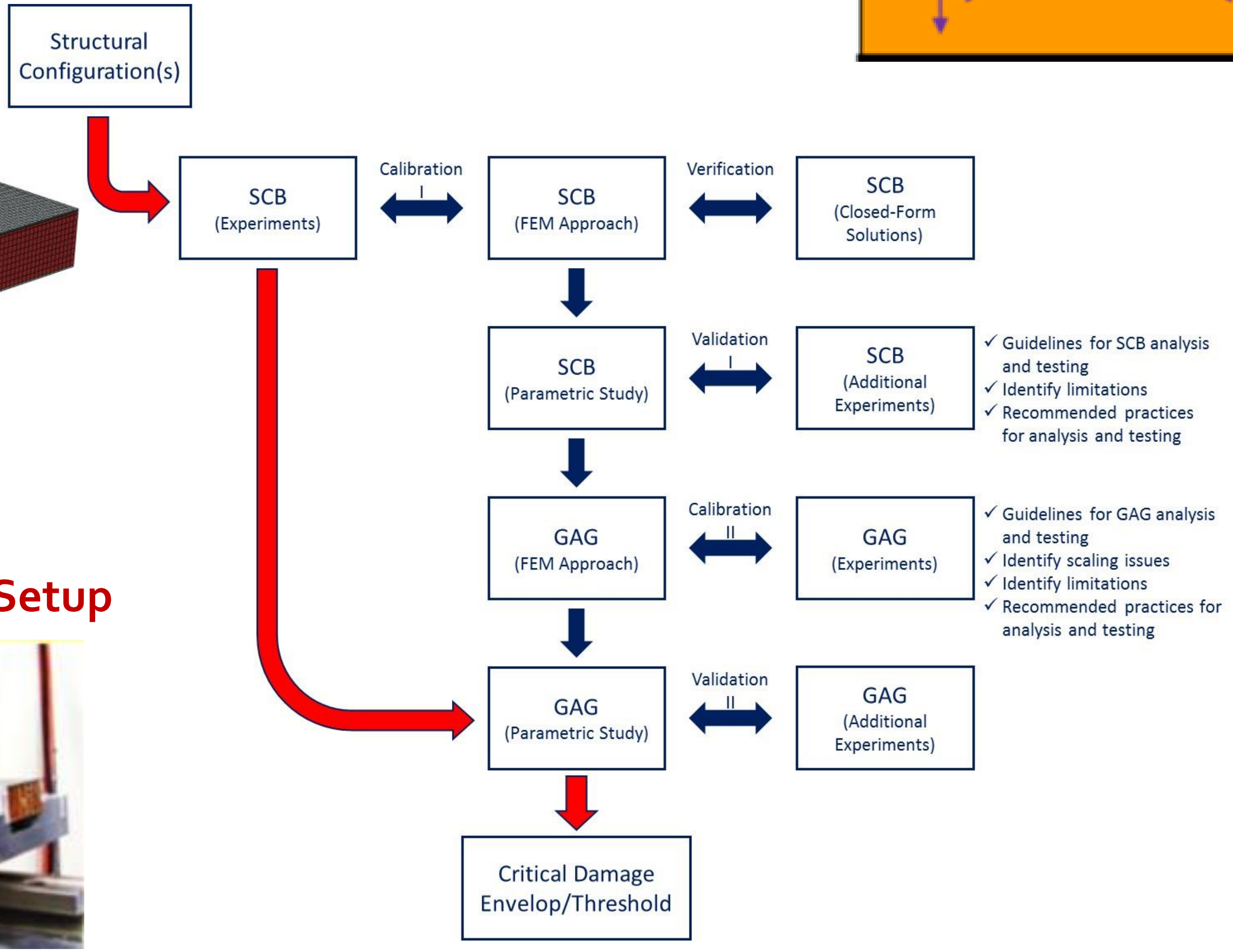
Other Publications

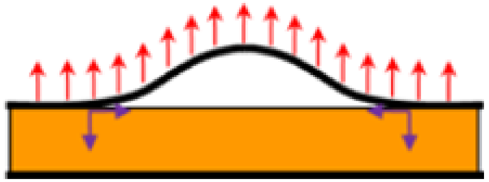
- Damage Initiation and Fracture Analysis of Honeycomb Core Single Cantilever Beam (SCB) Sandwich Specimen *(submitted to JSSM)*
- Damage Growth Analysis of Sandwich Structures Subjected to Combined Compression and Pressure Loading *(Accepted for ASC 34th Technical Conference)*



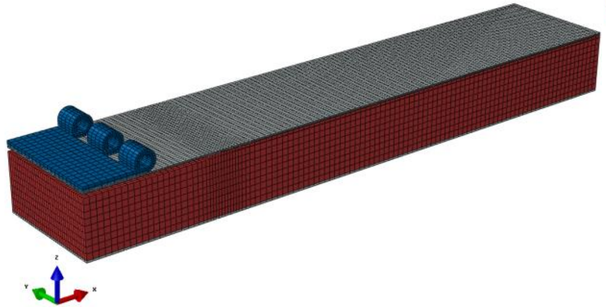
Analysis – Engineering Approach

- SCB ➔ GAG



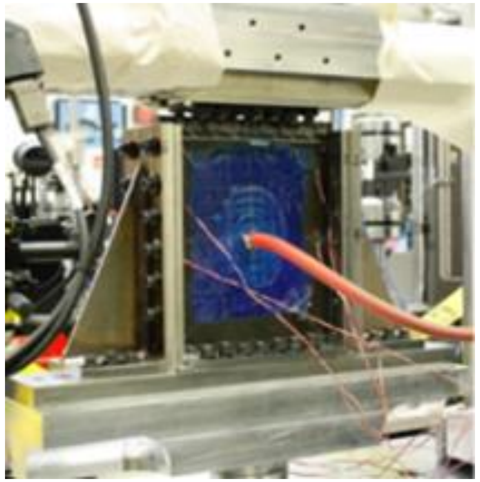


SCB FE Model

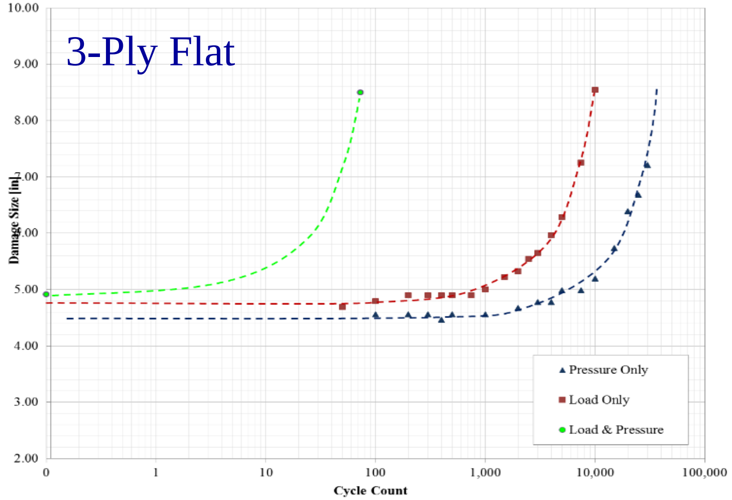


SCB Experimental Setup

GAG Experimental Setup



GAG Loading Cycles



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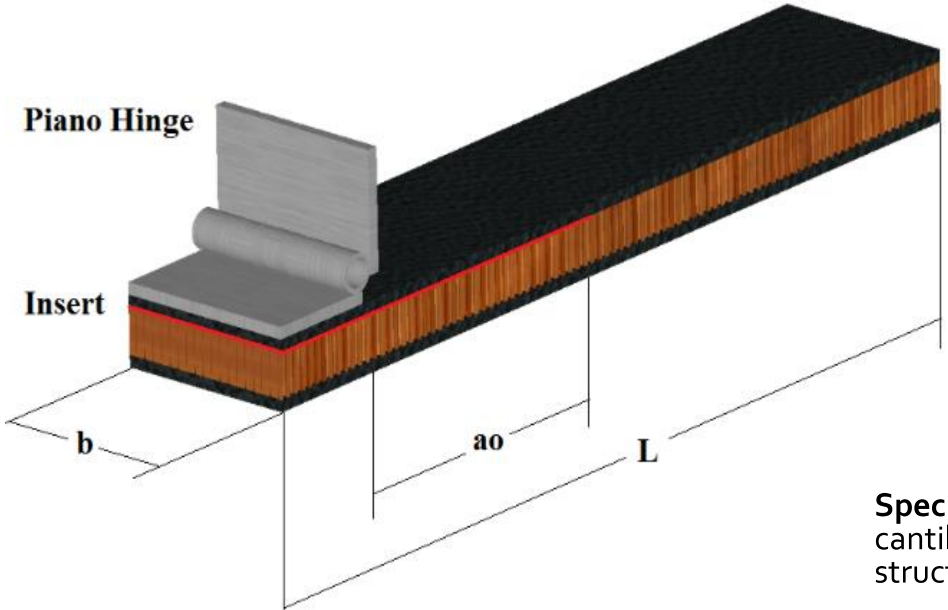
Outline

- **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_o = 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
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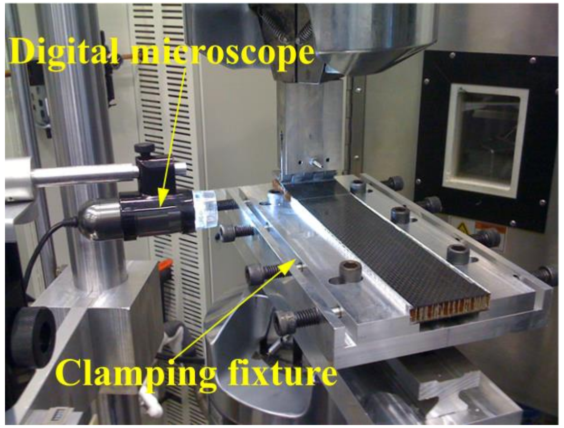

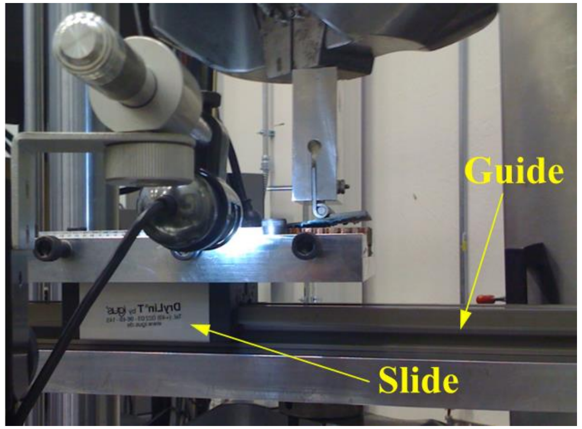

Specimen sizing conforms w/t: Ratcliffe, James G., and James R. Reeder. "Sizing a single cantilever beam specimen for characterizing facesheet–core debonding in sandwich structure." *Journal of Composite Materials* 45.25 (2011): 2669-2684.

