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Fatigue Damage Growth Rate of Sandwich Structures using Single Cantilever Beam (SCB) Test

2014 Technical Review

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Wichita State University/NIAR

Fatigue Damage Growth Rate of Sandwich Structures using Single Cantilever Beam Test

- **Motivation and Key Issues**
  - Fluid ingression phenomenon and the progressive damage growth due to entrapped fluids in sandwich structures
  - Thermo-mechanical loads during ground-air-ground (GAG) cycling result in localized mode I stresses that cause further delamination/disbond/core fracture growth creating more passageways for fluid migration.
- **Objective**
  - The influence of sandwich parameters such as core size, density, and facesheet/core stiffness ratio on the onset and damage growth rate of sandwich composite
  - Understand the Ground-air-ground effect on onset and damage growth
- **Approach**
  - Damage growth in sandwich structures
    - Core types, core densities (24, 32 and 48kg/m^3) & F/C thicknesses
  - Mechanics of different damage sources
    - Fluid ingression (GAG effects)
    - Impact damages
    - Repairs (improper repairs and process deviations)

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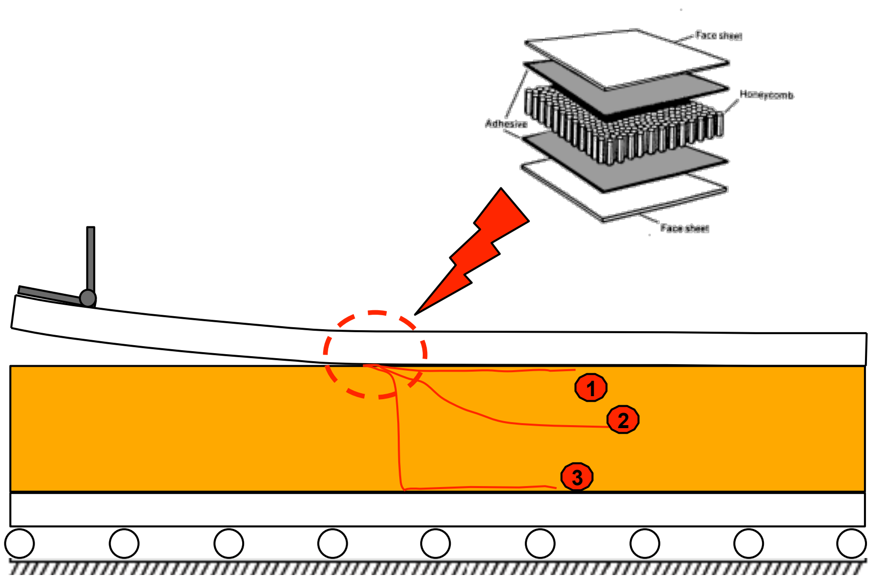
Fatigue Damage Growth Rate of Sandwich Structures using Single Cantilever Beam Test

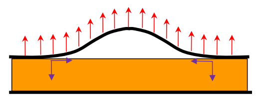
- **Principal Investigators & Researchers**
  - John Tomblin, *PhD*, and Waruna Seneviratne, *PhD*
  - *Shawn Denning*
- **FAA Technical Monitor**
  - Curtis Davies and David Westlund
- **Other FAA Personnel Involved**
  - Larry Ilcewicz, *PhD*
- **Industry Participation**
  - Cessna, Bombardier and Spirit Aerosystems

Challnges

- Standardized test methods
  - Test procedures
  - Data reduction techniques
- Complex damage mechanics
  - Onset
  - Propagation
  - Multiple constituents
- Tools for stress analysis
  - Crack-tip mode mixity
- Publically available data
  - Service findings
  - Component-level test data



