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

2018 Technical Review

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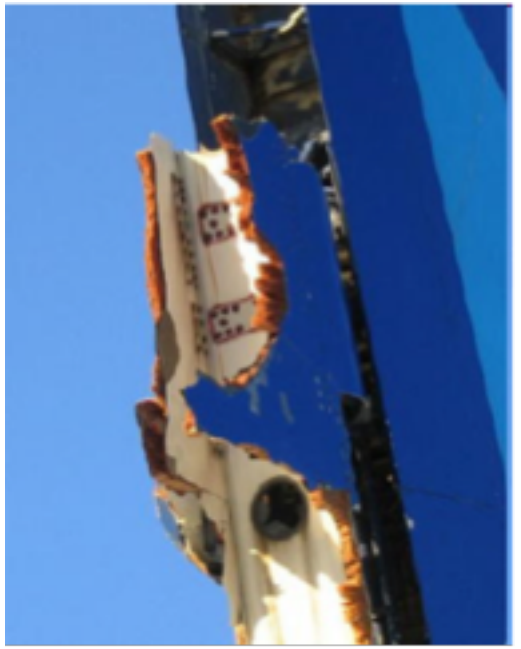
Kansas Aviation Research & Technology Growth Initiative

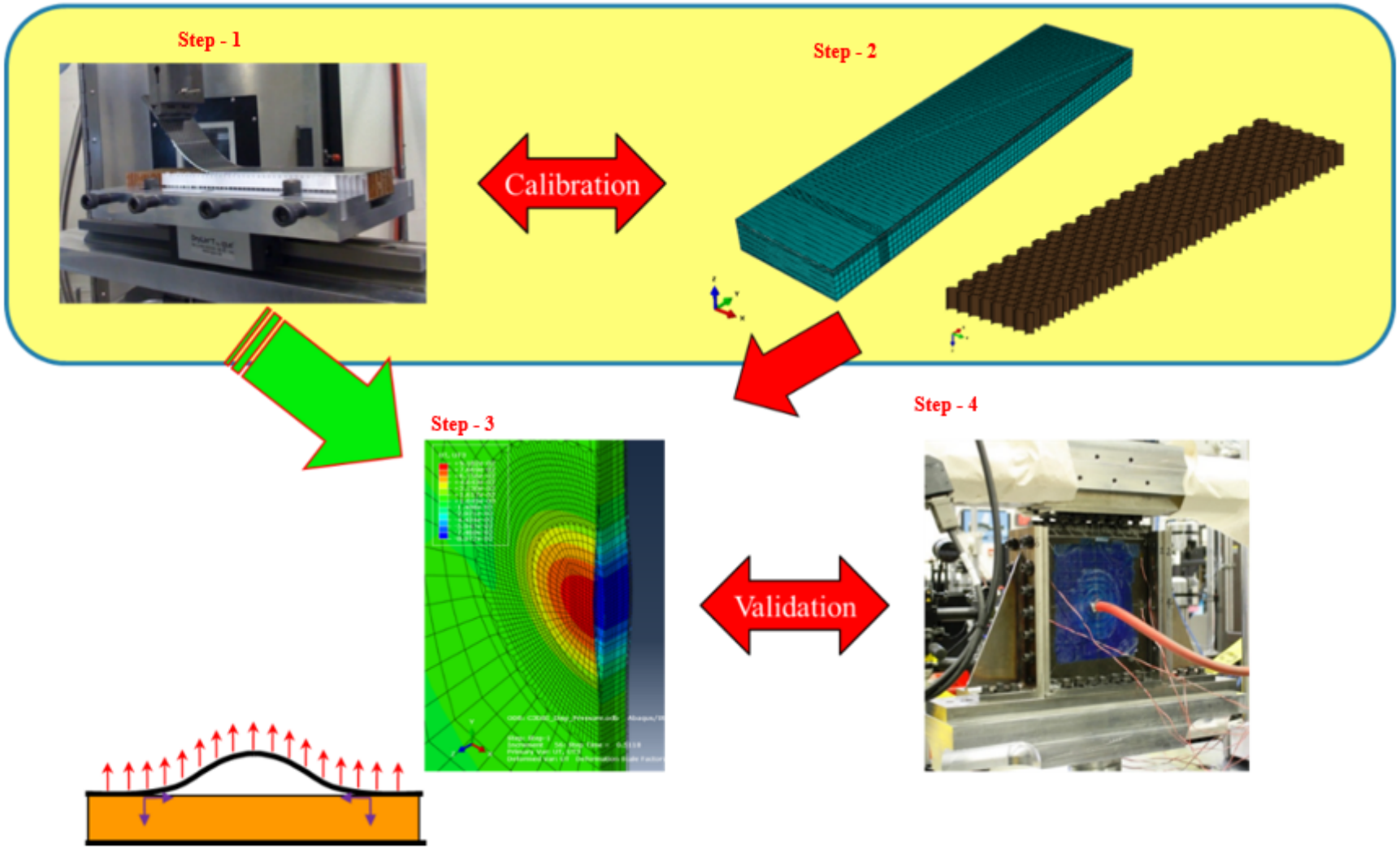
An Engineering Approach for Damage Growth Analysis of Sandwich Structures Subjected to Combined Compression and Pressure Loading

- **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

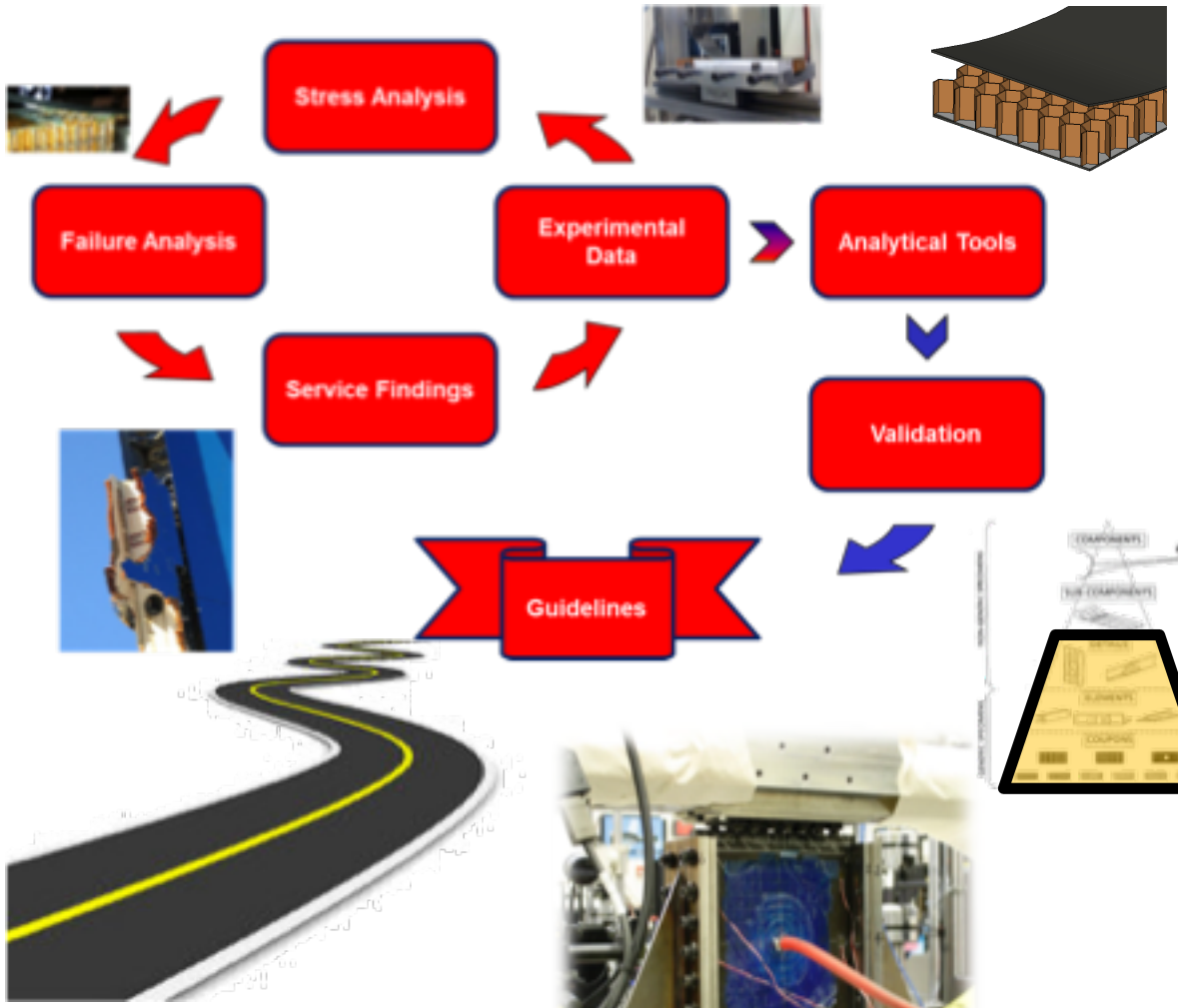


Analysis – Engineering Approach

- SCB ➔ GAG



Research Overview

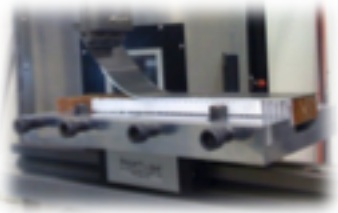


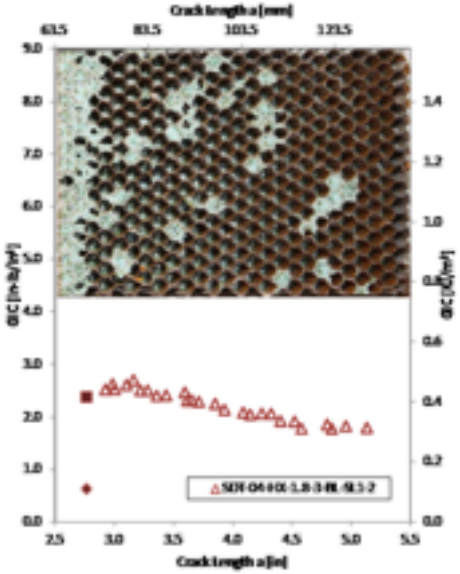
- Single-cantilever beam (SCB) testing/simulations
  - Test/conditioning procedures (2009 - 2010)
  - Static (2010-2012)
  - Fatigue (2010-2012)
  - Finite element analysis (2017-2018)
- Ground-air-ground (GAG) testing/simulations
  - Edgewise compression (2015 - 2018)
    - Static/Fatigue
- Further studies (2018– ……)
  - Sandwich damage growth simulations
    - SCB to GAG

Accomplishments

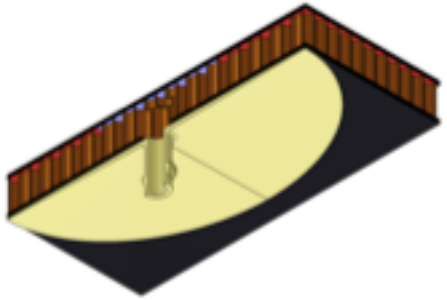
Mode I (G1c) Fracture Toughness of Composite Sandwich Structures for Use in Damage Tolerance Design and Analysis