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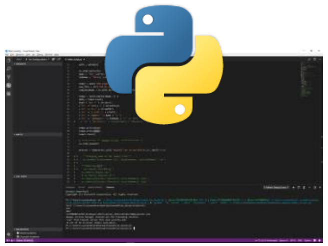
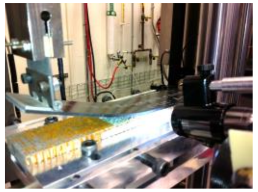
Foundation Model Approach & Validation

Python Based Suite

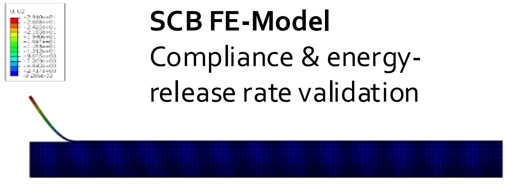
Python Suite



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

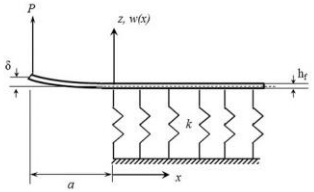


SCB FE-Model
Compliance & energy-release rate validation



Core properties:
Gibson-Ashby model

Foundation model
Compliance & energy-release rate validation



Closed – Form Expressions

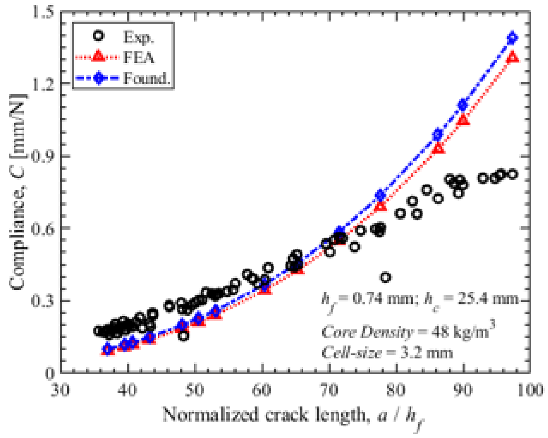
$$C = \frac{\delta(x=-a)}{P} = \frac{4\lambda}{k}\left[\frac{\lambda^3 a^3}{3} + \lambda^2 a^2 + \lambda a + \frac{1}{2}\right]$$

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

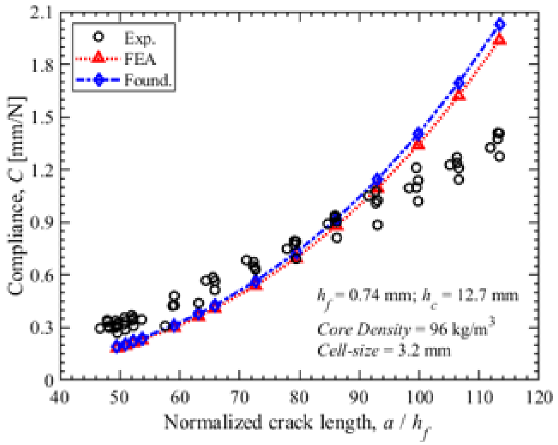
$$\lambda = \sqrt[4]{\frac{k}{4E_f I}} \qquad k = \frac{E_c b}{h_c/4}$$

Winkler-based foundation model

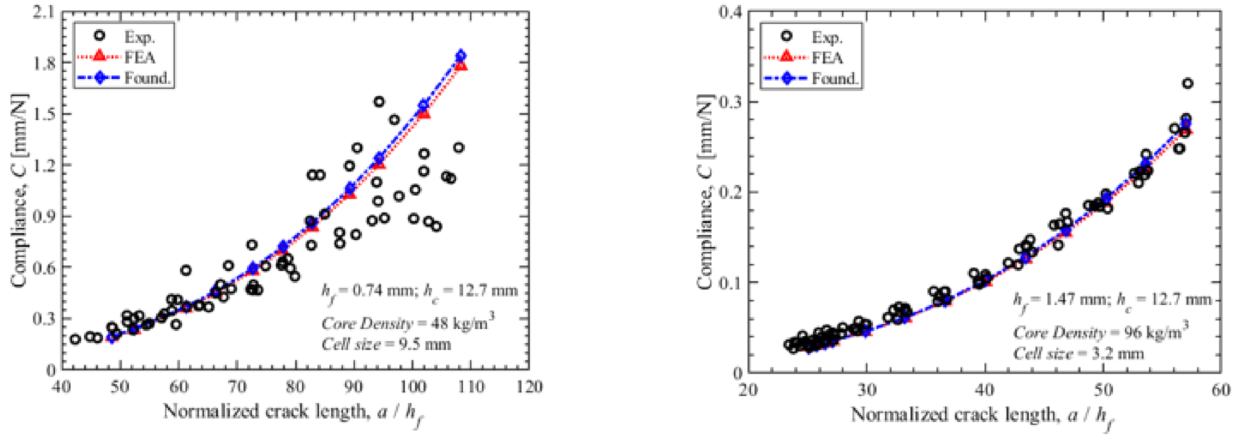
Compliance vs. crack length



(a)



(b)



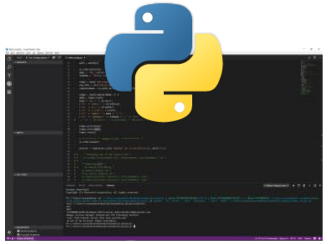
(c)

(d)

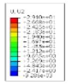
Foundation Model Approach & Validation

Python Based Suite

Python Suite



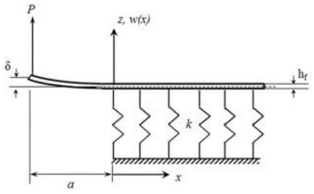
SCB Fracture Tests
Compliance, C = δ/P
crack length, a
Initiation fracture toughnss:
Modified Beam Theory (MBT)



SCB FE-Model
Compliance & energy-release rate validation

Core properties:
Gibson-Ashby model

Foundation model
Compliance & energy-release rate validation



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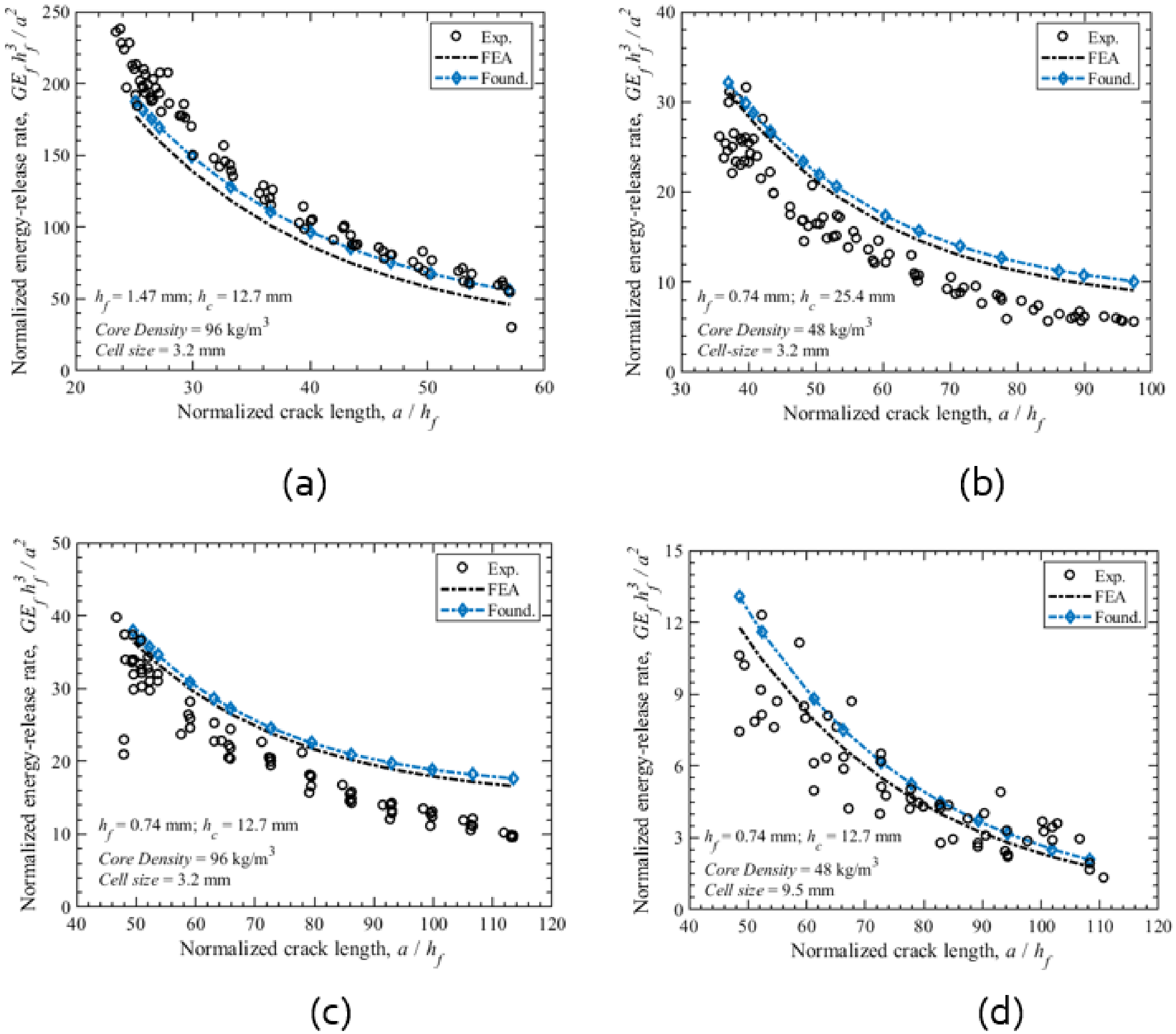
$$G = \frac{2P^2\lambda^2}{bk}\left[\lambda^2 a^2 + 2\lambda a + 1\right]$$