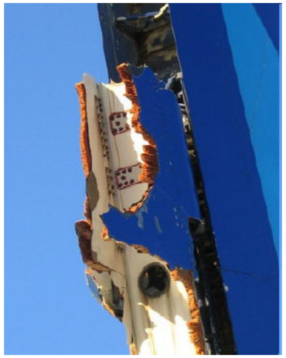
Approach



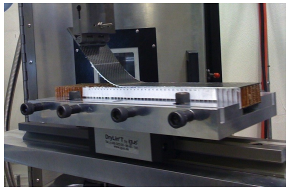
Stress Analysis

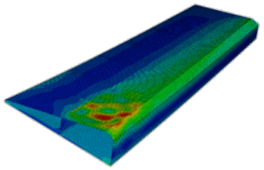
Failure Analysis

Service Findings



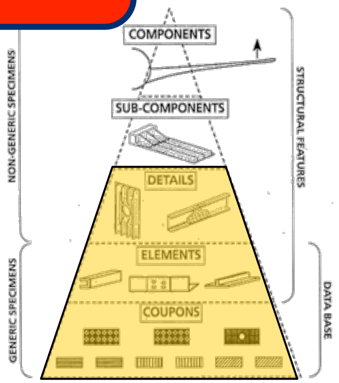
Experimental Data





Analytical Tools

Validation



Guidelines

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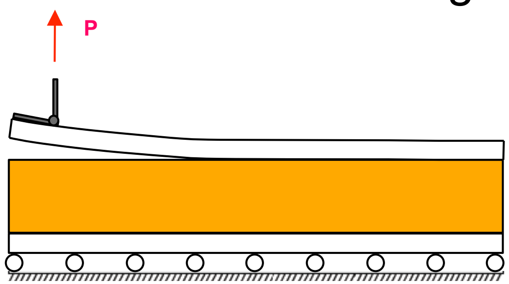
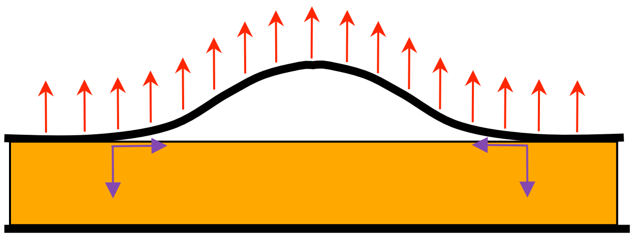
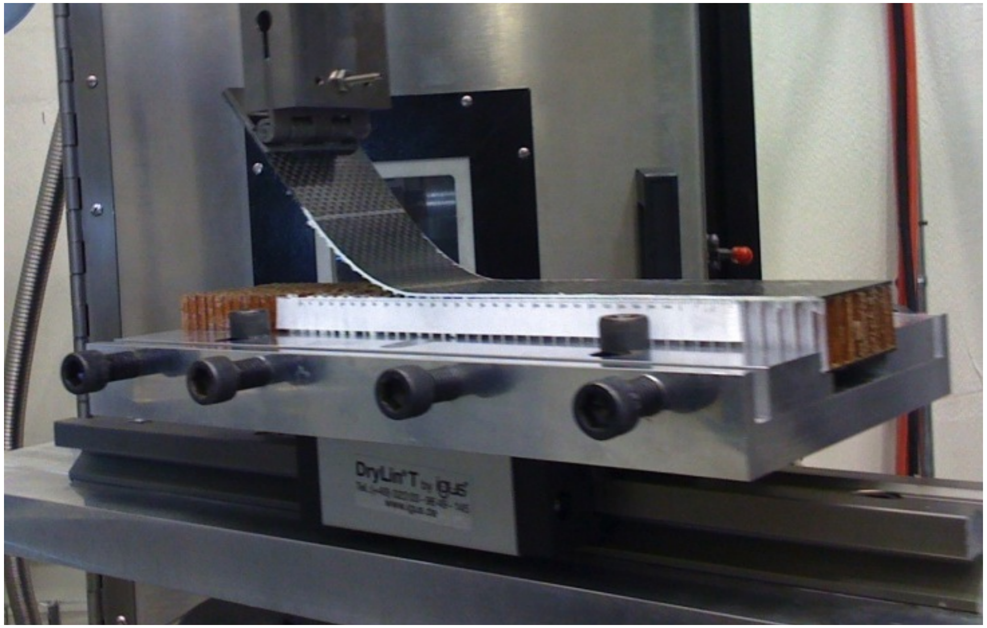
SCB Method

- Static testing follows Modified ASTM D 5528-01
  - 2 X 10-inch specimen
  - Initial disbond length = 2.5-inch
  - Use SCB fixture instead of DCB fixture
    - Prevents asymmetric loading
    - Prevents mixed-mode mechanics
    - Prevents kinking



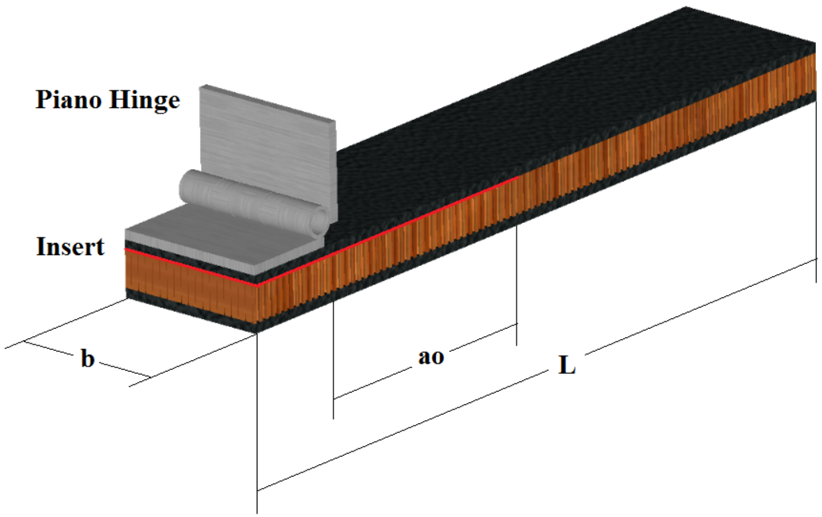




Test Specimen

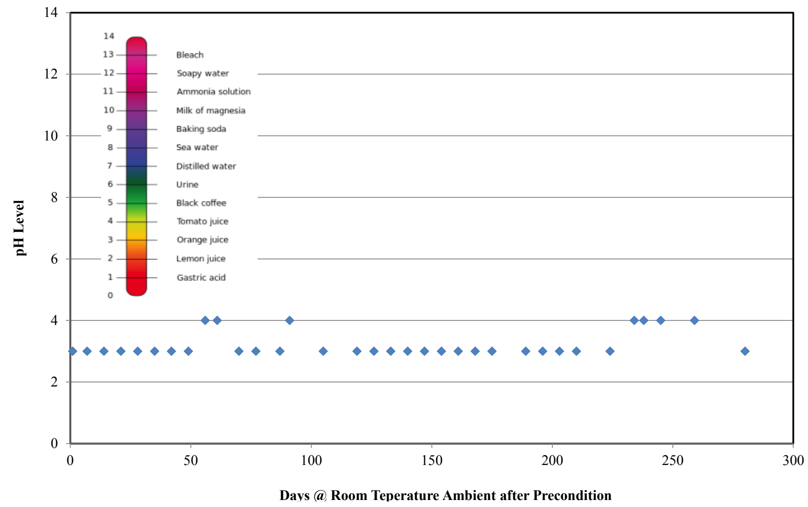
- Material
  - Facesheet: AS4 E7K8 PW
  - Core: Hexcel HRH-10 Aramid Fiber/Phenolic Honeycomb
  - Adhesive: FM300 epoxy film adhesive
- Prescribed Crack
  - Created with Teflon (placed on bag-side)
  - ao=2.5in (1.0in for shortened)
    - Specimens were shortened in order to obtain better non-linear displacements and are indicated with an *
- Co-cured (one cycle)