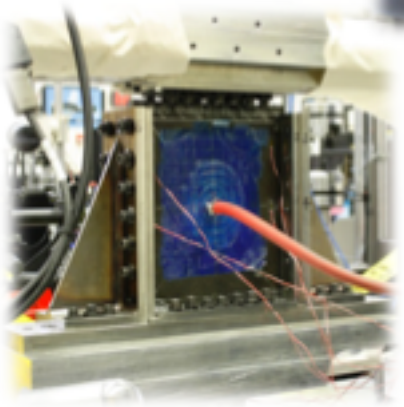
- Volume 1: ***Static Testing Including Effects of Fluid Ingression*** **(DOT/FAA/TC-16/23)**
- Volume 2: ***Fatigue Testing Including Effects of Fluid Ingression*** **(DOT/FAA/TC-17/06)**
- Volume 3: ***Damage Growth in Sandwich Structures*** ***(under review)***



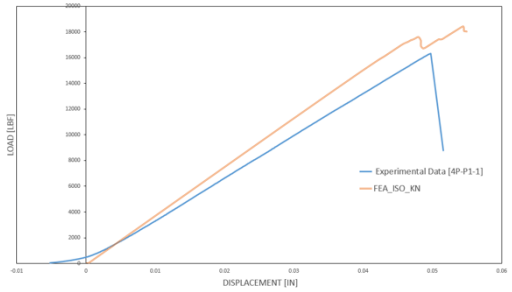


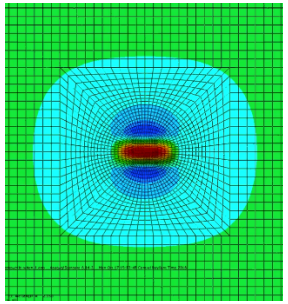
Ground-Air-Ground testing (Load + Pressure + Environment)

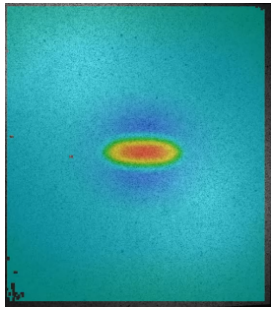




Engineering approach for analysis of GAG element *(On going)*







Outline

- **SCB Test Configuration**
  - **Test Setup**
- Finite Element Model Description for SCB Specimens
  - Modeling approach
  - Comparison to test data
- GAG - Edgewise Compression [EWC] Test Configuration
  - Test Setup
  - Static and fatigue testing
- Finite Element Model description for GAG Specimens
  - Modeling approach
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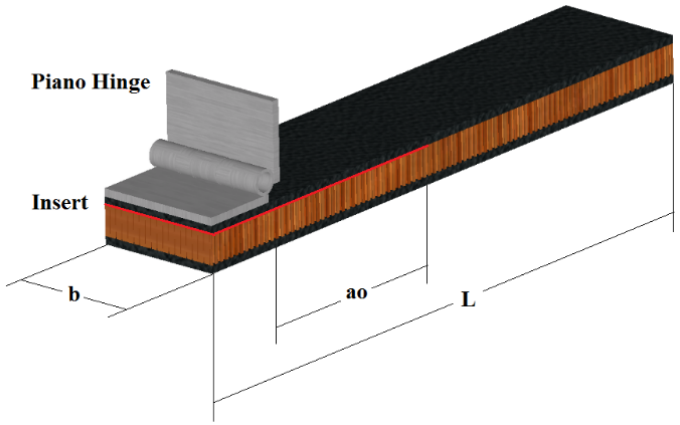
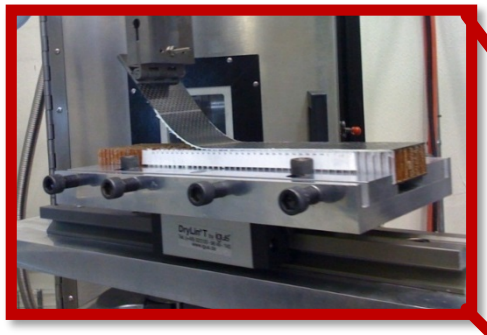
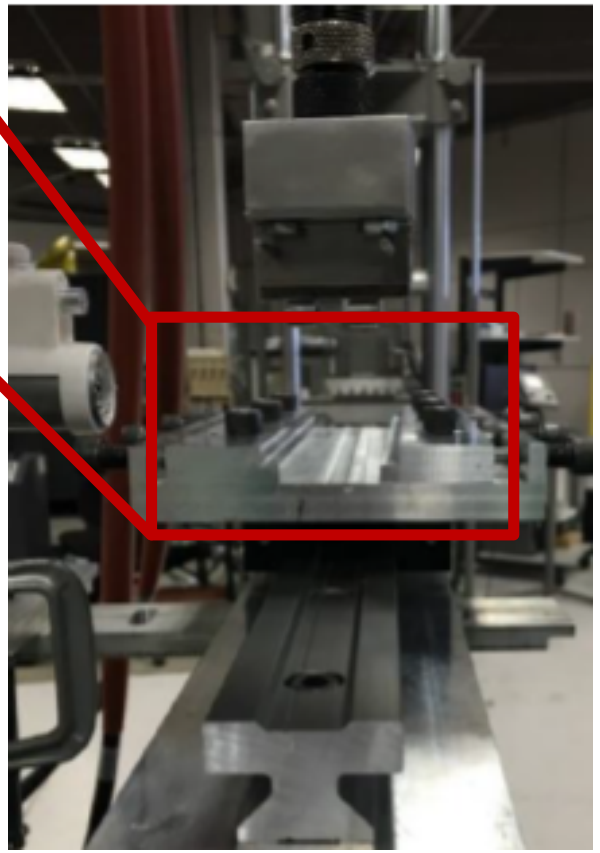
- Summary

SCB Test Configuration

- Material
  - Facesheet: T650 - 5320
  - Core: Hexcel HRH-10
  - Adhesive: FM300 - 2
- Prescribed Crack
  - Created with Teflon inserts
  - ao = 2in
- Machined
  - L=10.0in
  - b=2in
- Piano Hinge
  - Bonded using EA9394







Facesheet = [45/0/0/45]

Test Matrix

Case	Facesheet Material	Plies	Cell Size (in)	Core Density (lb/ft^3)	Core Thickness (in)
1	T650/5320-PW	4	1/8	3.0	1.0
2	T650/5320-PW	4	1/8	6.0	0.5
3	T650/5320-PW	4	3/8	3.0	0.5
4	T650/5320-PW	8	1/8	6.0	0.5

Outline – Moving Forward

- SCB Test Configuration
  - Test Setup
- **Finite Element Model Description for SCB Specimens**
  - **Modeling approach**
  - **Comparison to test data**
- GAG - Edgewise Compression [EWC] Test Configuration
  - Test Setup
  - Static and fatigue testing
- Finite Element Model description for GAG Specimens
  - Modeling approach
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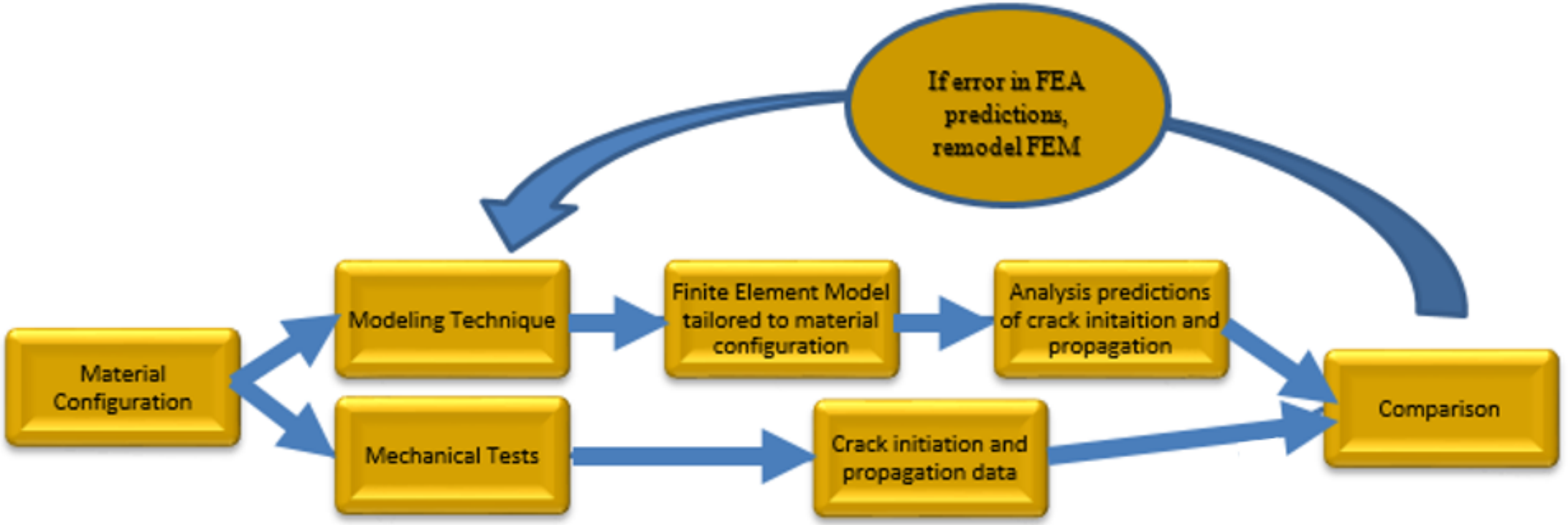
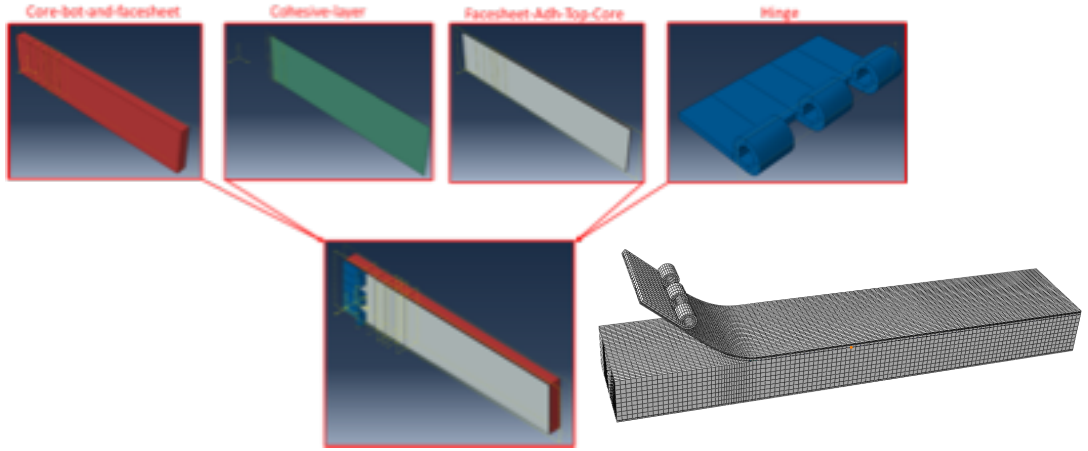
FEA – SCB Model Approach