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

Winkler-based foundation model

Energy-release rate vs. crack length



(a) (b)

(c) (d)

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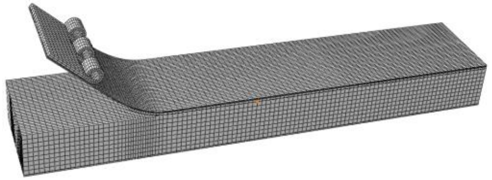
FEA – SCB Model Description and Approach

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/m3) & 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)

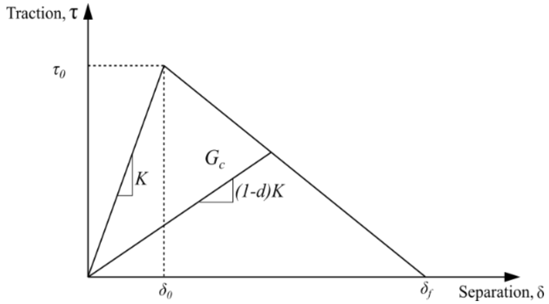


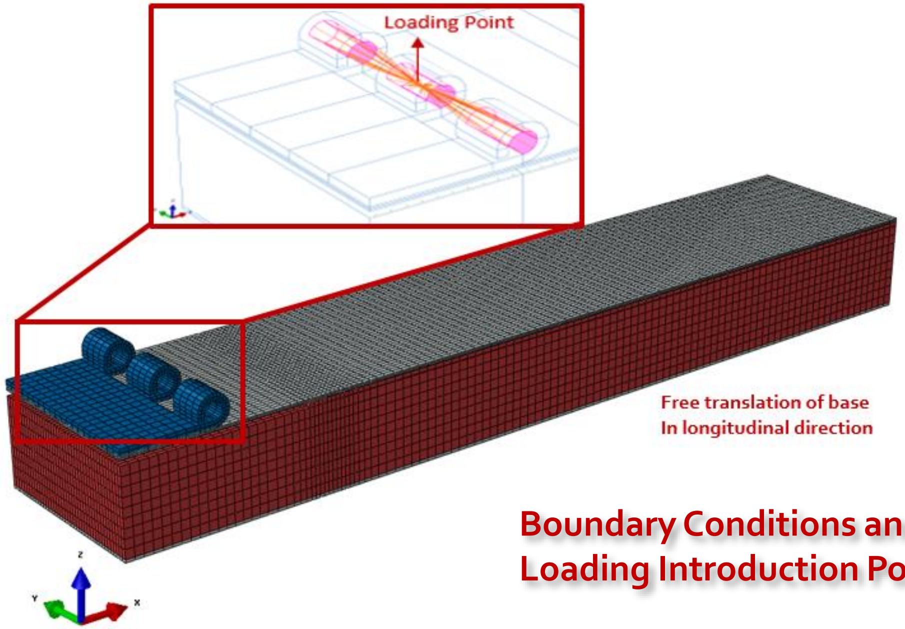
Core - Homogenous medium

(Gibson-Ashby Approach)

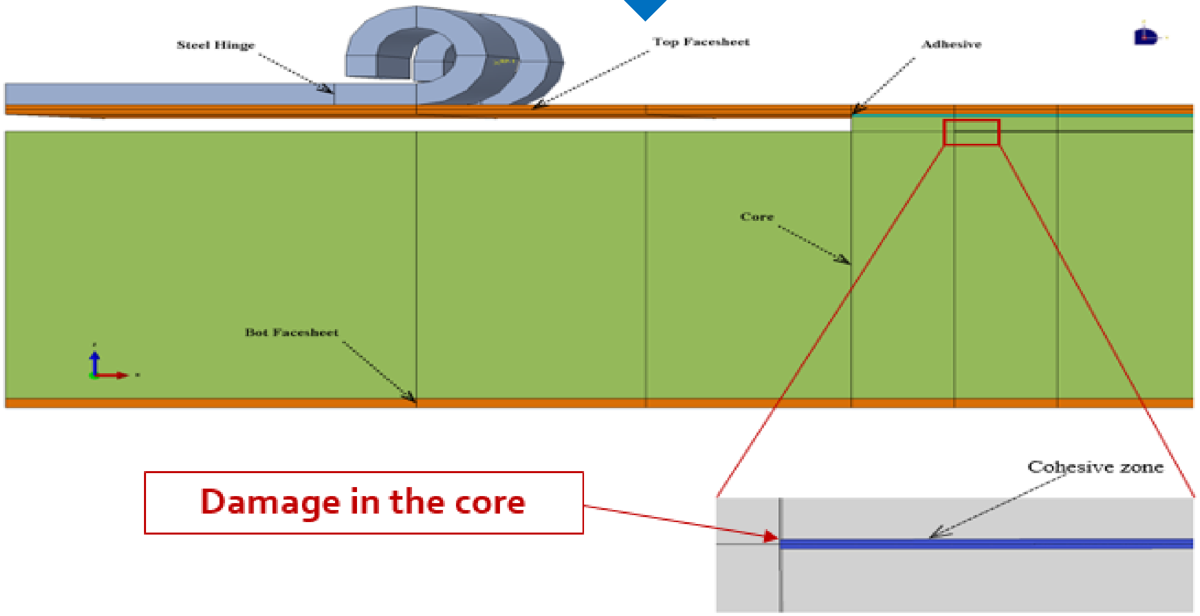
G1c

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



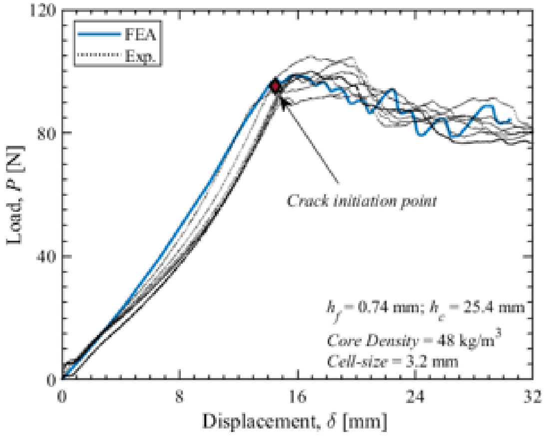


Boundary Conditions and Loading Introduction Point

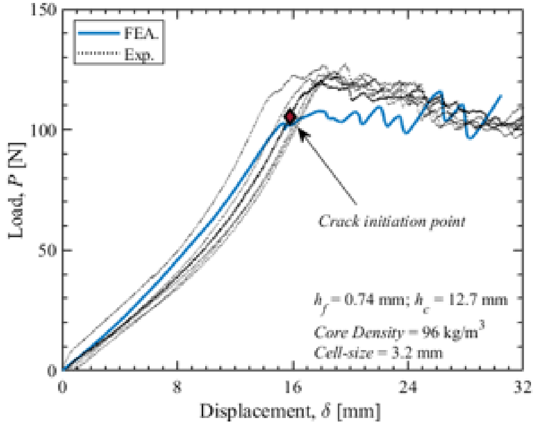


Damage in the core

Comparison of FE & Exp. Results



(a)



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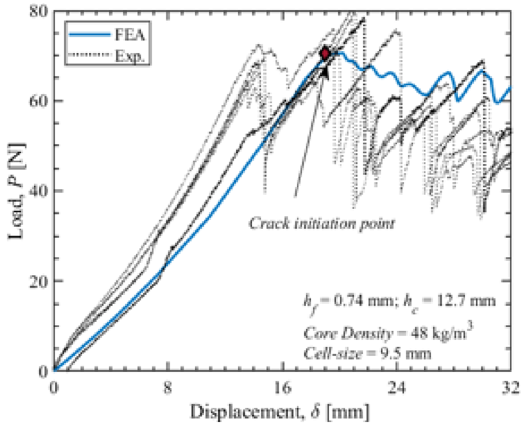
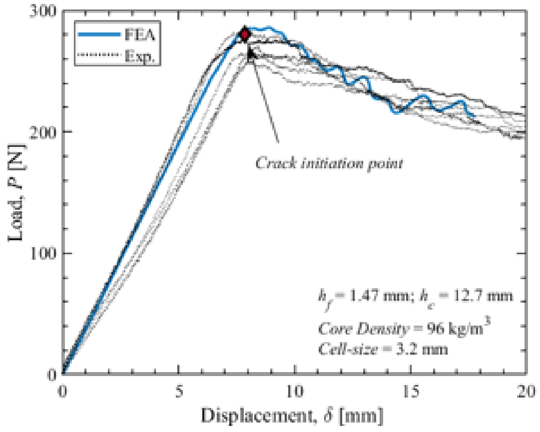
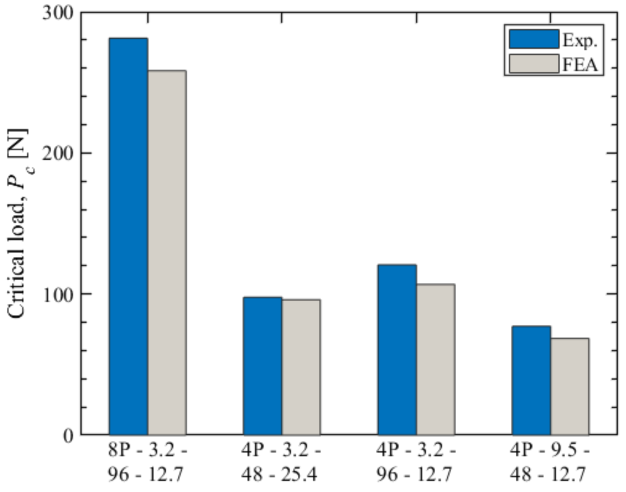


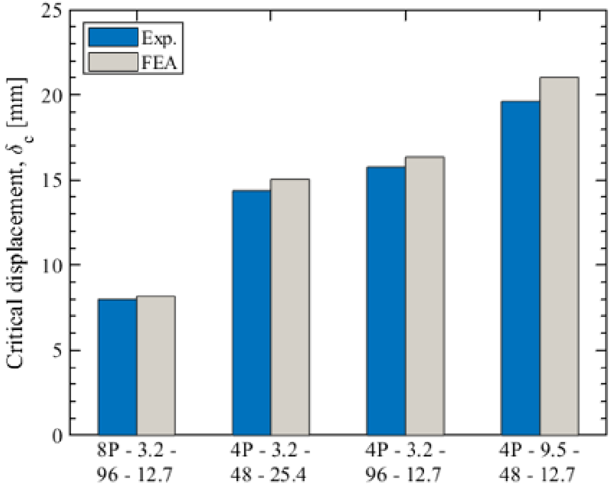
(c)