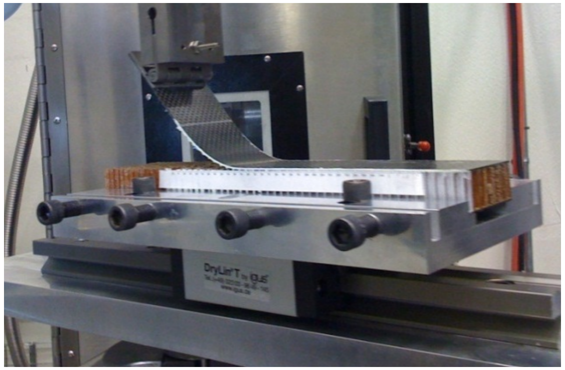
- Machined
  - L=10.0in (8.5in for shortened)
  - b=2in
- Piano Hinge
  - Bonded using EA9394



Test Parameters

- Facesheet Thickness
  - 4 ply: $[0°/45°]_S$
  - 16 ply: $[0°/45°]_{4S}$
- Core Type
  - Hexagonal and Over-Expanded
- Cell Size
  - 1/8, 3/16, and 3/8 inch
- Core Density
  - 2 , 3, and 6 pcf
- Environmental Condition
  - Baseline RTA, Skydrol-Ingressed, Extended Skydrol-Ingressed, Water-Ingressed
- Prescribed Crack Length
  - ao = 2.5 and 1.0 inch





Static Data Reduction

- Critical Strain Energy Release Rate
  - Euler Beam Theory

$$G_{IC} = \frac{3P\delta}{2ba}$$

- Modified Beam Theory (MBT)
  - Beam theory assumes the crack front is perfectly built-in, however; the crack tip may have small displacements and rotations
  - This can be corrected for by artificially lengthening the crack an additional Δa

$$G_{IC} = \frac{3P\delta}{2b(a+\Delta a)}$$

- Large Deflection Correction Factor
  - Beam theory assumes small deflections, however; the crack tip experiences large deflection, especially in the 4 ply (thin facesheet) specimens
  - This can be corrected for by artificially shortening the moment arm by the correction factor F

$$G_{IC} = \frac{3P\delta}{2b(a+\Delta a)}F$$

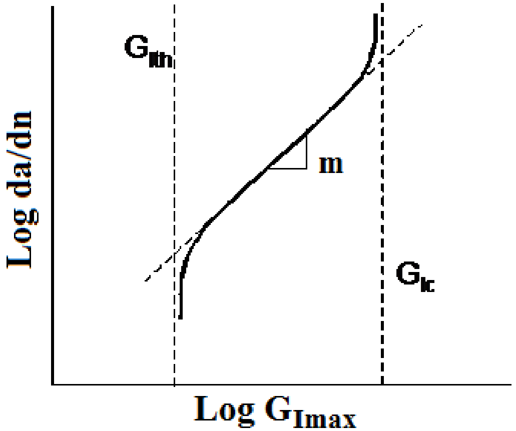
Fatigue Data Reduction

- Fatigue loads were determined from static baseline non-linear displacements
  - A few specimens used the fluid-ingressed non-linear displacements and are indicated with an **
- Crack growth rate was an average and fracture toughness was determined using MBT
- Paris' region was defined using a power law
- The shaping parameter, m, was evaluated

$$\frac{\delta_{\max}^2}{\delta_{nl}^2} = 0.9 \qquad \frac{\delta_{\min}}{\delta_{\max}} = 0.1$$

$$\frac{da}{dn} = \frac{a_{i+1} - a_i}{n_{i+1} - n_i} \qquad G_{\mathrm{I}\max} = \frac{3P_{\max}\delta_{\max}}{2b\left(\bar{a} + |\Delta|_{av}\right)}$$