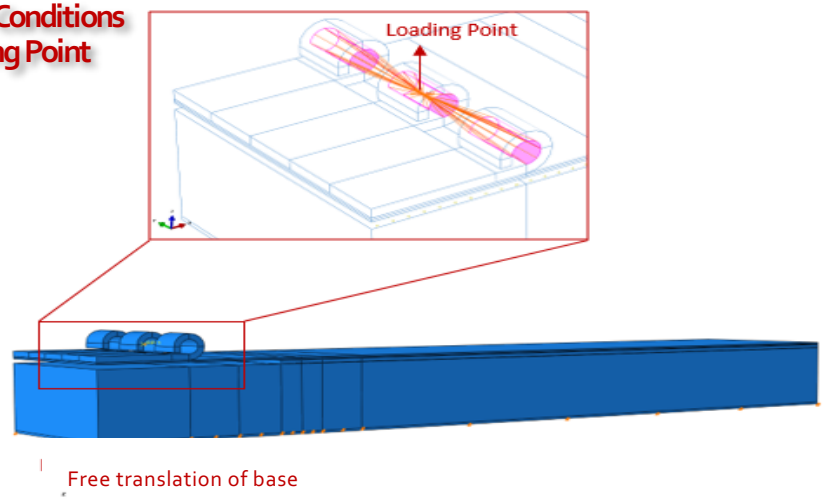


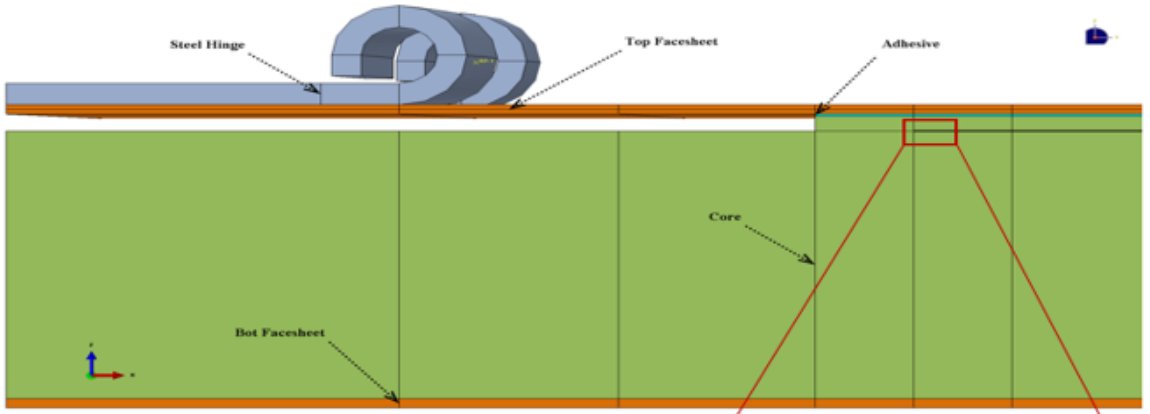
FEA – SCB Model Description and Approach

- Four configurations with different core density, cell size and face-sheet size were considered.
- Core - core failure.
- Cohesive zone to model the damage in the core.

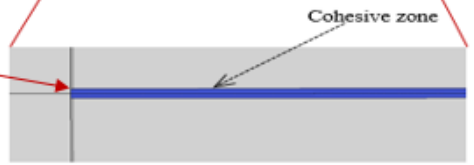


Boundary Conditions and Loading Point





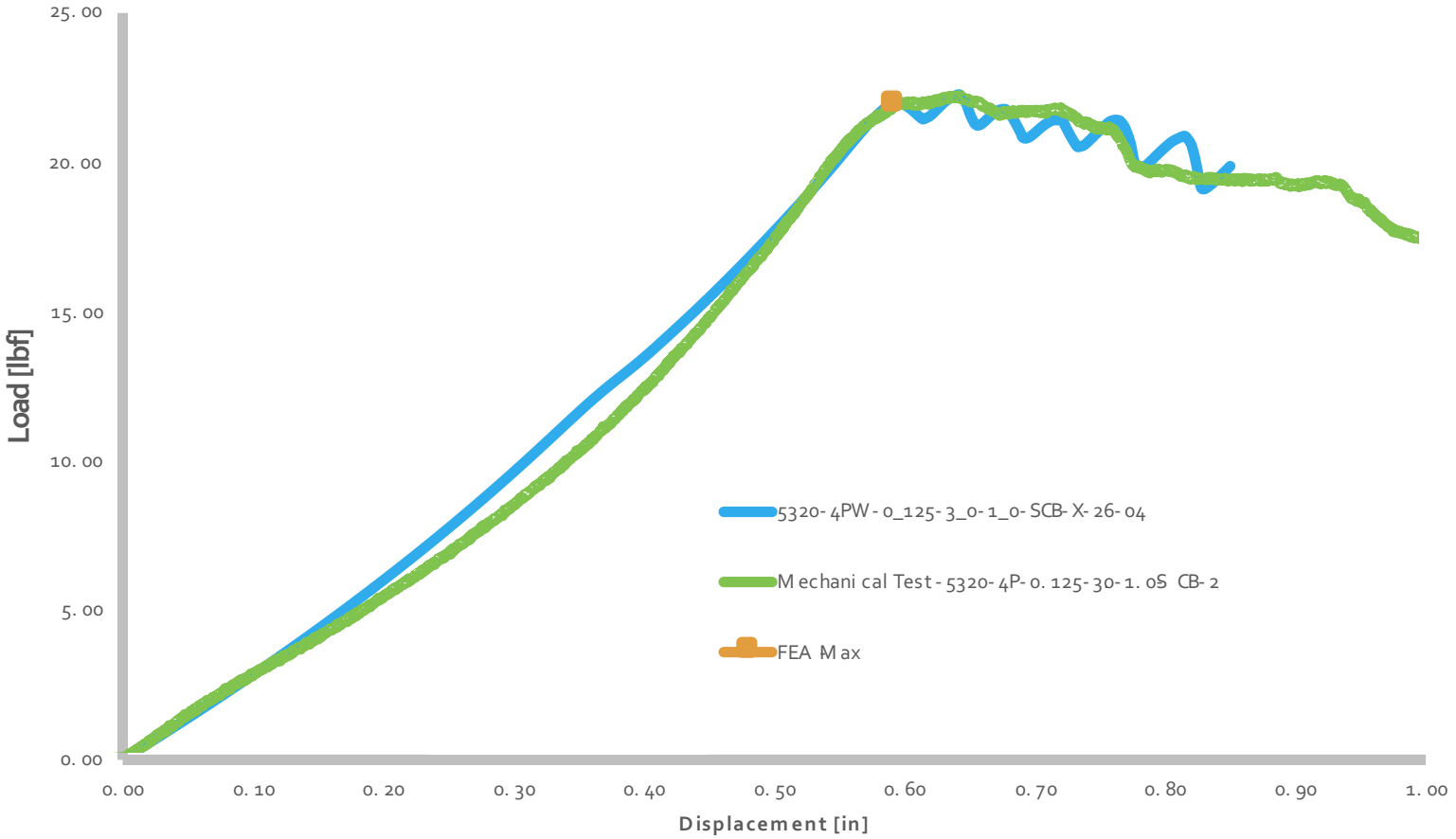
Damage in the core

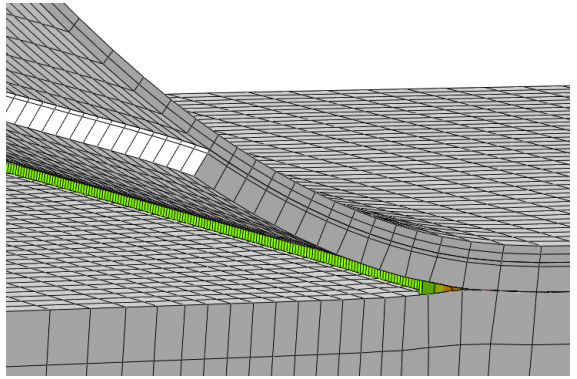


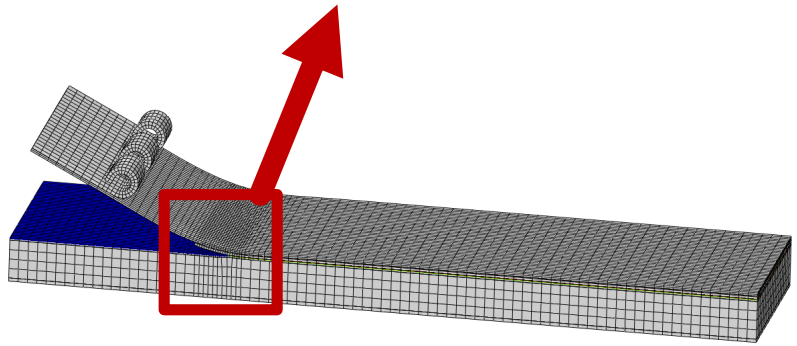
Test Data Comparison – Summary

Case	Facesheet Material	Plies	Cell Size (in)	Core Density (lb/ft^3)	Core Thickness (in)	Exp .5%Max Load (lbs)	Simulation Crack Initiation Load	
							FEA Load (lbs)	Error (%)
1	T650/5320-PW	4	1/8	3.0	1.0	21.38	22.0	2.90
2	T650/5320-PW	4	1/8	6.0	0.5	27.53	28.0	1.71
3	T650/5320-PW	4	3/8	3.0	0.5	15.52	14.63	6.08
4	T650/5320-PW	8	1/8	6.0	0.5	60.67	57.9	4.57