(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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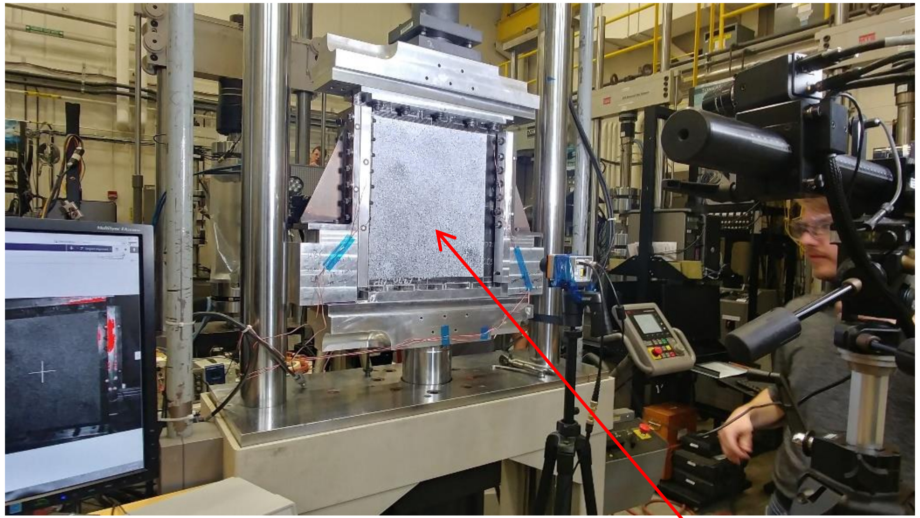
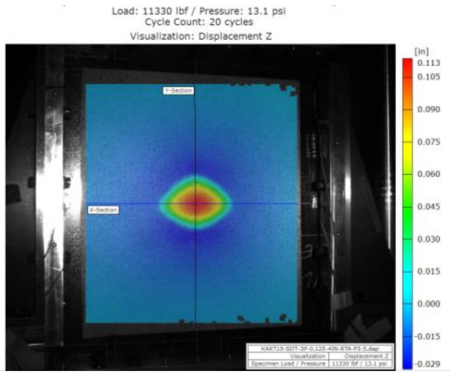
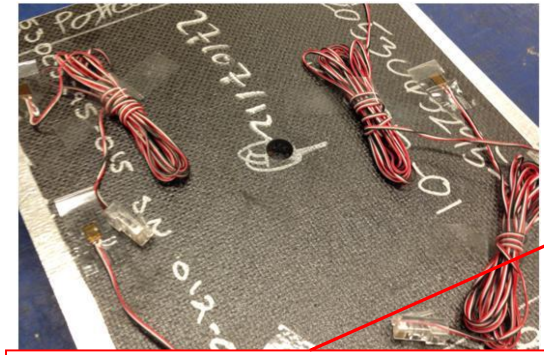
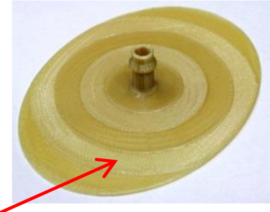
GAG - Edgewise Compression (EWC) Test Setup





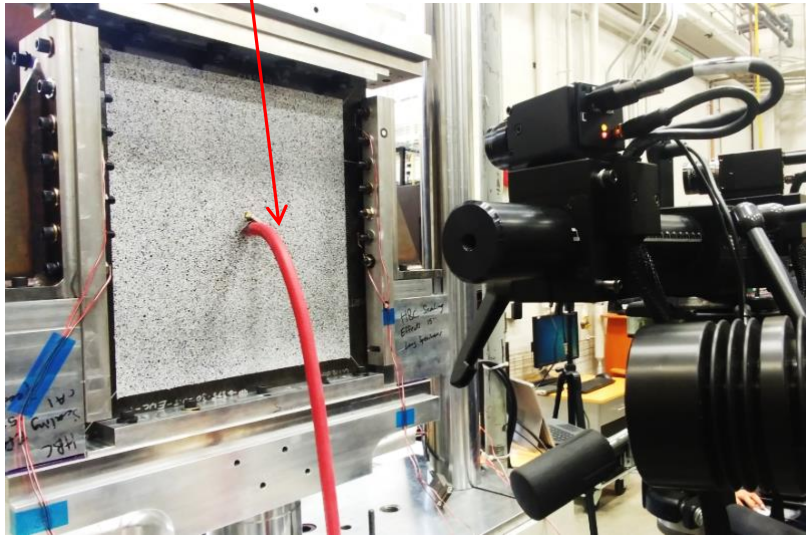
DIC speckle pattern on front and back sides





Hysol EA9309.3NA Epoxy

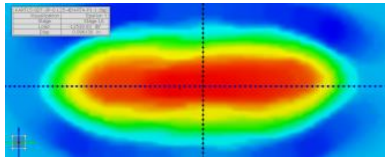
3D printed (Ultem) pressure port



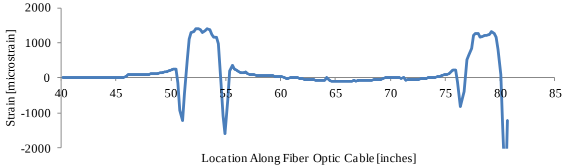
Ability to accommodate various specimen sizes

•10x12 (shown) and 18x20 (test size)

Damage Growth monitoring

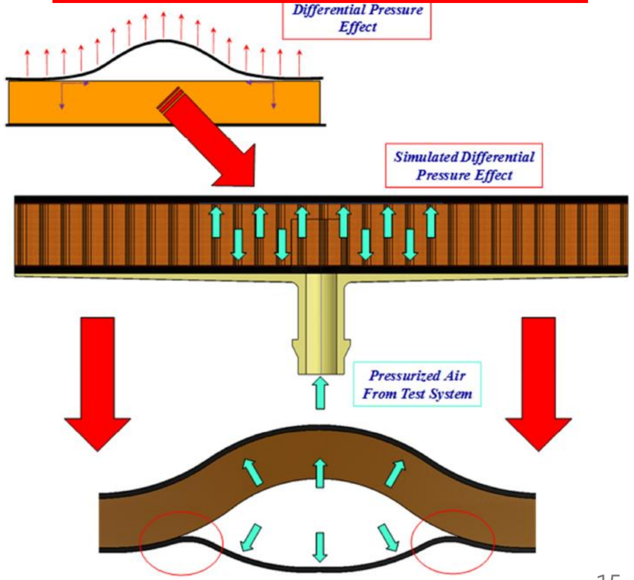


Digital Image Correlation (DIC)



Distributed fiber optic strain sensors

Pressure Simulation



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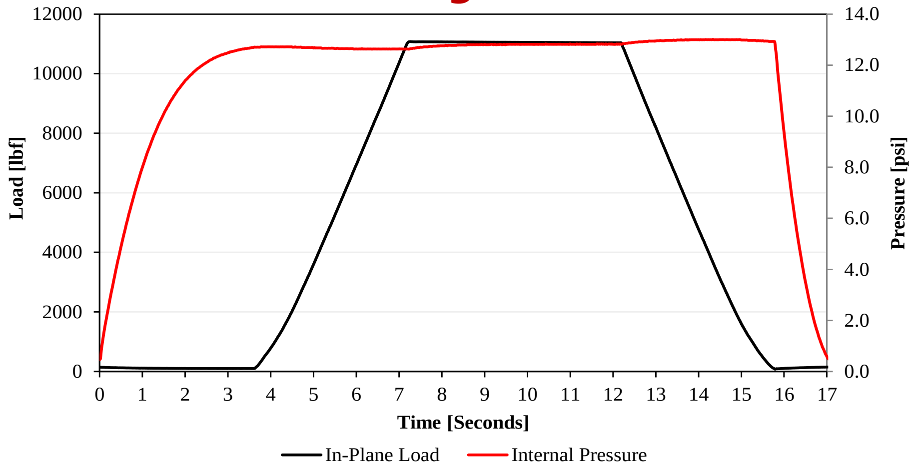
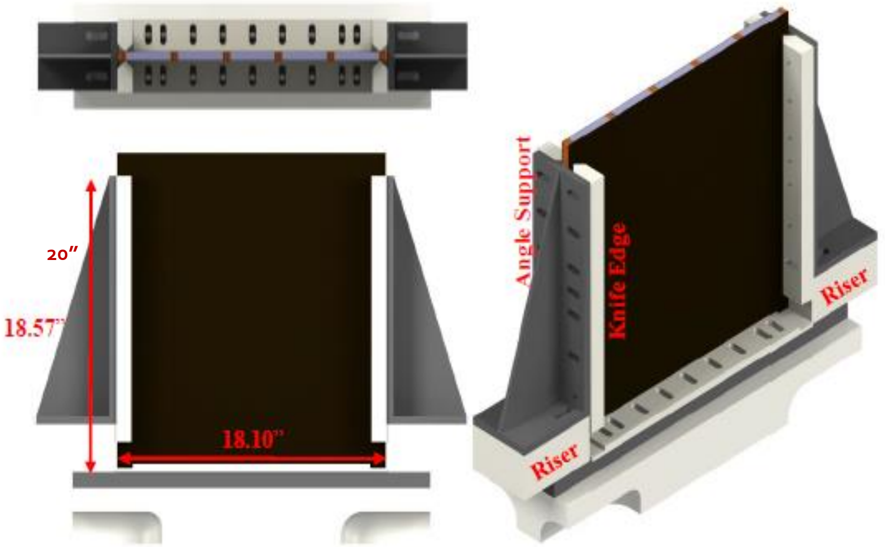
GAG (EWC) Quasi Static Testing w/t Pressure Loading