$$\frac{da}{dn} = BG_{\mathrm{I}\max}^m$$



SCB Test Matrix

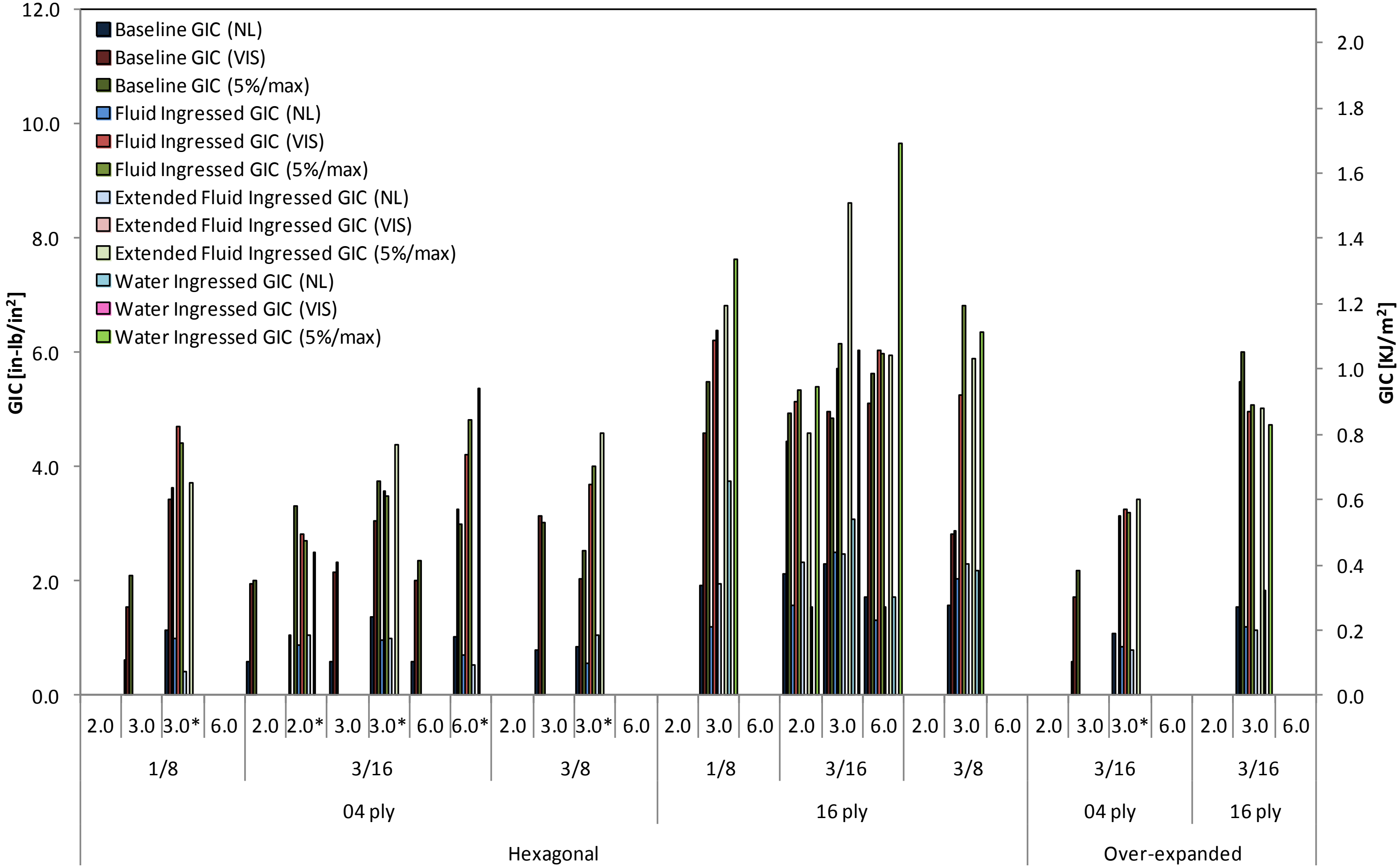
Core Material	Core Type	Core Thickness [in]	Facesheet	Cell Size [in]	Core Density [lb/ft^3]	Number of Static Test Specimens				Number of Fatigue Test Specimens	
						Baseline	Fluid Ingressed	Extended Fluid Ingressed	Water Ingressed	Baseline	Fluid Ingressed
HRH-10	HX	0.5	4-ply [0/45]s	1/8	3	6					
					3.0*	3	6	1		6	6
				3/16	2	6					
					2.0*	3	6	1		6	6
					3	6					
					3.0*	3	6	1		6	6
					6	6					
					6.0*	3	6	2		6	6
				3/8	3	6					
					3.0*	3	6	2		6	6
			16-ply [0/45]4s	1/8	3	6	6	2	4	6	3
					3**						4
				3/16	2	6	6	2	4	6	1
					2**						6
					3	6	6	2	3	6	3
					3**						5
					6	6	6	1	4	6	4
					6**						4
				3/8	3	6	6	2	4	6	6
	OX	0.5	4-ply	3/16	3.0*	3	6	2		6	6
			16-ply	3/16	3	6	6	1	4	6	6
Total Specimens						198				150	

* ao=1.0in (shortened)

** δmax derived from FI data

Static Test Results

[FAA Report 1: Damage Growth in Fluid-Ingressed Sandwich Structures]



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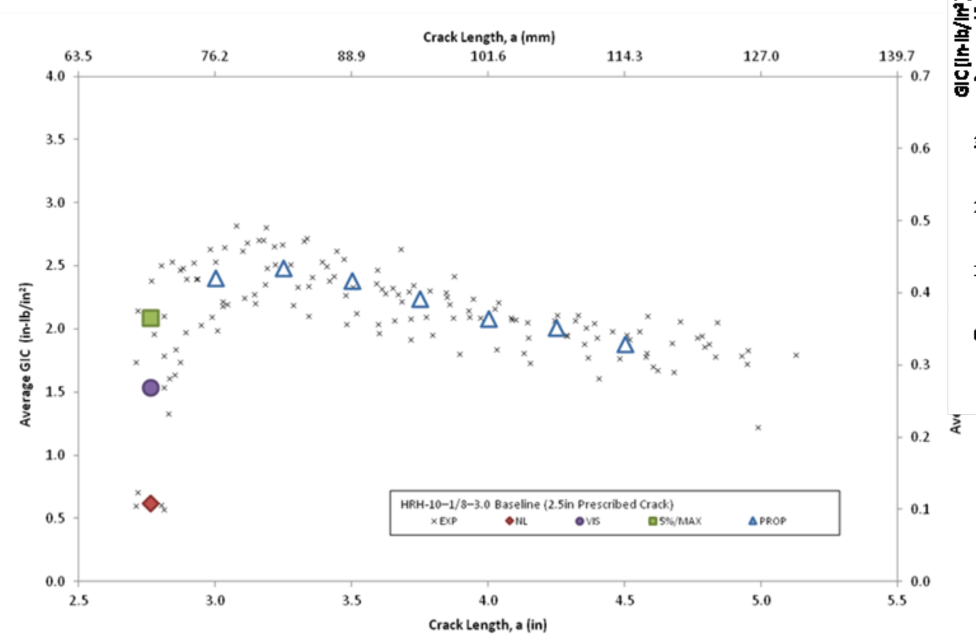
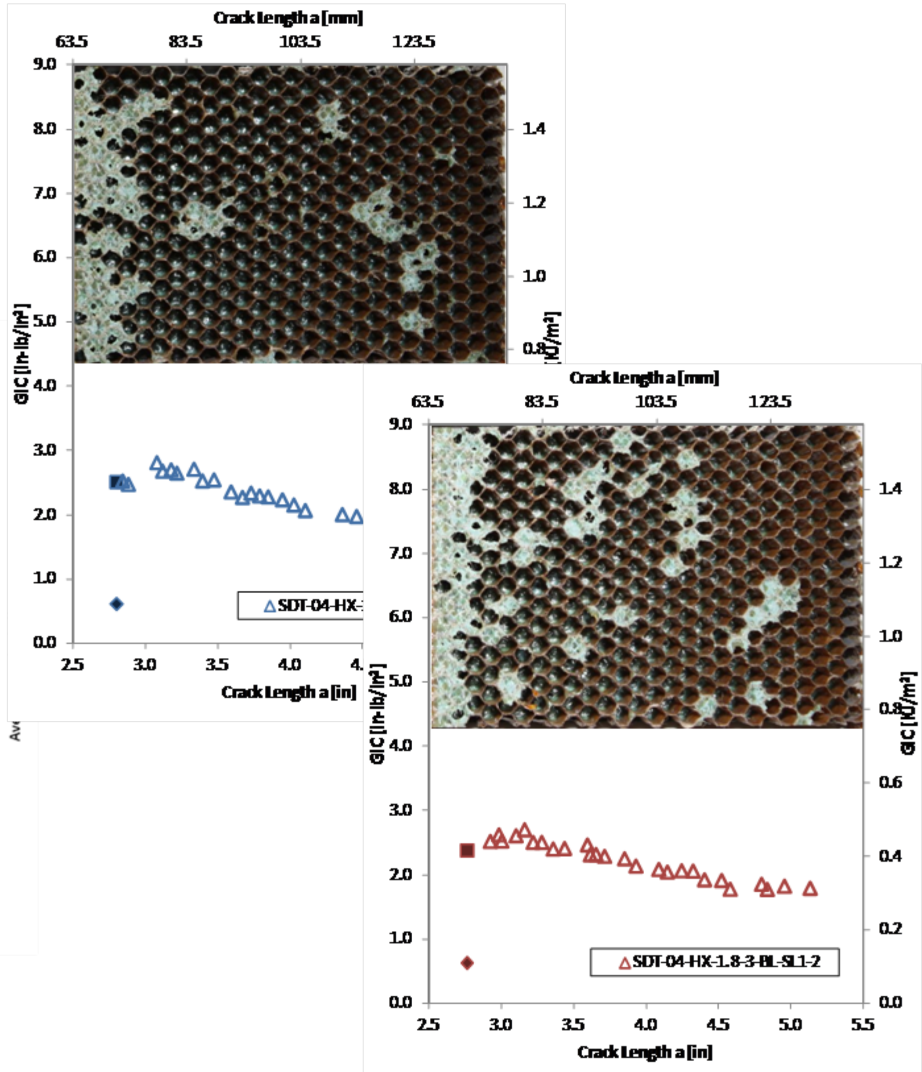
Failure Modes