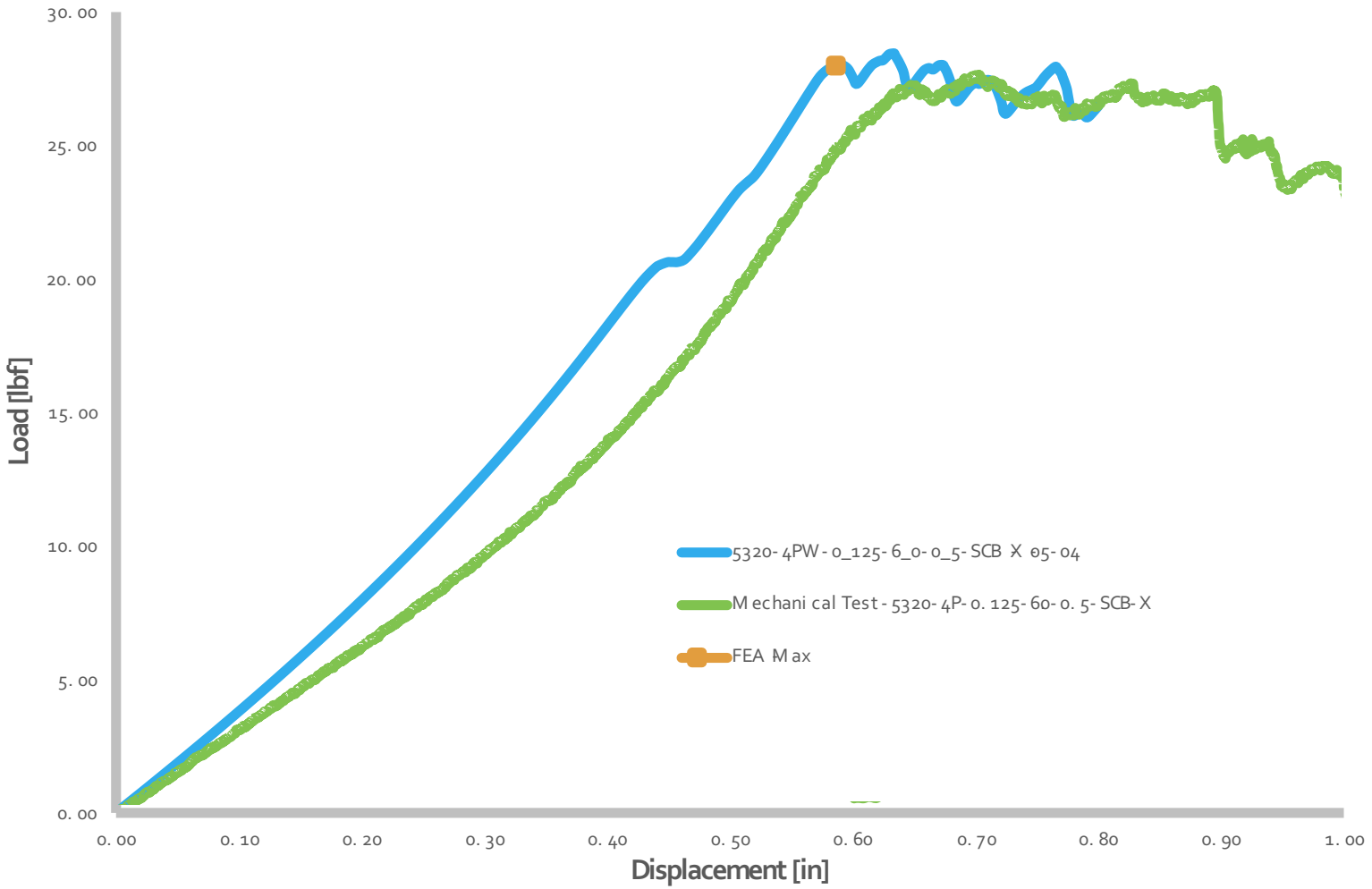
T650/5320-PW-4P-1/8-3.0-1.0

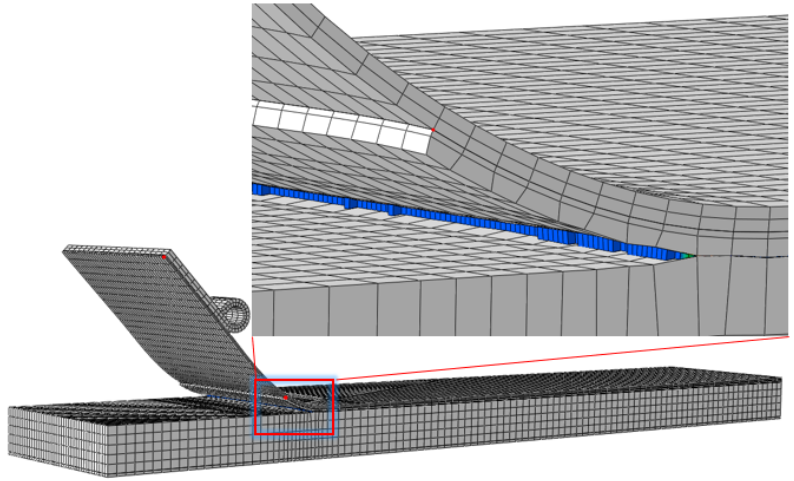




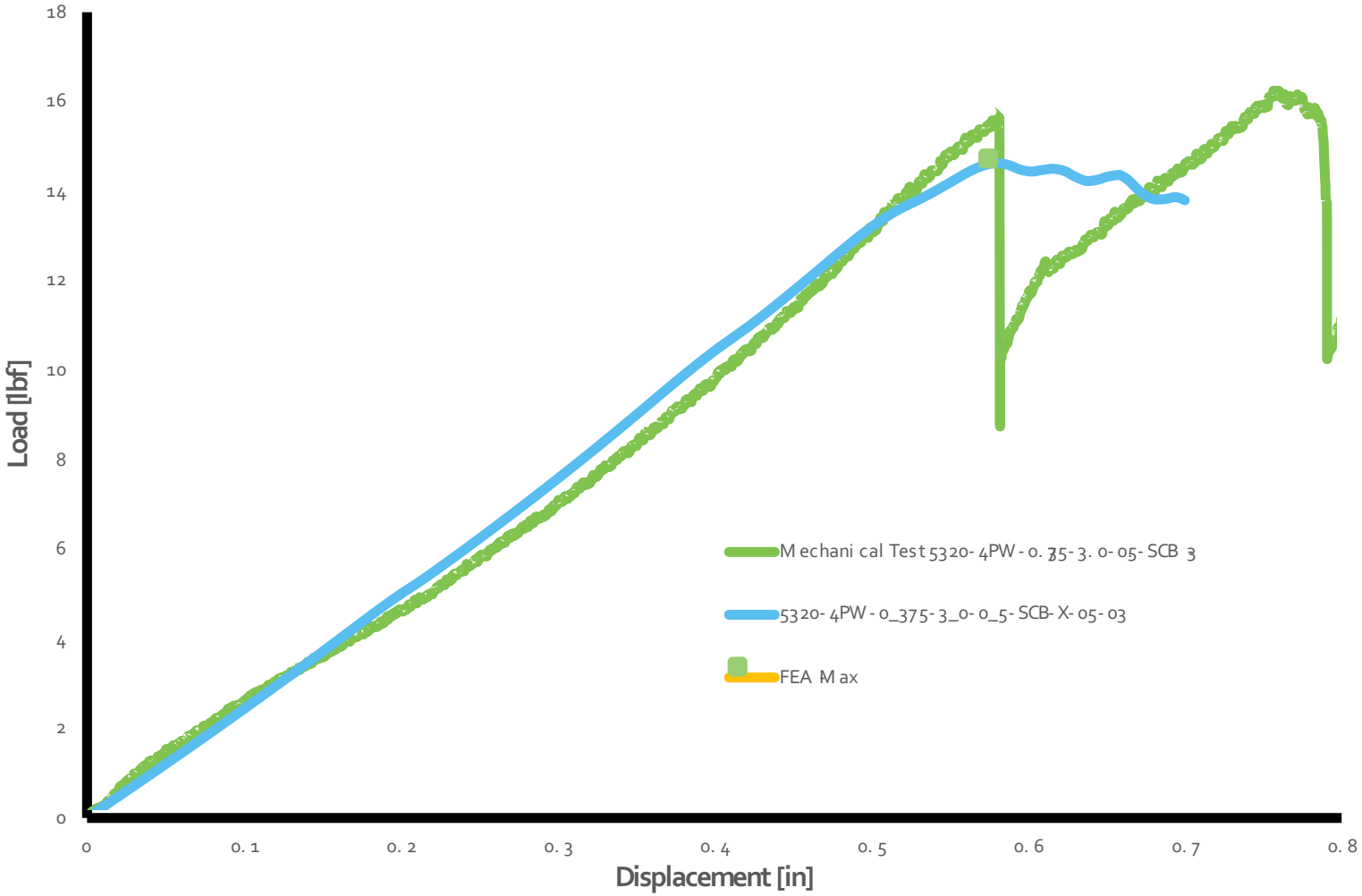


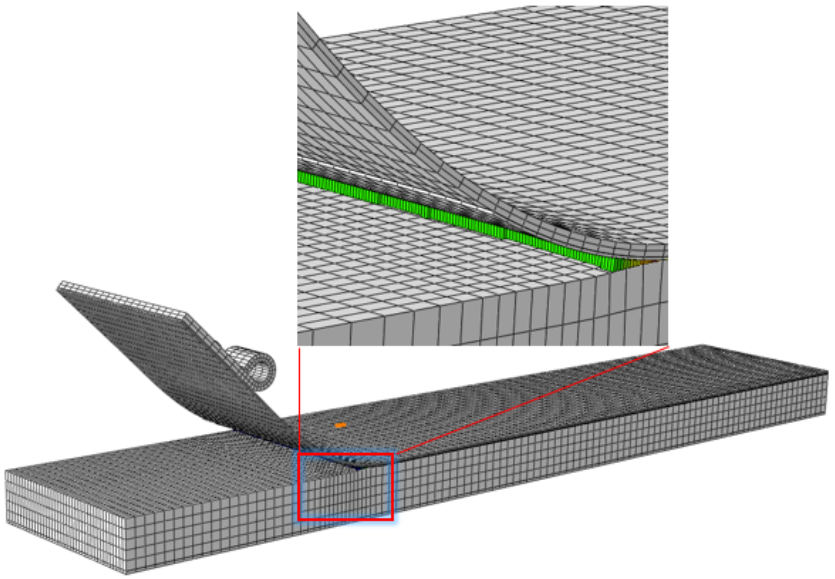
T650/5320-PW-4P-1/8-6.0-0.5



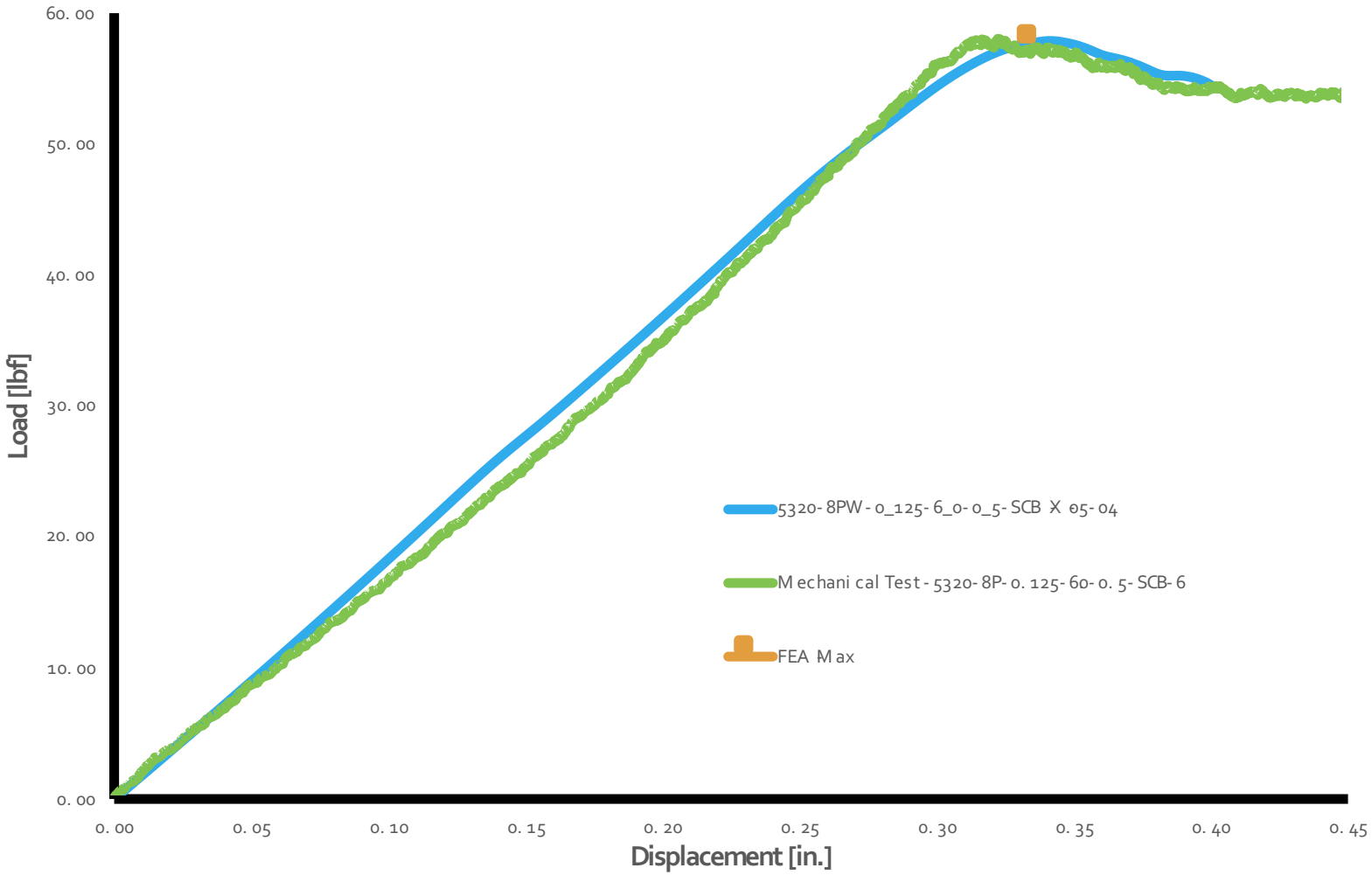


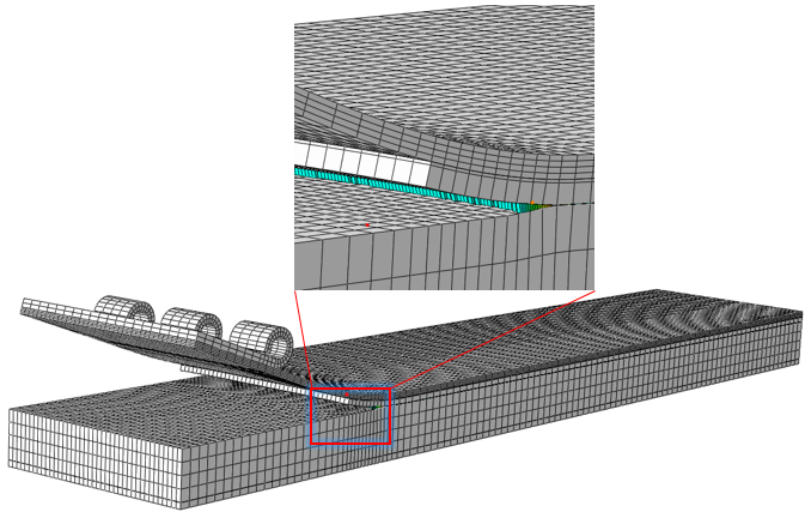
T650/5320-PW-4P-3/8-3.0-0.5





T650/5320-PW-8P-1/8-6.0-0.5





Outline – Moving Forward

- SCB Test Configuration
  - Test Setup
  - Failure moods. [As in final FAA report 1 and 2]
- Finite Element Model description for SCB Specimens
  - Modeling approach
  - Comparison to test data
- **GAG - Edgewise Compression [EWC] Test Configuration**
  - **Test Setup**
  - **Static and fatigue testing**