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

Loading Condition





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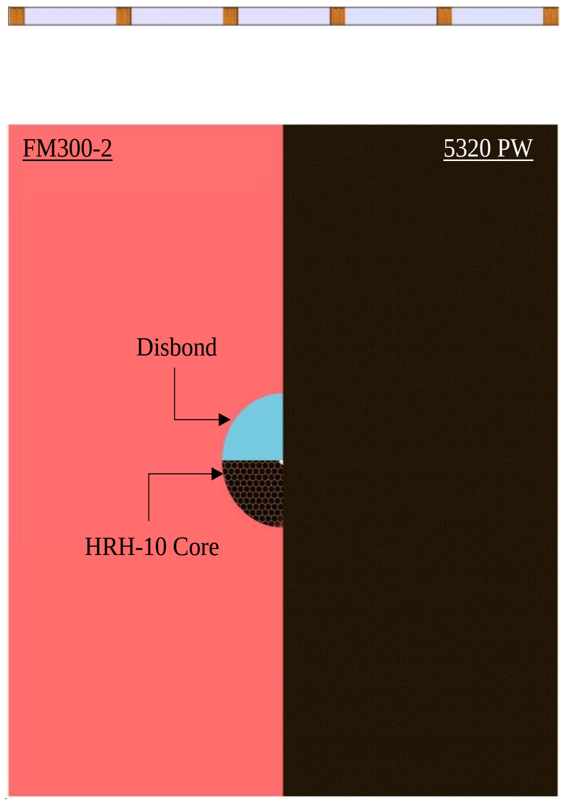
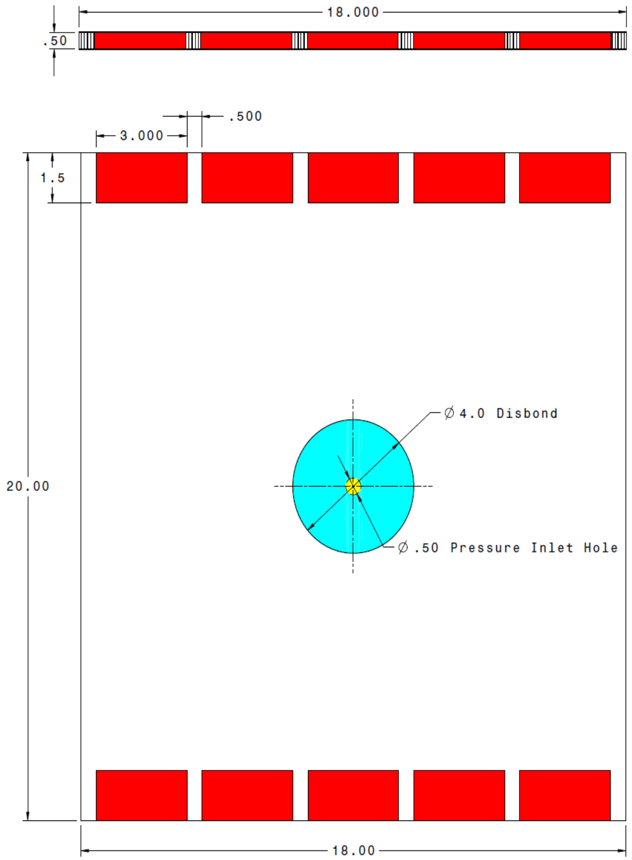
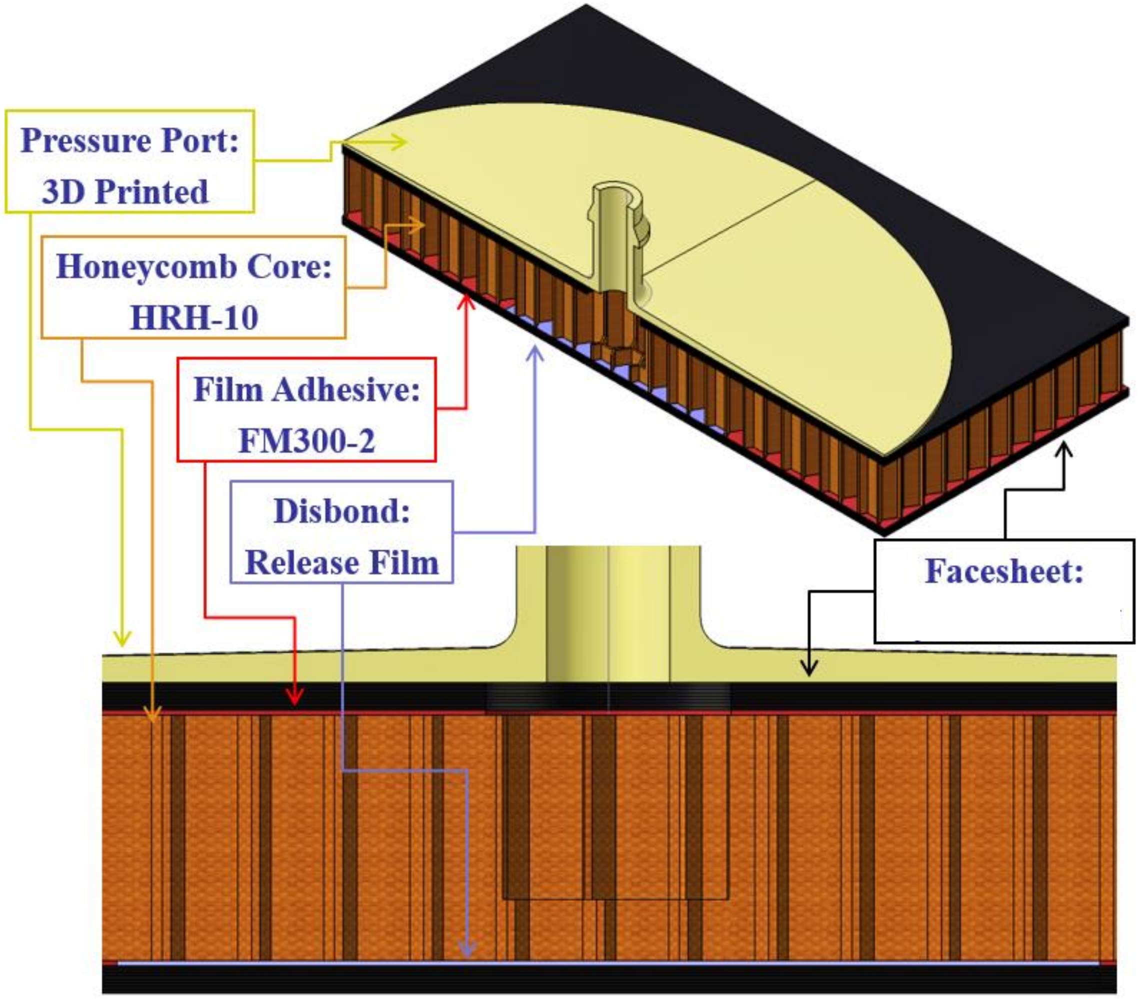
GAG - Edgewise Compression (EWC) Specimen Configuration







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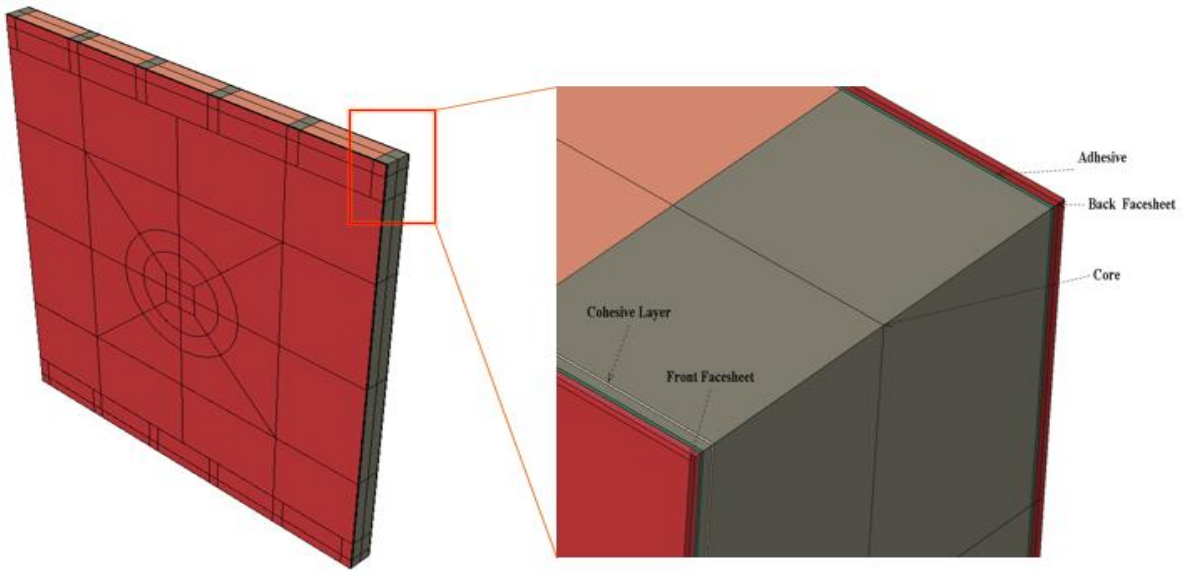
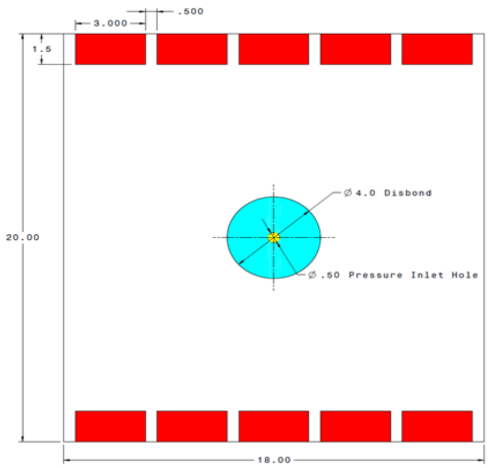
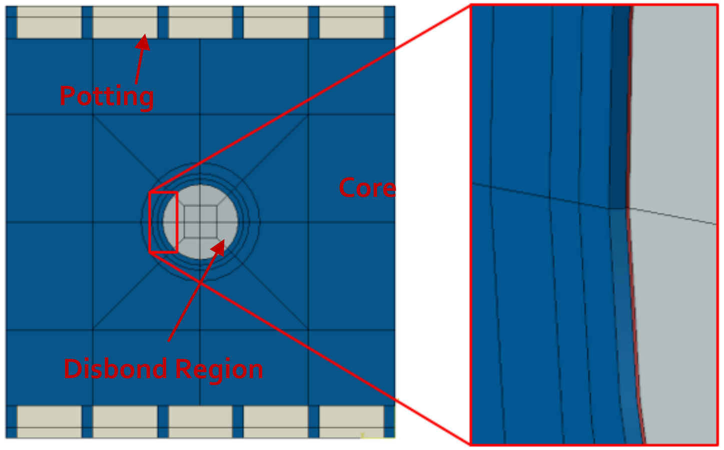
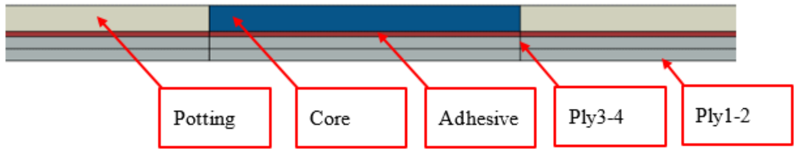
FEA – GAG (EWC) FE-Model Description and Approach