- Detailed documentation of failure modes are included in two FAA final reports





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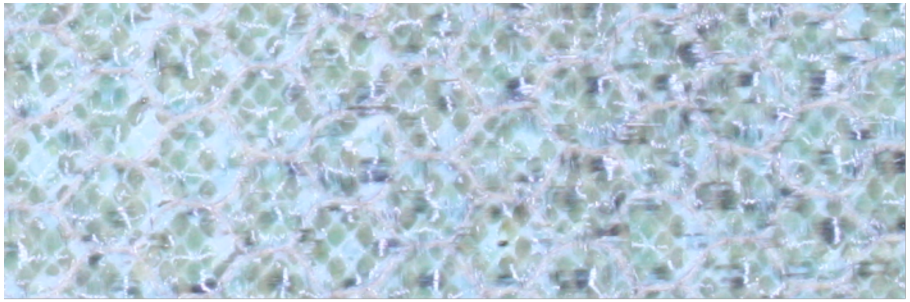
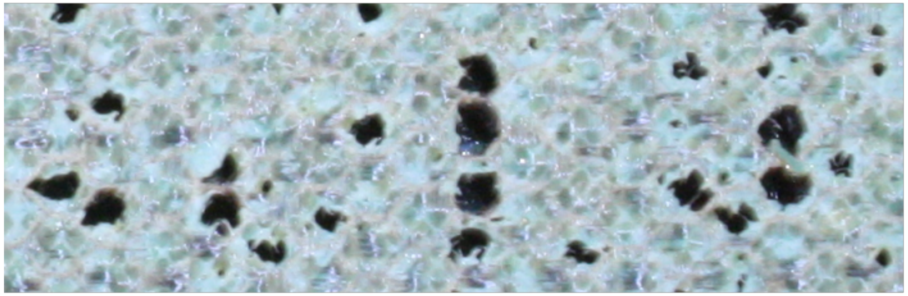
Primary Failure Modes

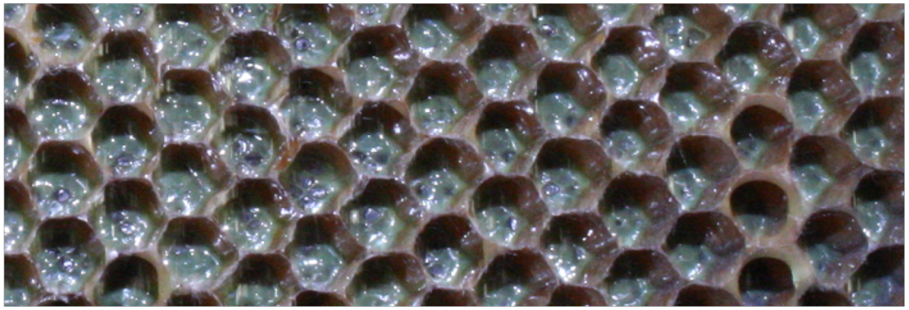
- Adhesive Interface Disbond (A)



- Adhesive Pullout (PO)



- Tensile Core Failure (S)