- Finite Element Model description for GAG Specimens
  - Modeling approach
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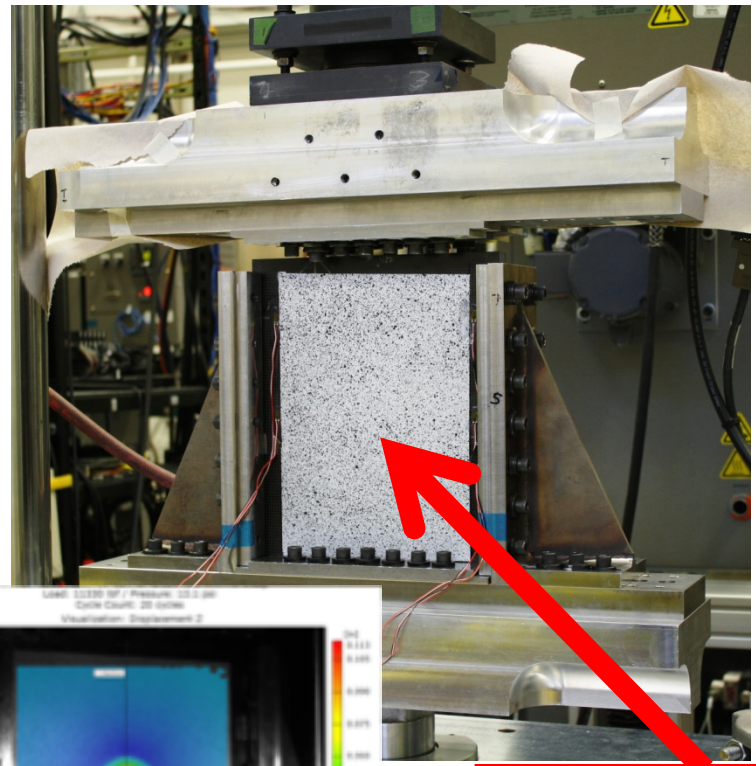
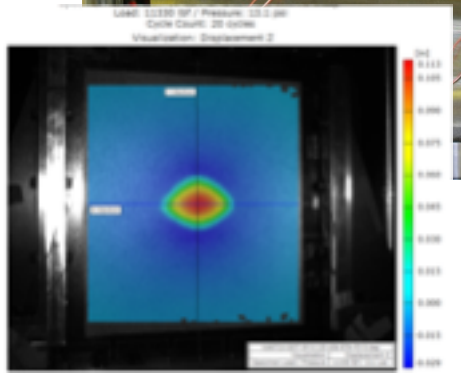
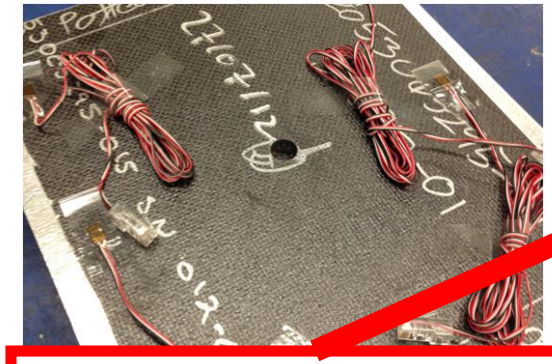
- Summary

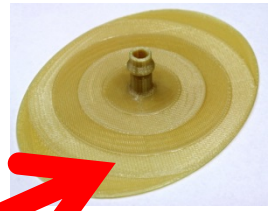
GAG - Edgewise Compression [EWC] Test Setup





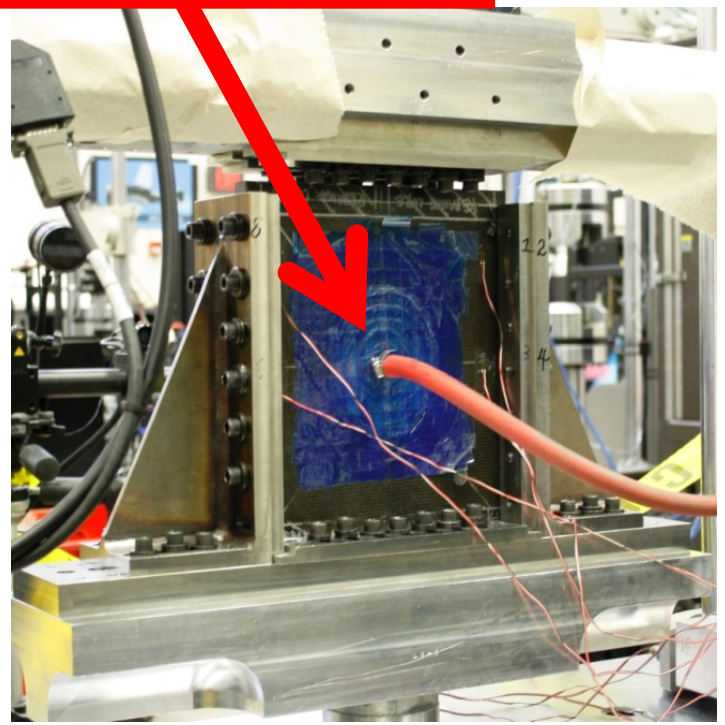
DIC speckle pattern on Damage Side





Hysol EA9309.3NA Epoxy

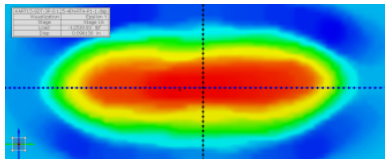
3D printed (Ultem) pressure port



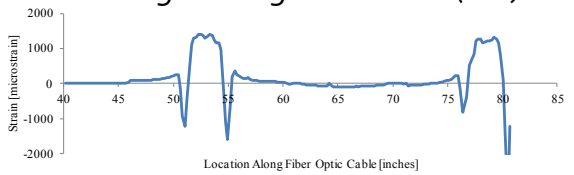
Ability to accommodate various specimen sizes

- 10x12 (shown) and 18x20 (test size)

Damage Growth monitoring

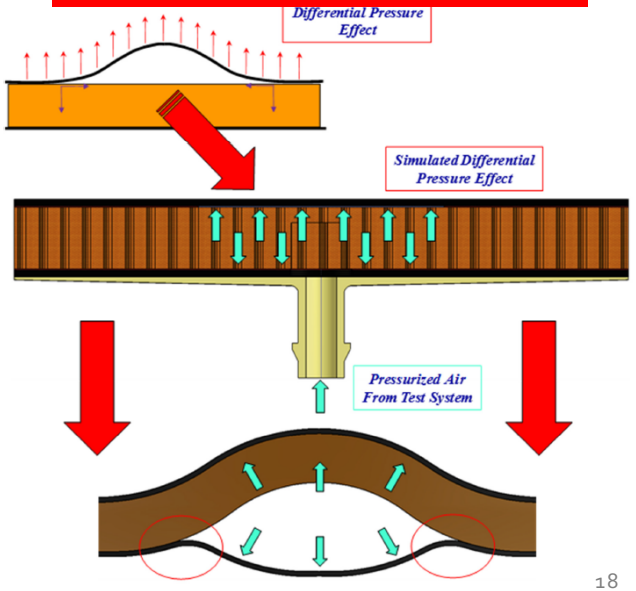


Digital Image Correlation (DIC)