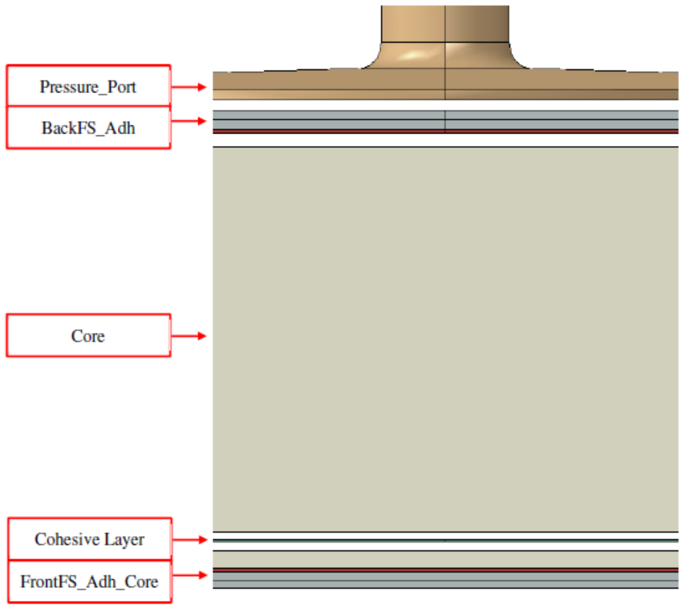
- Cohesive based FE analysis – combined static & pressure loading.
- Cohesive parameters from SCB analysis.
  - *G1c*, Penalty parameters (stiffness, K_n & strength, τ_n)
- Damage modeled in the core (similar to SCB specimens)







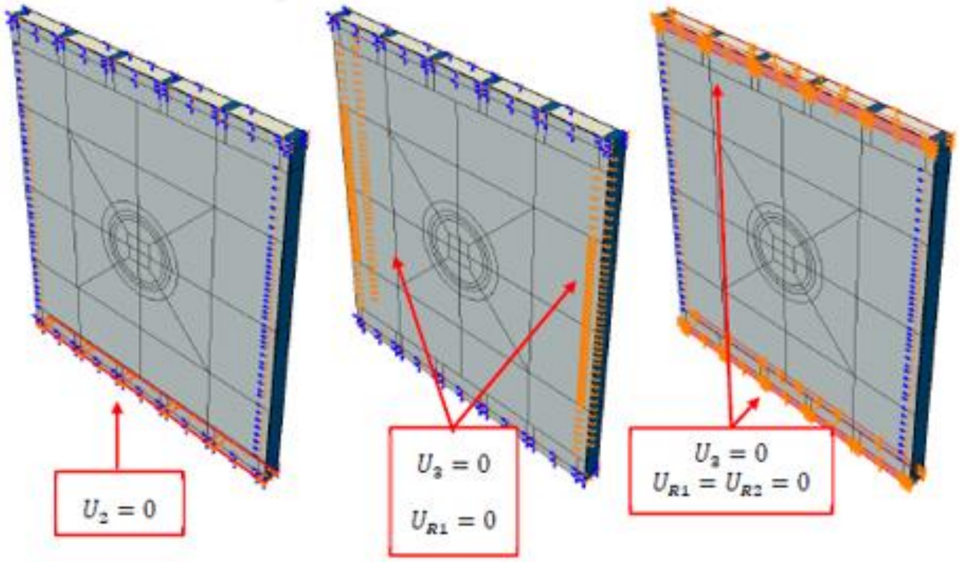




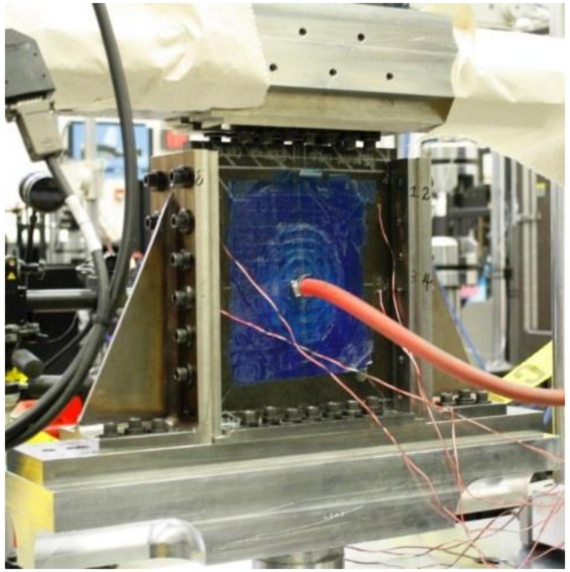
FEA – GAG (Model Description: Loading and Boundary Conditions)

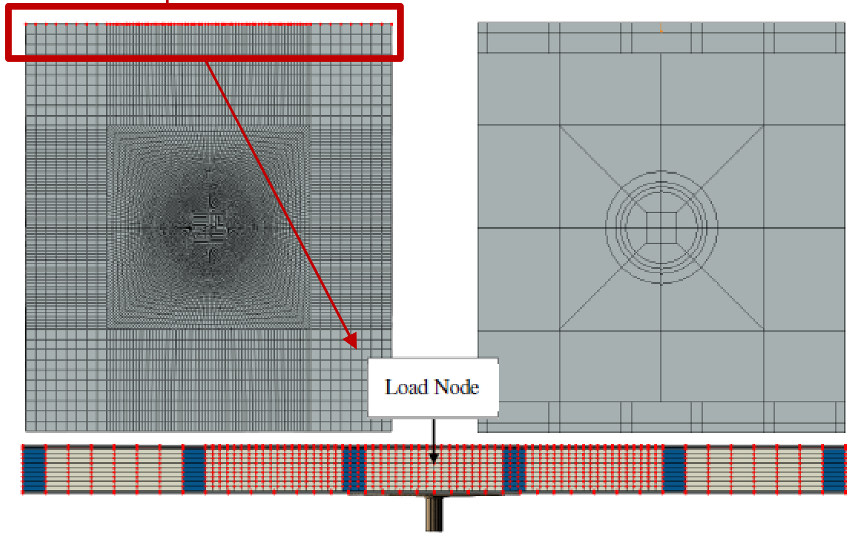
- Displacement applied at top surface
- Constant pressure (13.1 Psi) applied
- BCs applied on specimen edges to closely replicate the test setup

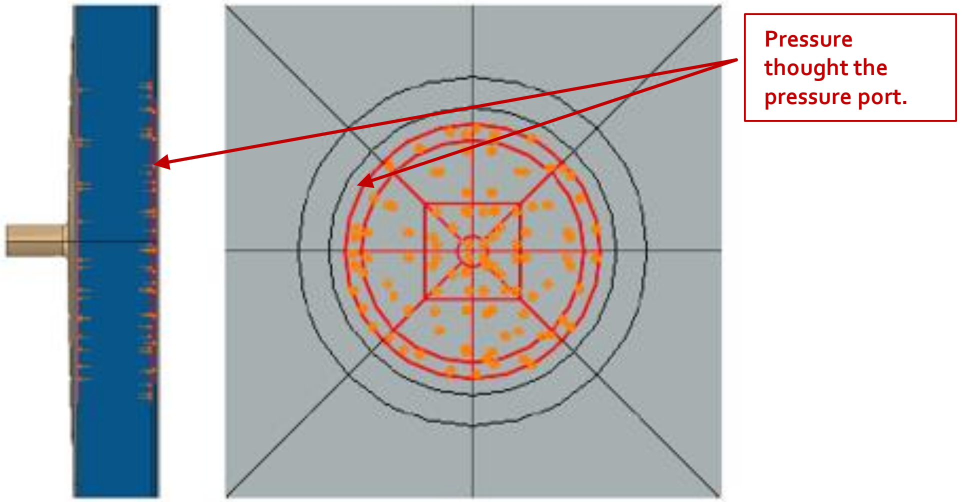
Boundary Conditions and Load Introduction



Test Setup







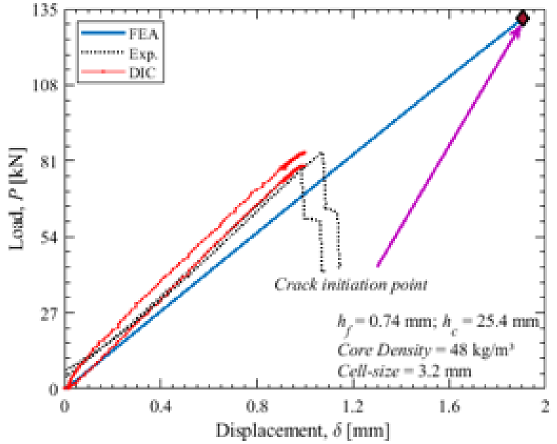
GAG Test Data Comparison Summary

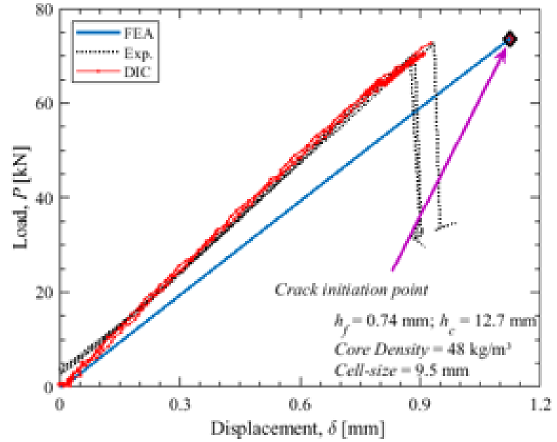
Initial predictions

Case	Facesheet Material	Plies	Cell Size (mm)	Core Density (kg/m³)	Core Thickness (mm)	Exp. Load (kN)	Predicted Crack Initiation Load	
							FEA Load (kN)	Error (%)
1	T650/5320-PW	4	3.2	48.0	25.4	81.8	131.6	60.9
2	T650/5320-PW	4	3.2	96.0	12.7	99.3	118	18.6
3	T650/5320-PW	4	9.5	48.0	12.7	70.9	73.7	3.9
4	T650/5320-PW	8	3.2	96.0	12.7	215.7	248.9	15.4