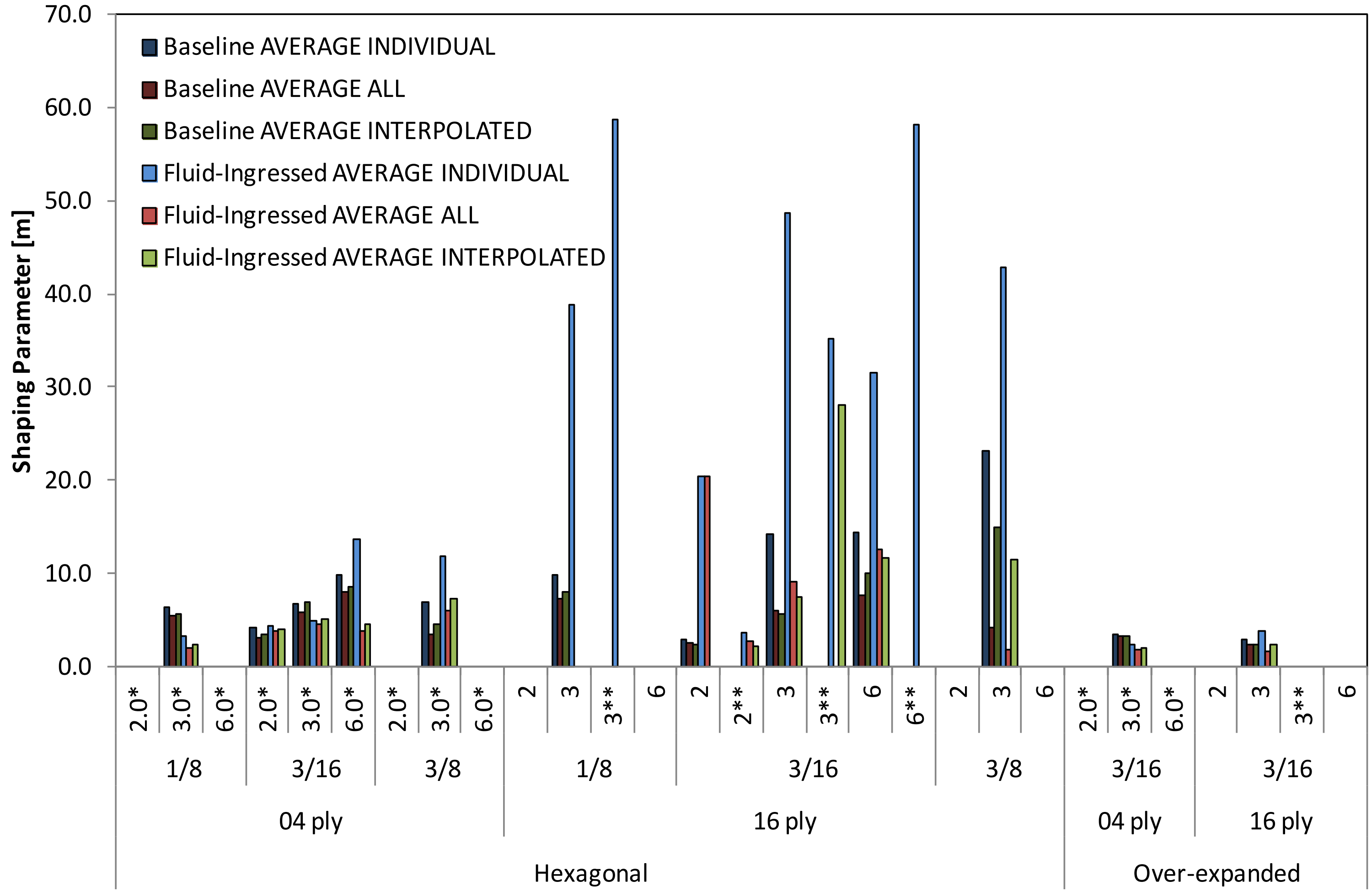
Fatigue Results

Core Type	Facesheet	Cell Size (in)	Core Density (lb/ft^3)	Baseline Average INDIVIDUAL	Baseline Average ALL	Baseline Average INTERPOLATED	Fluid-Ingressed Average INDIVIDUAL	Fluid-Ingressed Average ALL	Fluid-Ingressed Average INTERPOLATED
HX	4-ply [0/45]S	1/8	2.0*						
			3.0*	6.389	5.483	5.678	3.297	1.859	2.286
			6.0*						
		3/16	2.0*	4.059	3.045	3.441	4.318	3.704	4.026
			3.0*	6.770	5.767	6.833	4.823	4.447	5.000
			6.0*	9.891	7.934	8.528	13.654	3.733	4.434
		3/8	2.0*						
			3.0*	6.828	3.399	4.419	11.770	6.007	7.296
			6.0*						
	16-ply $[0/45]_{4S}$	1/8	2						
			3	9.739	7.297	8.039	38.823	N/A	N/A
			3**				58.739	N/A	N/A
			6						
		3/16	2	2.837	2.519	2.397	20.461	20.461	N/A
			2**				3.596	2.638	2.213
			3	14.258	6.044	5.516	48.758	9.068	7.396
			3**				35.113	N/A	28.134
			6	14.287	7.555	10.032	31.568	12.562	11.570
			6**				58.162	N/A	N/A
		3/8	2						
			3	23.081	4.136	14.947	42.943	1.803	11.481
			6						
OX	4-ply [0/45]S	3/16	2.0*						
			3.0*	3.407	3.159	3.235	2.254	1.686	1.903
			6.0*						
	16-ply [0/45]4S	3/16	2						
			3	2.774	2.368	2.316	3.831	1.529	2.254
			3**						
			6						

Notes: * ao = 1 inch; ** δ_{max} from static FI results

Fatigue Test Results

[FAA Report 2: Fatigue Damage Growth Rate of Sandwich Structures]