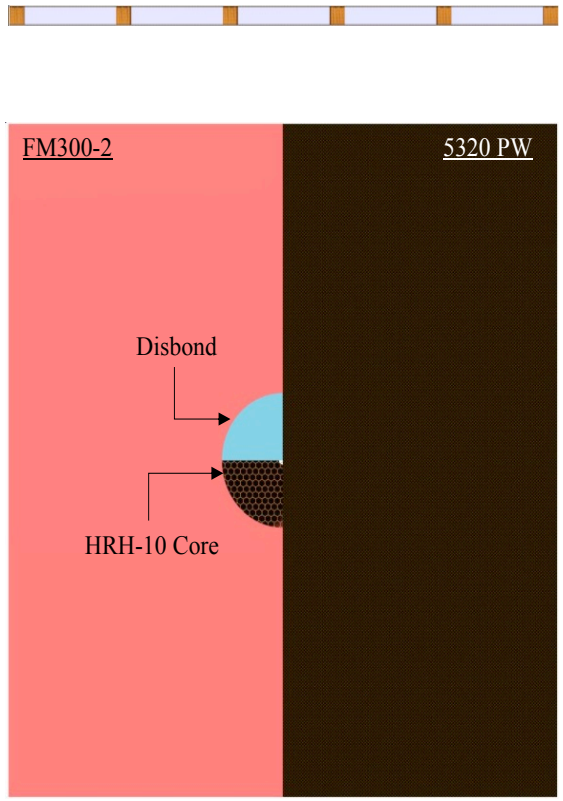


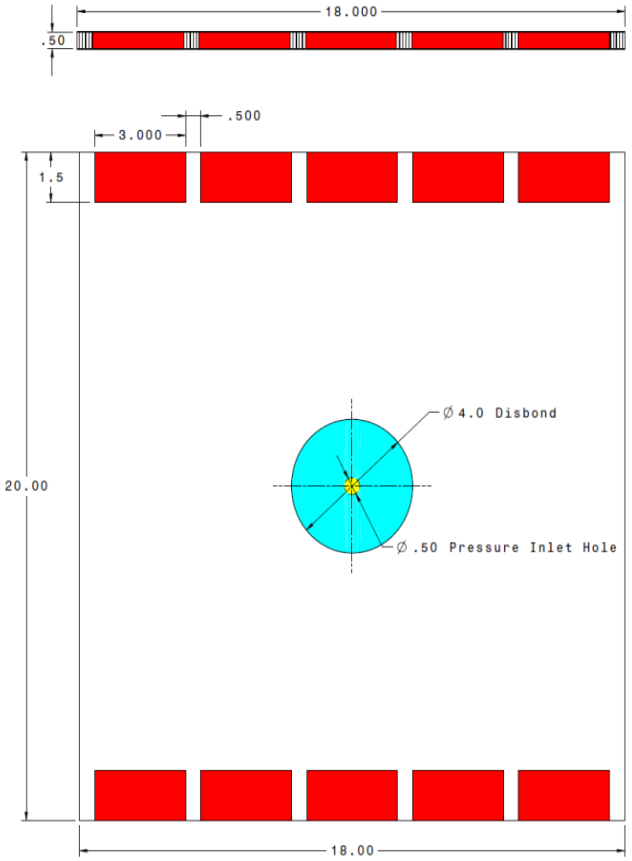
Distributed fiber optic strain sensors

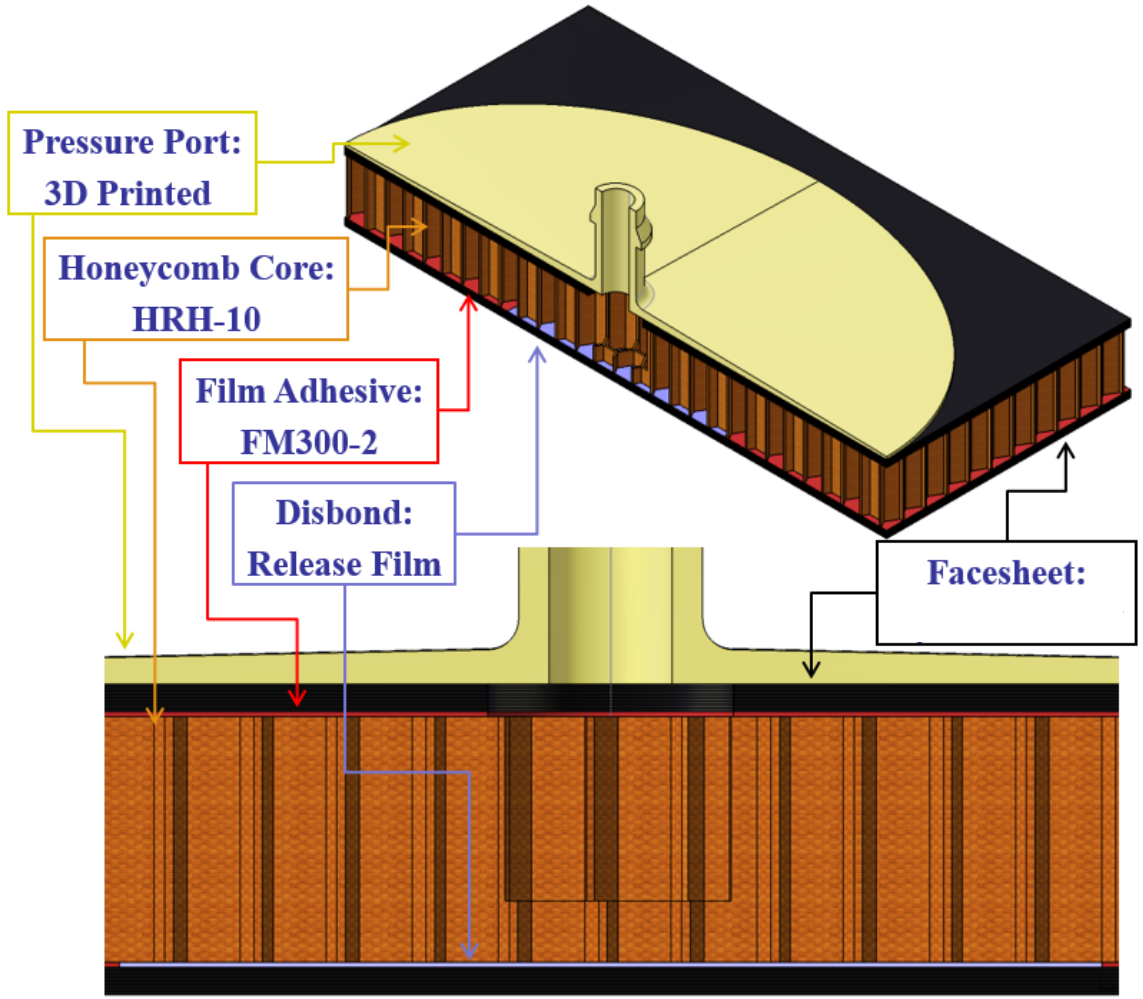
Pressure Simulation



GAG - Edgewise Compression [EWC] Specimen Configuration



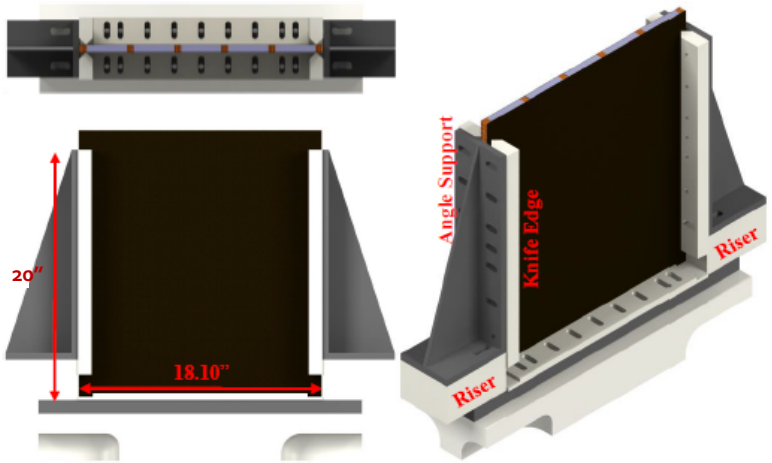


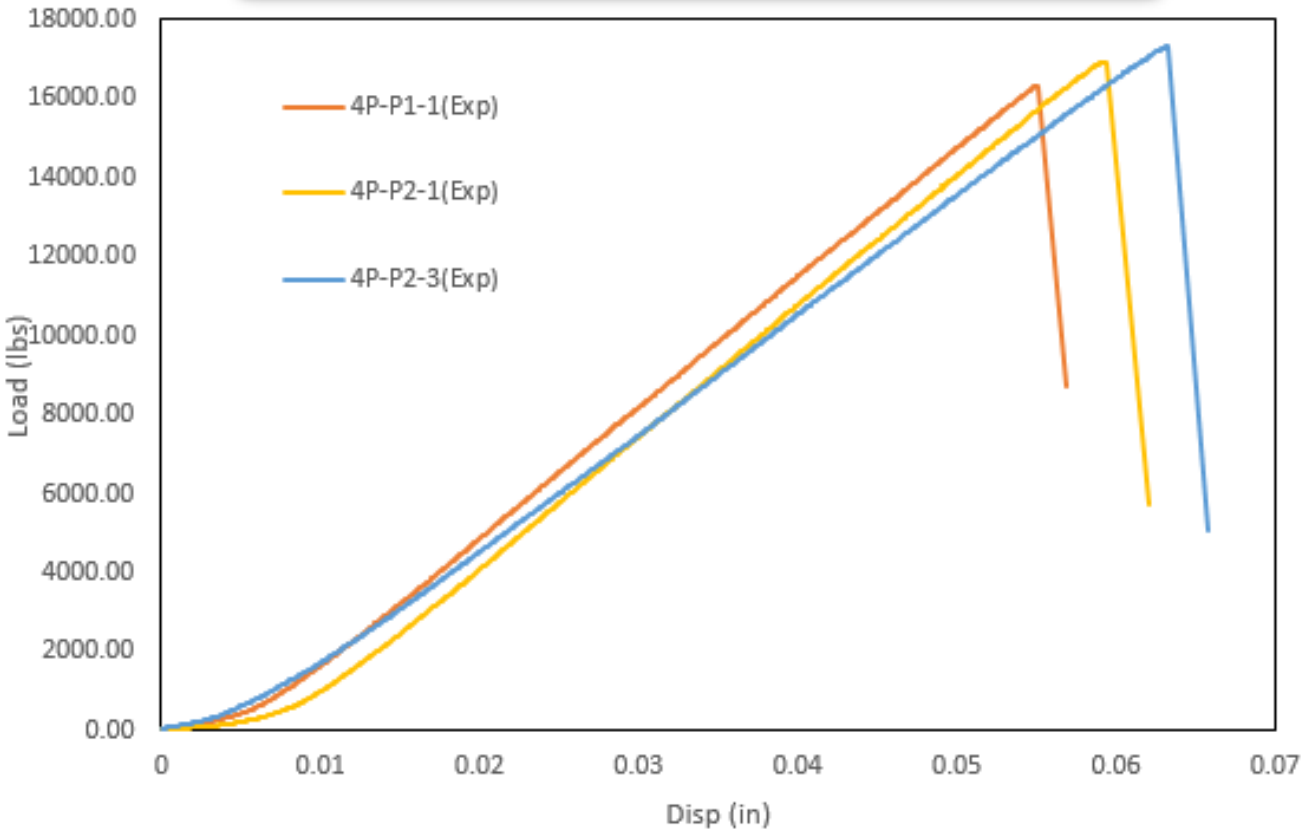


GAG [EWC] Testing - Static

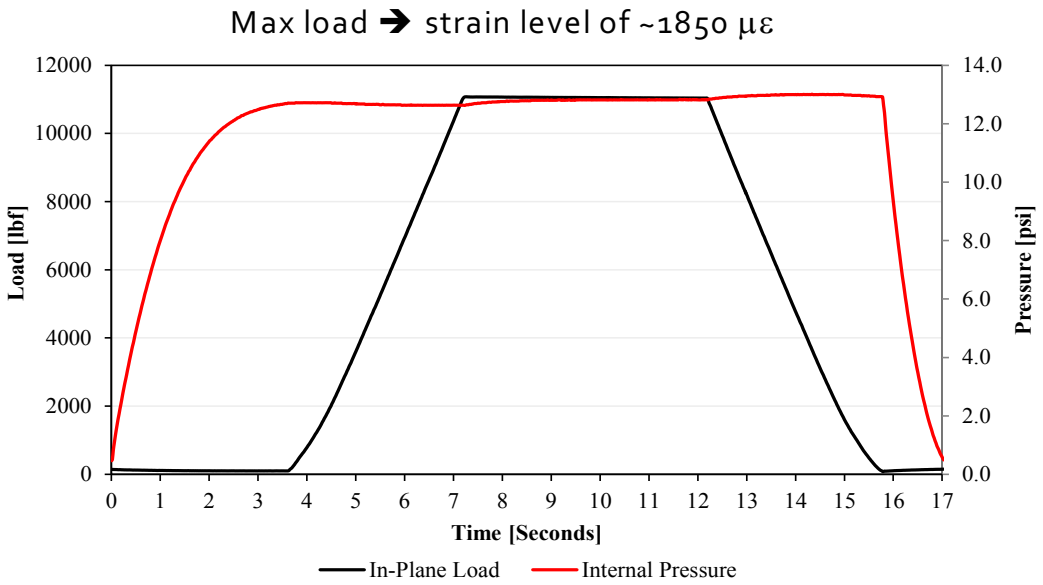
- Completed testing on selected configuration as a baseline for the FE model.
- Used this data to conduct initial comparison with FEA data.