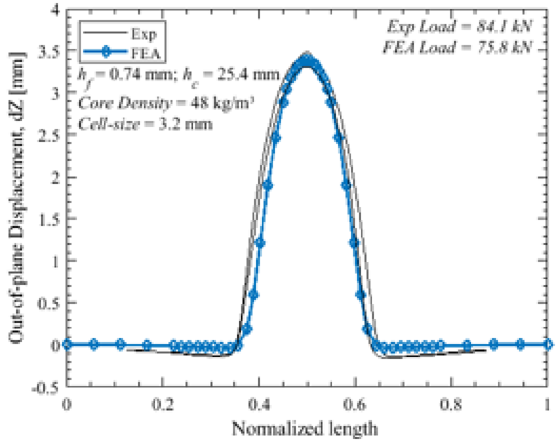
GAG Test Data Comparison Summary

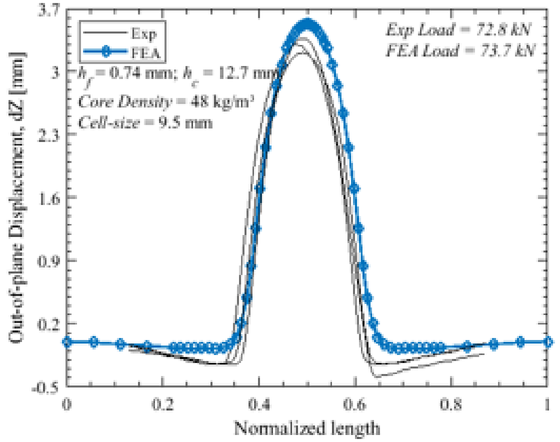
Load Vs Displacement



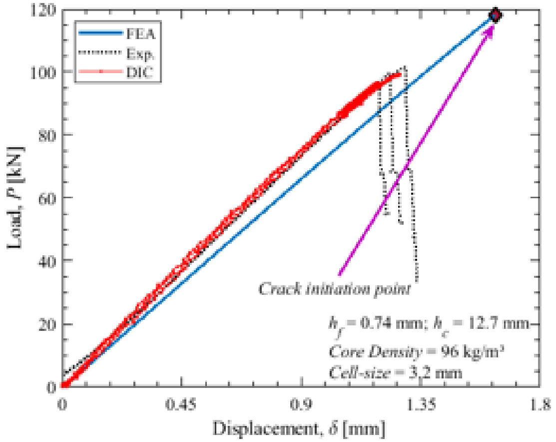


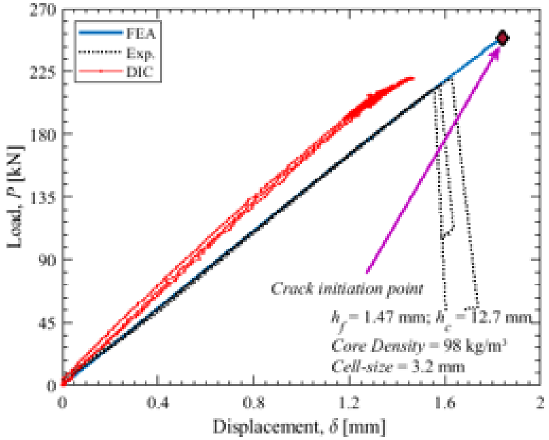
Out of plane Displacement



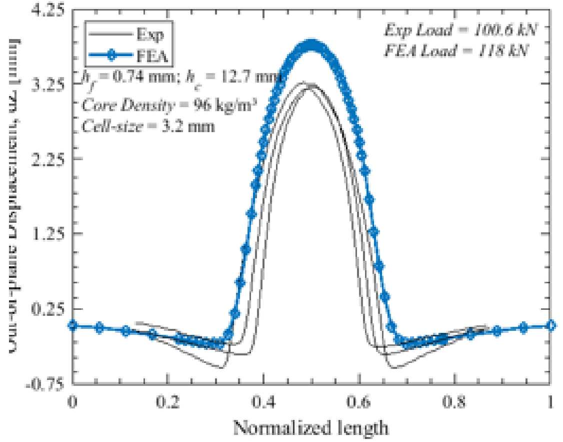


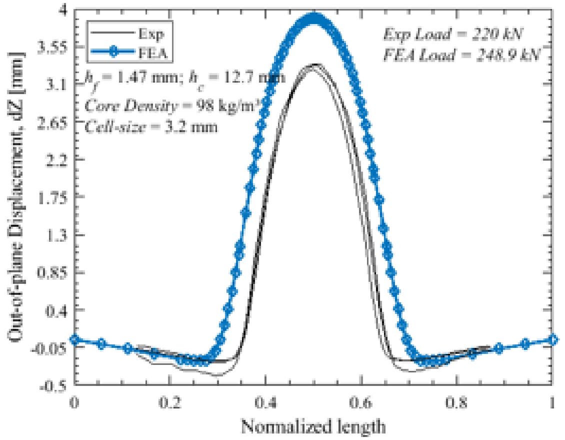
Load Vs Displacement





Out of plane Displacement

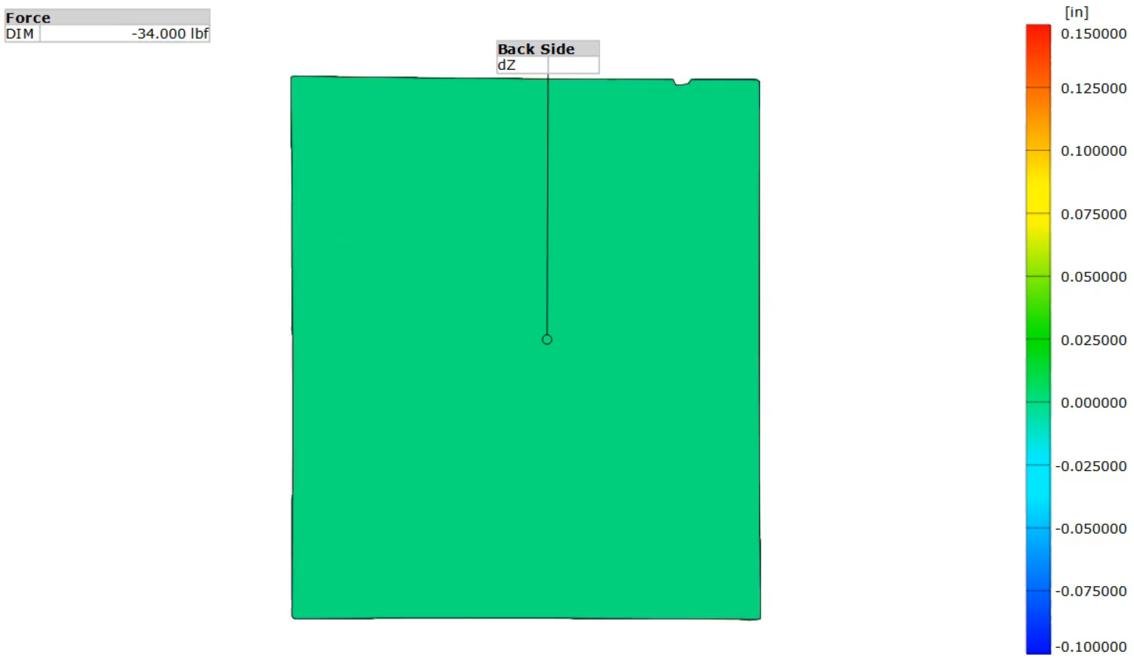


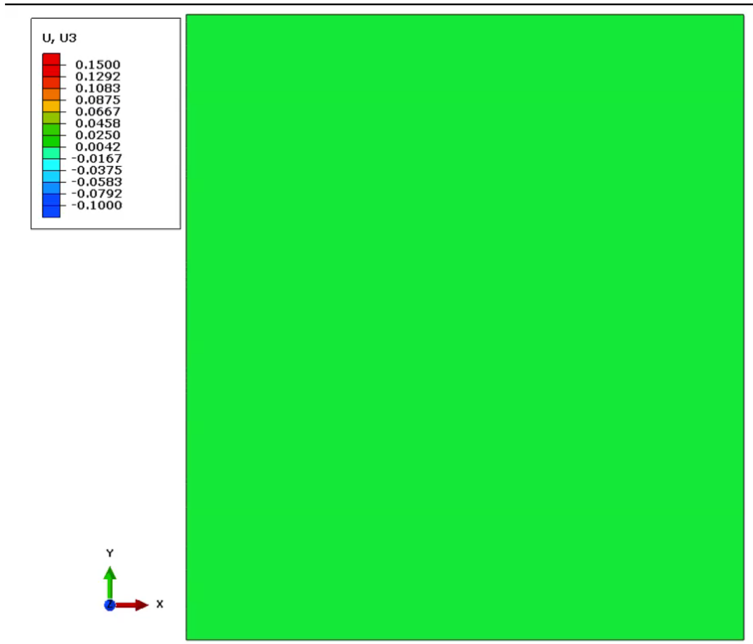


GAG Test Data Comparison Summary

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

8-ply facesheet; 0.5" core



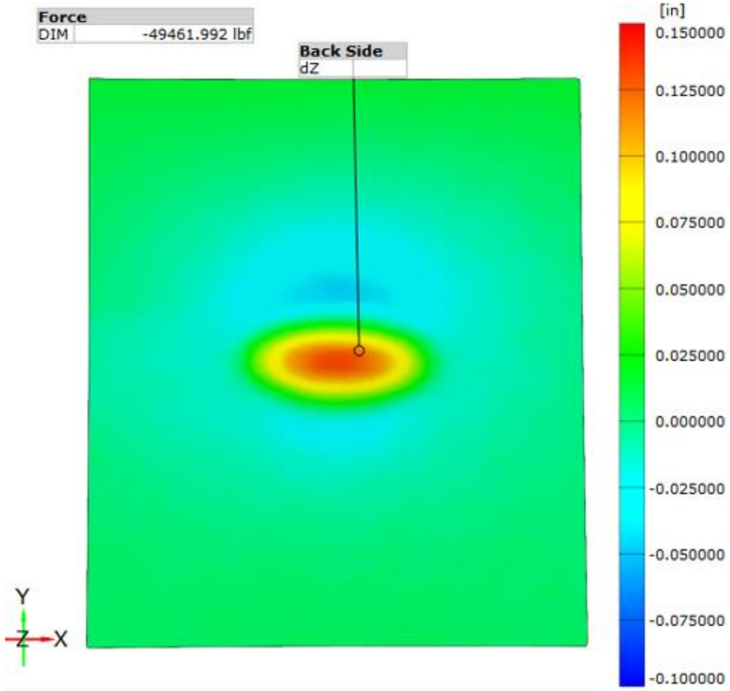


GAG Test Data Comparison Summary

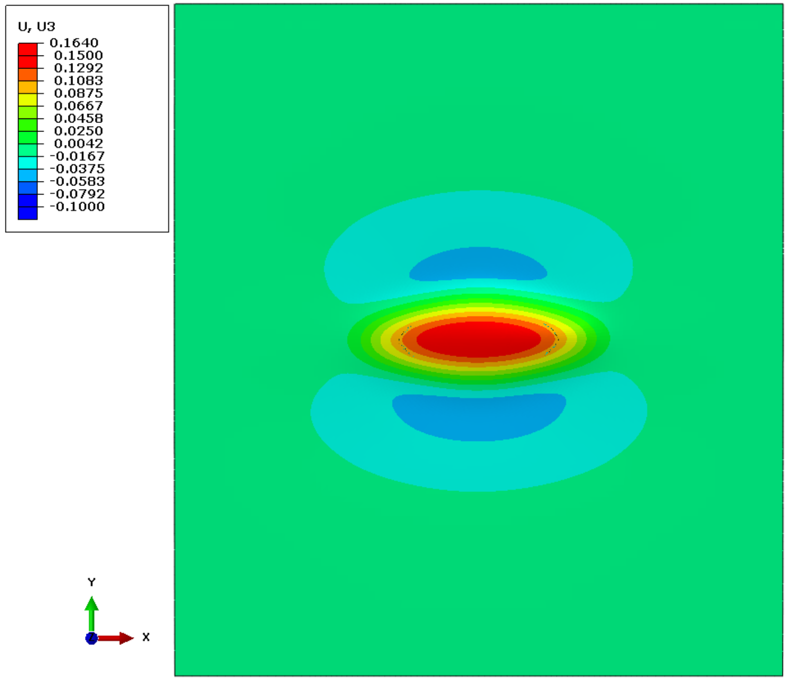
- Out-of-plane displacement plots *(disp. inches, force in lbf)*
- Crack initiation monitored by deletion of Cohesive elements

8-ply facesheet; 0.5" core

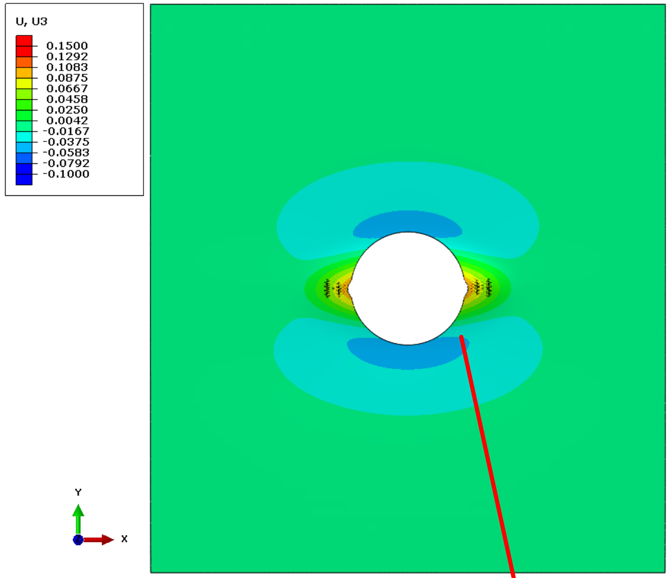
DIC

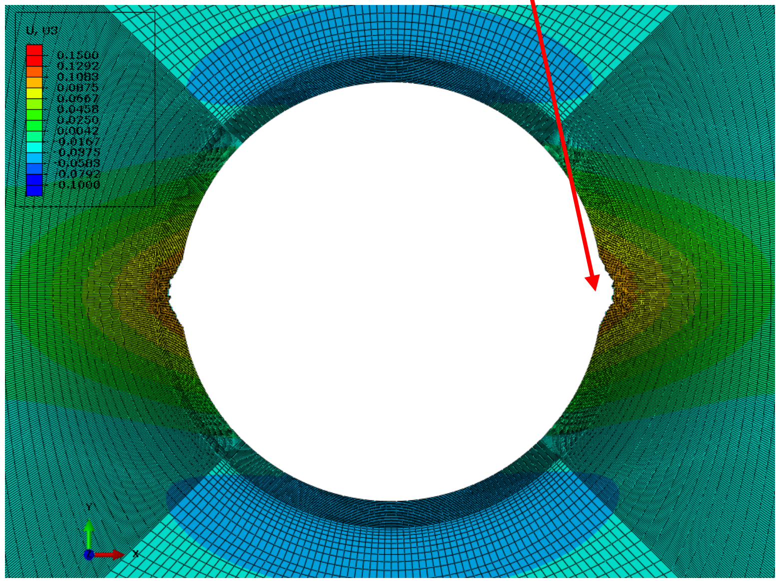


FEA



Cohesive elements





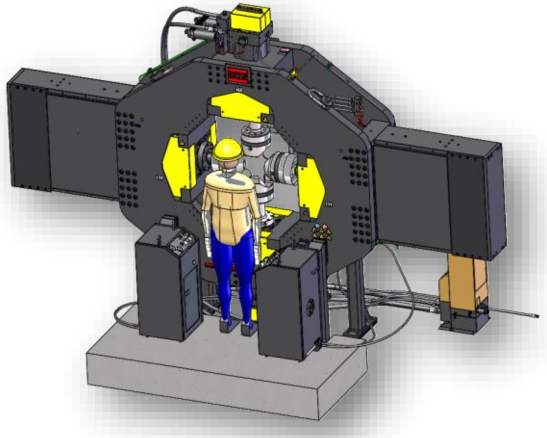
Outline – Moving Forward

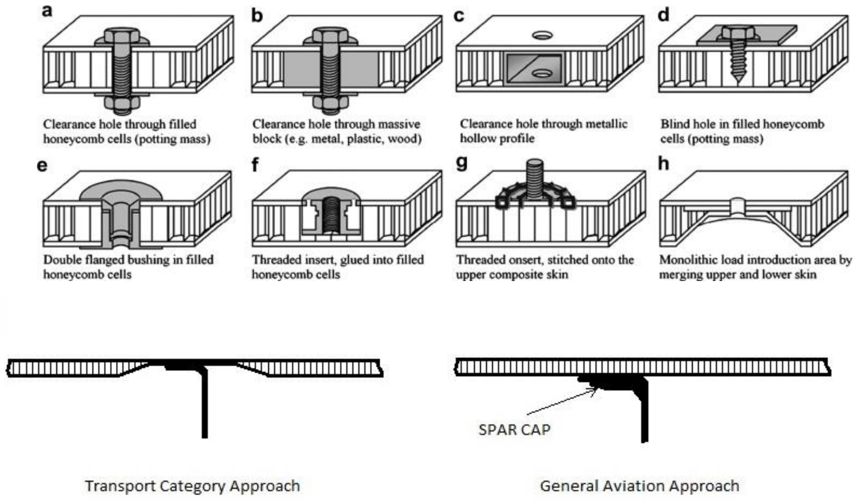
- SCB Test Configuration
  - Materials & Test Setup (translatable base)
- Foundation Model Approach & Validation
  - Comparison of Foundation, FE & Exp. Results
- Finite Element Model Description of SCB Specimens
  - Cohesive-base Modeling approach
- GAG - Edgewise Compression (EWC) Test Configuration
  - Test Setup & Loading