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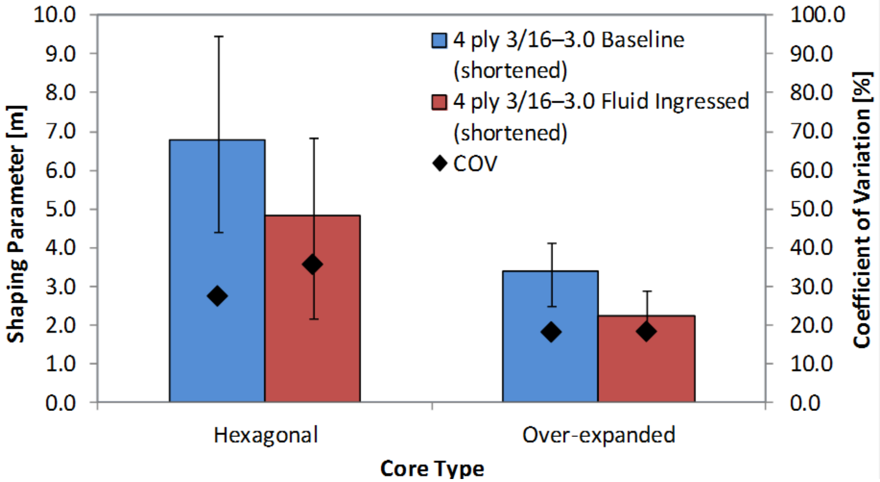
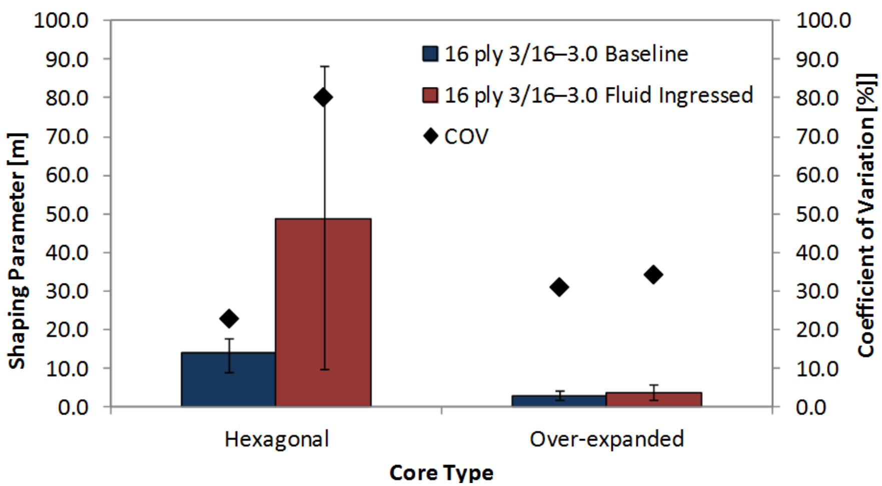
Effects of Core Type





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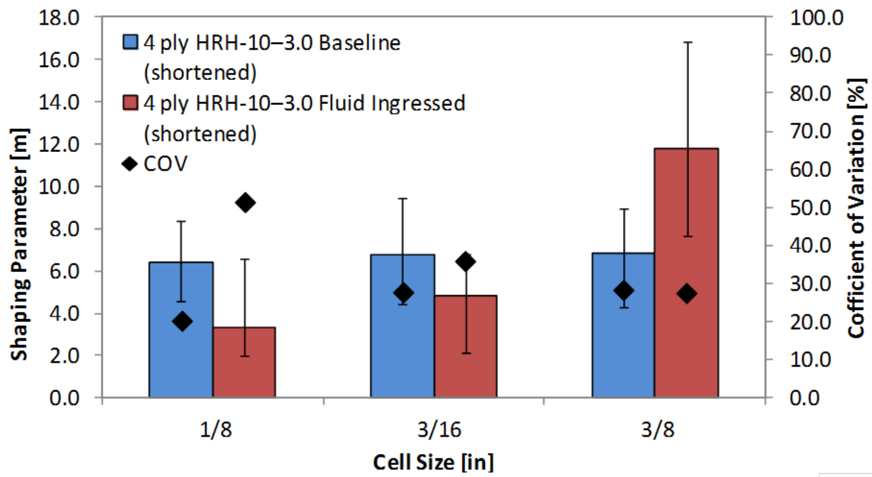
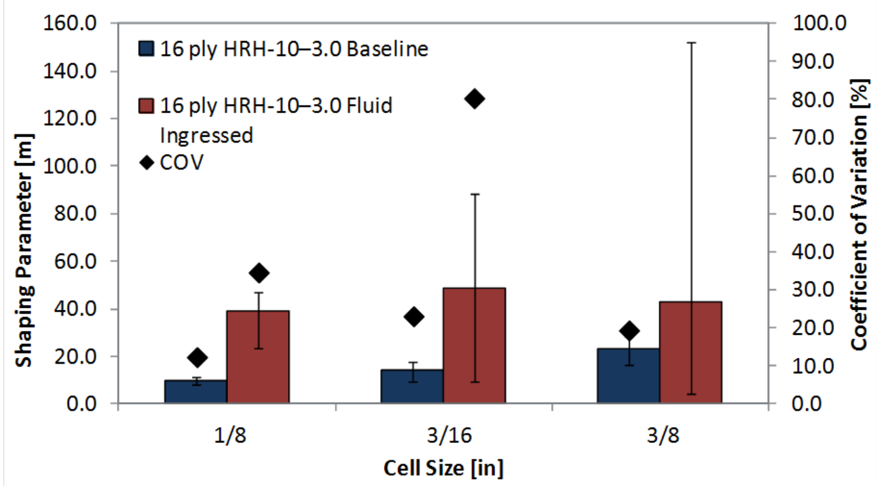
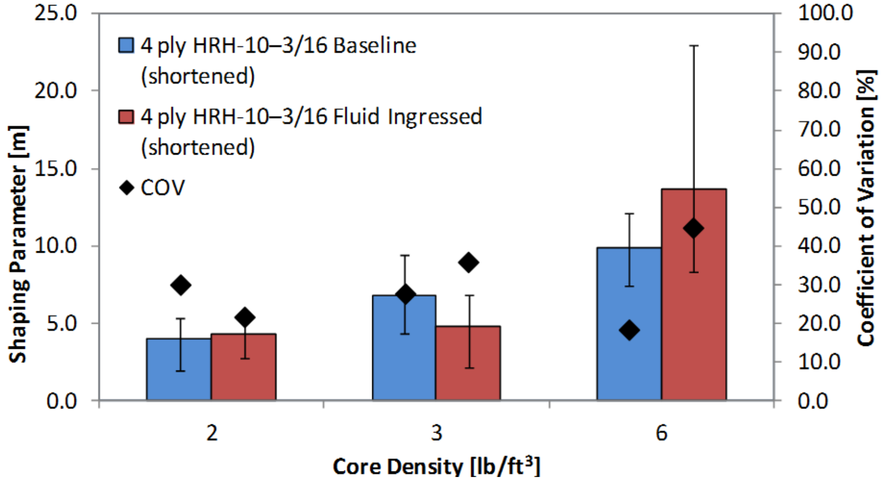
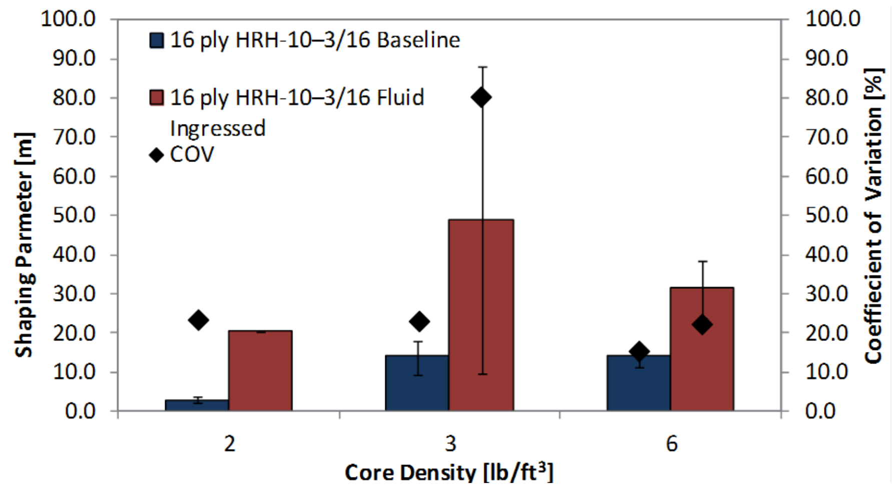
Effects of Cell Size