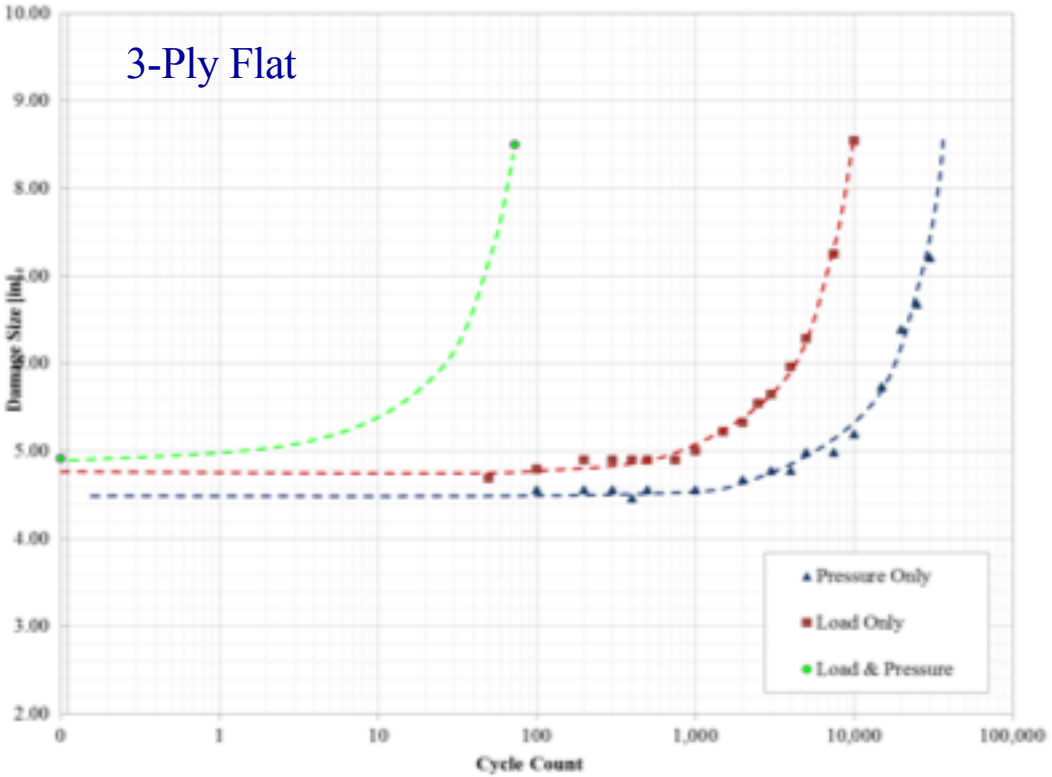
Case	Facesheet Material	Plies	Cell Size (in)	Core Density (lb/ft^3)	Core Thickness (in)
1	T650/5320-PW	4	1/8	3.0	1.0





GAG [EWC] Cyclic Testing - Fatigue





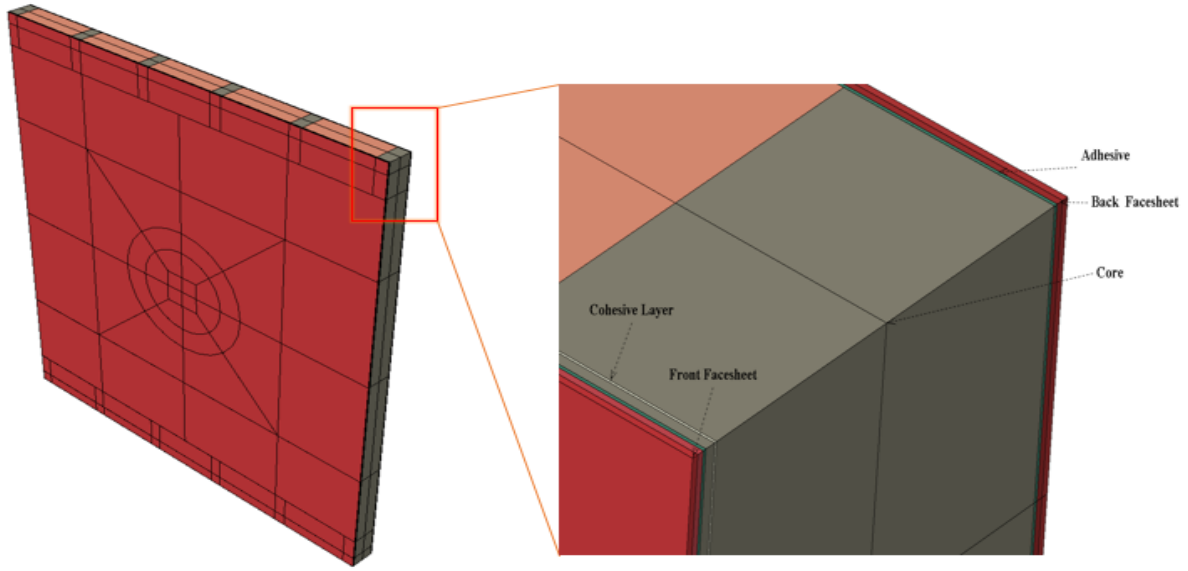
- Loading conditions
  - Pressure only
  - Load only
  - Pressure and load
- Environmental conditions
  - RTA

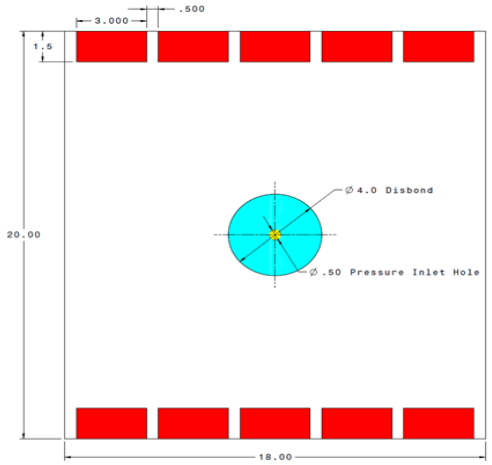
Outline – Moving Forward

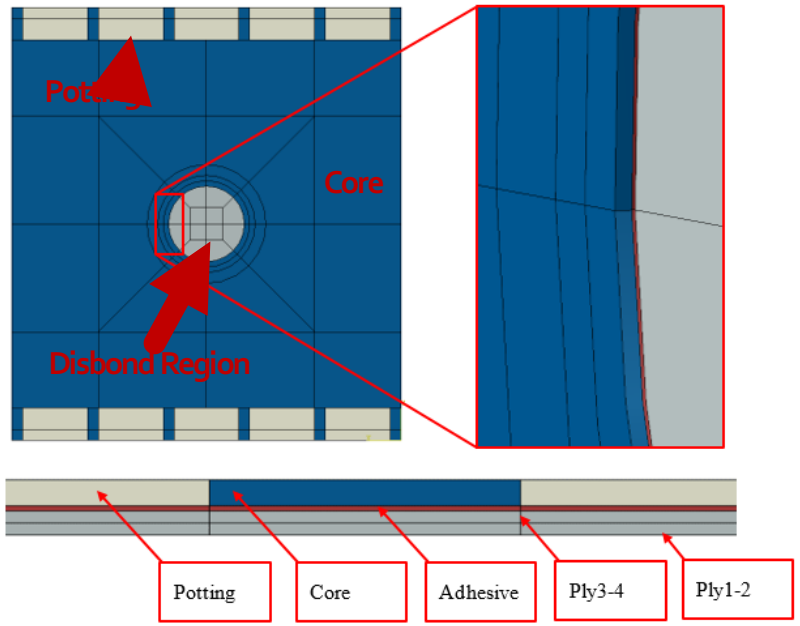
- SCB Test Configuration
  - Test Setup
  - Failure moods. [As in final FAA report 1 and 2]
- Finite Element Model description for SCB Specimens
  - Modeling approach
  - Comparison to test data
- GAG - Edgewise Compression [EWC] Test Configuration
  - Test Setup
  - Static and fatigue testing
- **Finite Element Model Description for GAG Specimens**
  - **Modeling approach**
  - **Comparison to test data**
- Summary

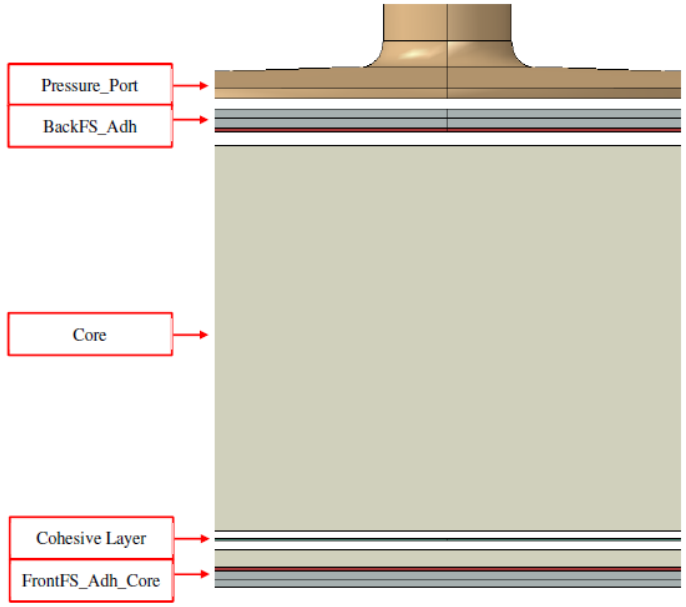
FEA – GAG [EWC] Model Description and Approach

- FE analysis for static loading.
- Took the same optimized parameters as in SCB analysis.
- Used cohesive zone method to model the damage in the core.
- Detail explanation of the modeling strategy will be in the final report.





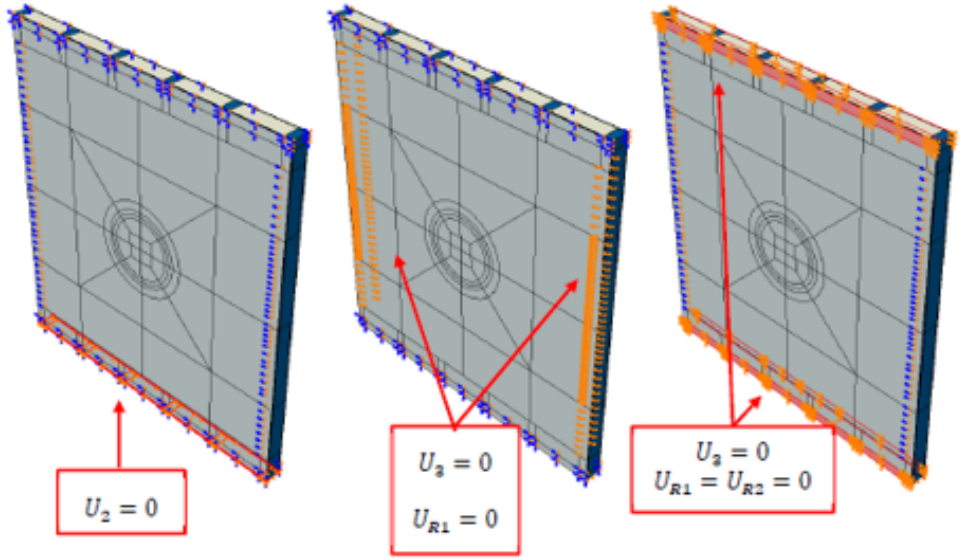




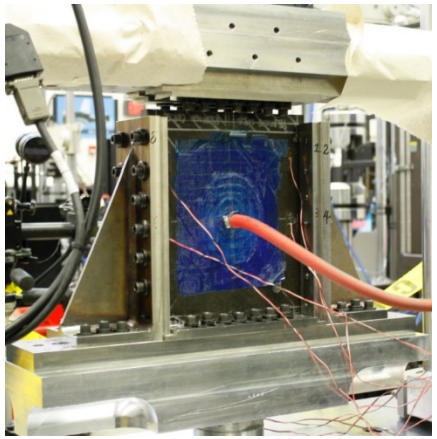
FEA – GAG [EWC] Model Description [Loading and Boundary Conditions]

- Apply loading from the top surface as displacement.
- Apply pressure through the pressure port.
- Apply BC's to the edges of the specimen to closely represent the test setup.