  - Static and fatigue testing
- Finite Element Model description of GAG Specimens
  - 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%

- Future work
  - The engineering approach can be expanded to study configurations w/t attachments/connections





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Thank You

Created using: B-Spline Analysis Method (BSAM)
Material: IM7/8552 [45]

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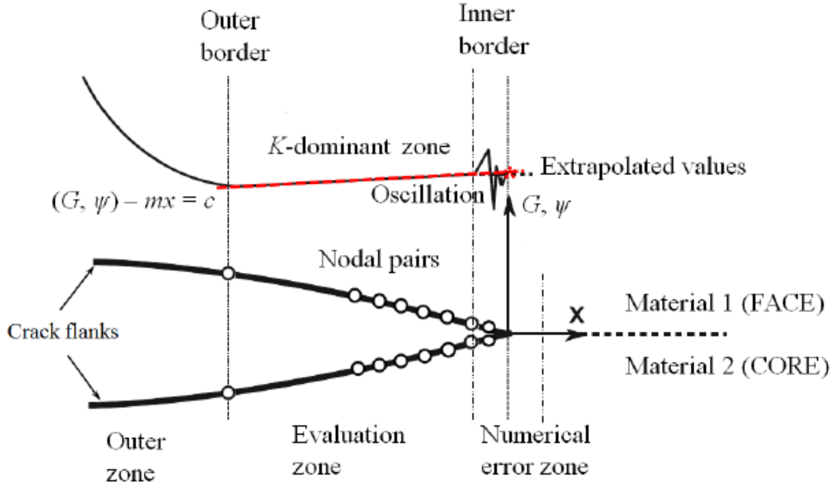
T650-5320 PW / Nomex® HRH-10 core: Energy-release rate Evaluation & Comparison



- A brief introduction to the **CSDE method**:
  - Solely based on relative crack flank displacements
  - Utilizes closed-form expressions for both ERR and mode-mixity proposed by Suo & Hutchinson (1990)
  - The numerical error zone close to the near-tip plastic zone avoided by linear extrapolation
  - Can be applied in 2-D and 3-D specimens (SCB studied here using a 2D model)

$$G = \frac{\pi\left(1+4\varepsilon^2\right)}{8H_{11}|x|}\left(\frac{H_{11}}{H_{22}}\delta_y^2+\delta_x^2\right)$$

$$\psi = \tan^{-1}\left(\frac{H_{11}\delta_x}{H_{22}\delta_y}\right) - \varepsilon\ln\left(\frac{|x|}{h}\right) + \tan^{-1}(2\varepsilon)$$

$$\varepsilon = \frac{1}{2\pi}\ln\left(\frac{1-\beta}{1+\beta}\right)$$

$$\beta = \frac{\left[S_{12}+\sqrt{S_{11}S_{22}}\right]_2 - \left[S_{12}+\sqrt{S_{11}S_{22}}\right]_1}{\sqrt{H_{11}H_{22}}}$$