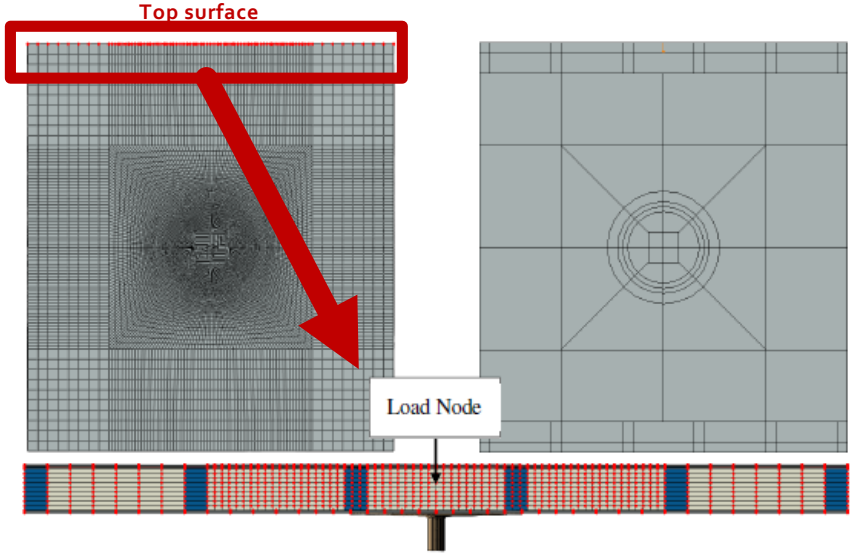
Boundary Conditions and Loading Points

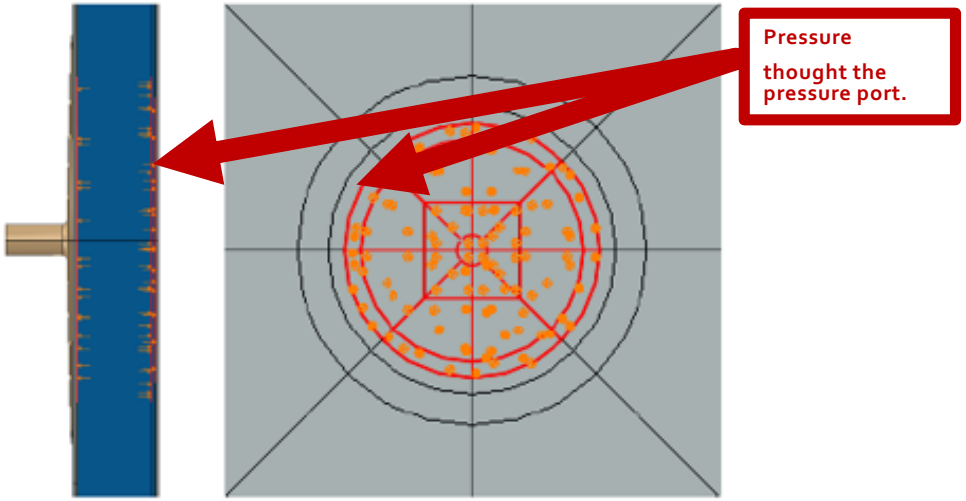


Test Setup



Top surface

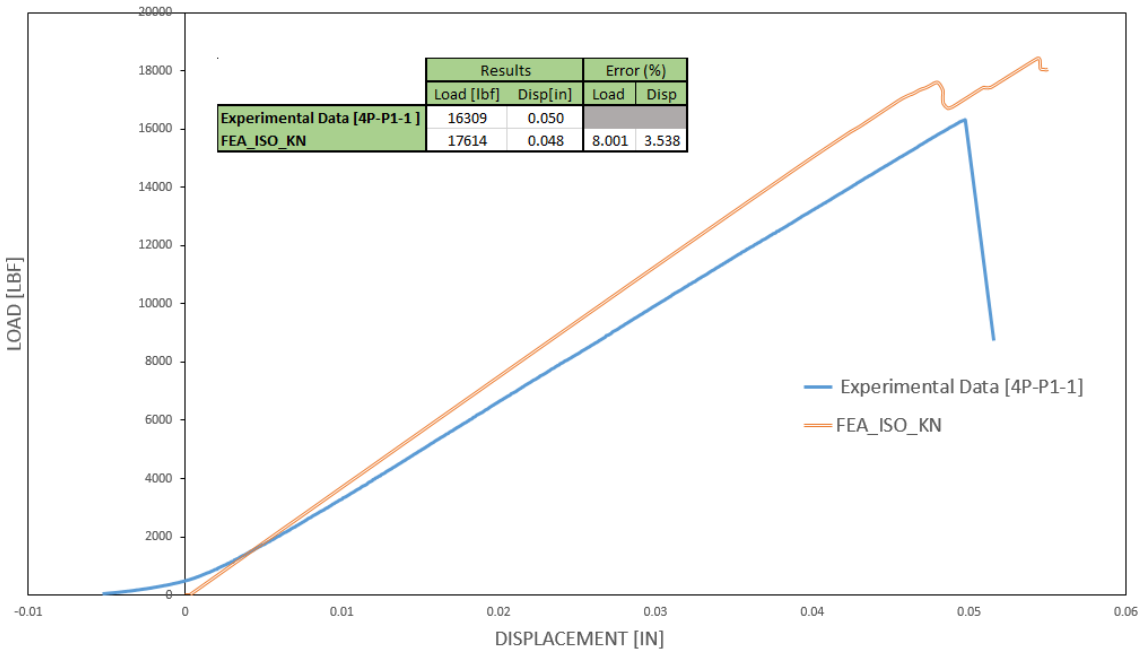




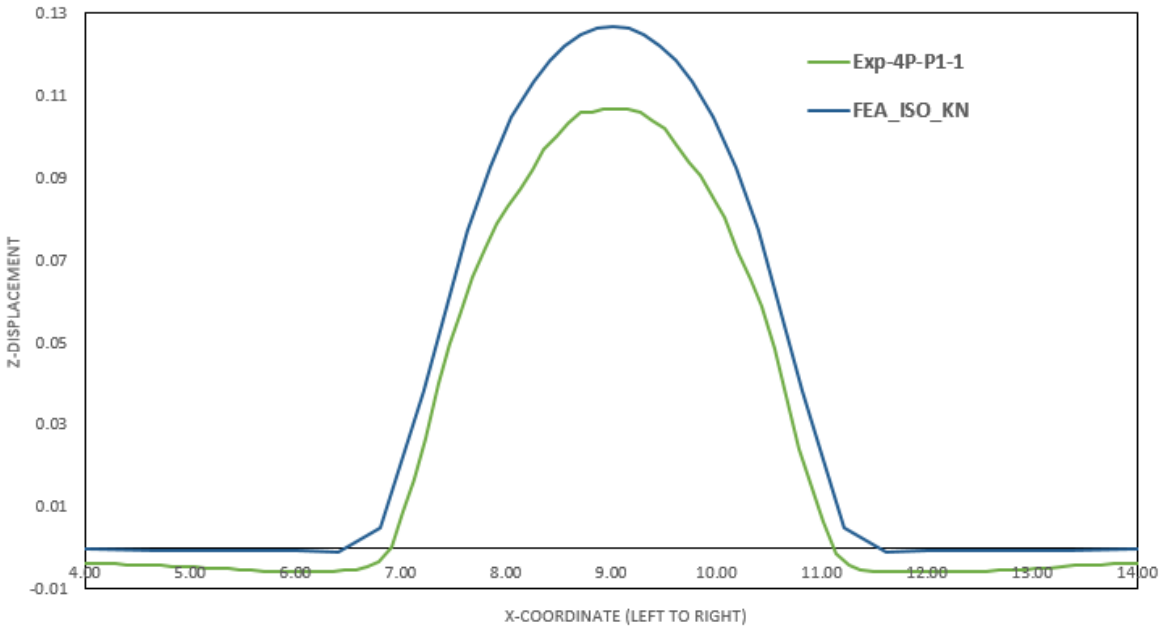
GAG Test Data Comparison Summary

Load Vs Displacement

	Results		Error (%)	
	Load [lbf]	Disp[in]	Load	Disp
Experimental Data [4P-P1-1]	16309	0.050		
FEA_ISO_KN	17614	0.048	8.001	3.538



Out of plane Displacement



Case	Facesheet Material	Plies	Cell Size	Core Density	Exp .5%Max Load (lbs)	Simulation Crack Initiation Load	
						FEA Load (lbs)	Error (%)
1	T650/5320 PW	4	1/8	3.0	16309	17614	8
2	T650/5320 PW	4	1/8	6.0	*	19958	-
3	T650/5320 PW	4	3/8	3.0	*	17438	-
4	T650/5320 PW	8	1/8	6.0	*	*	-

* Awaiting Results

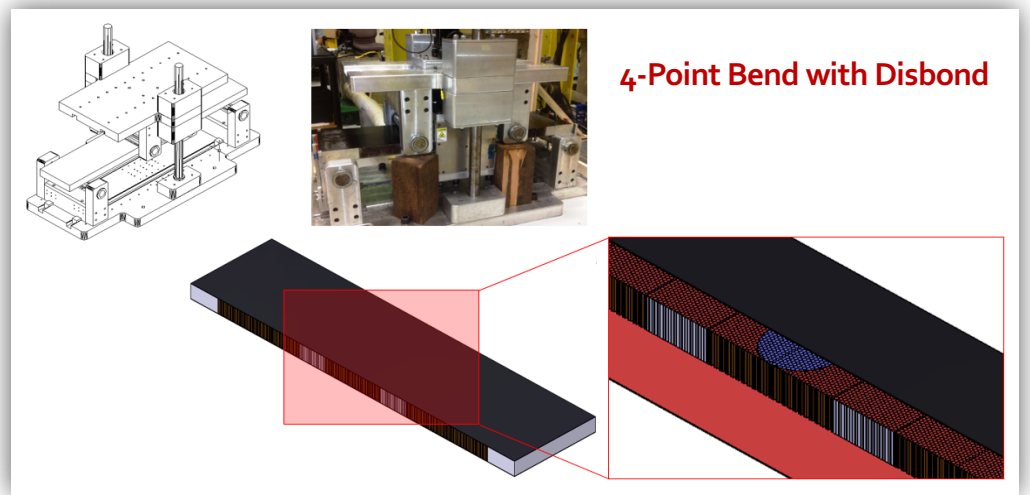
Blind prediction on going.

Outline – Moving Forward

- SCB Test Configuration
  - Test Setup
- Finite Element Model description for SCB Specimens
  - Modeling approach
  - Comparison to test data
- GAG - Edgewise Compression [EWC] Test Configuration
  - Test Setup
  - Static and fatigue testing
- Finite Element Model description for GAG Specimens
  - Modeling approach
  - Comparison to test data
- **Summary**

Summary

- Activity Summary
  - SCB analysis methods are presented with results and compared with test data.
    - SCB FEA data is within 16% compared to test data [after GAG (EWC) feedback]
  - GAG analysis methods are presented with results and compared with initial test data.
    - Initial GAG FEA data is within 9% compared to test data
- Future Work
  - Improve analysis using "orthotropic values" as cohesive zone parameters (Fracture toughness and penalty stiffness values).
  - After validating Flat Edgewise Compression models move on to curved Edge wise Compression models and validate it.
  - Automation of modeling technique.
  - Preform GAG testing with large flex test and validate with FEA models.



Looking Forward

- **Benefit to Aviation**
  - Guidelines for substantiating sandwich structures
    - GAG effects on damage growth
- **Future needs**
  - Field history data related to sandwich data growth phenomenon