Effects of Core Density





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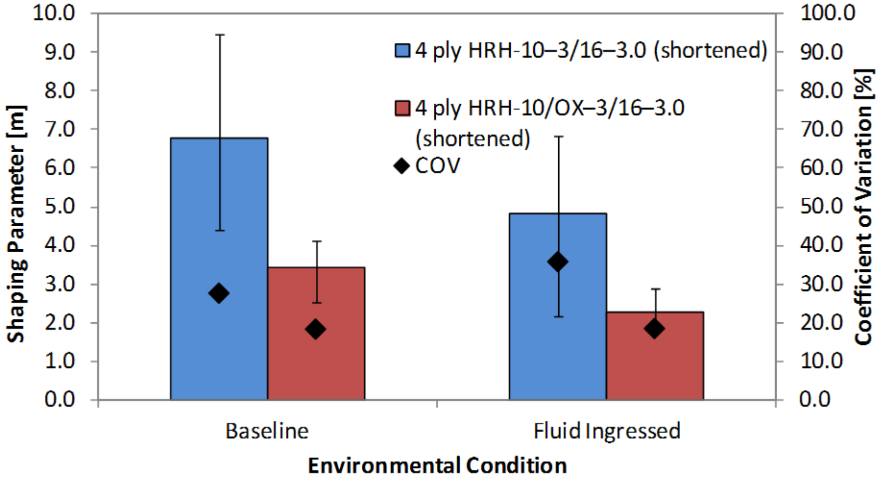
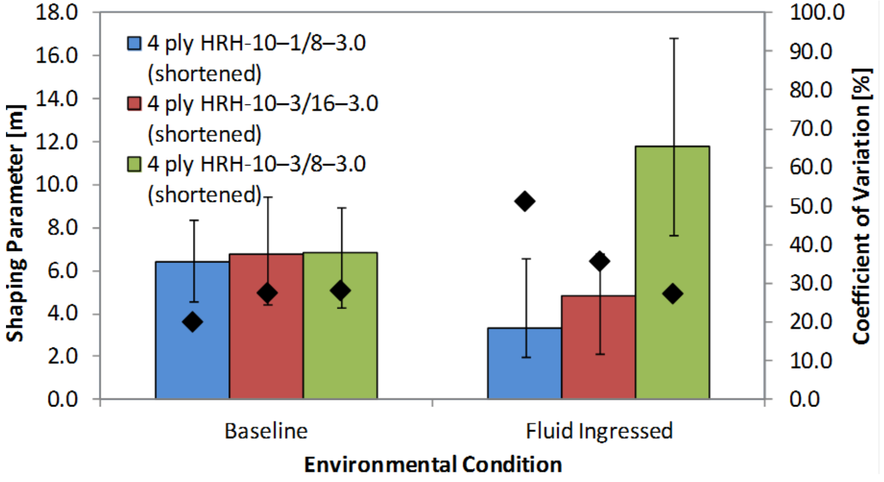
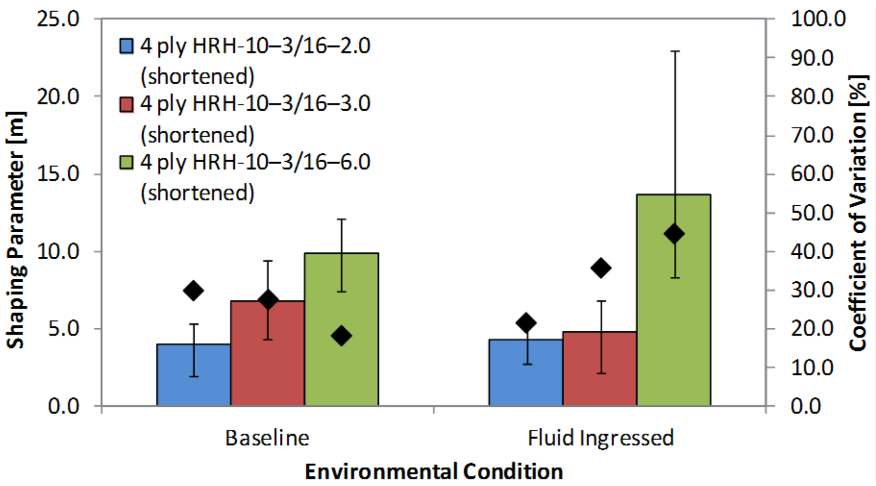
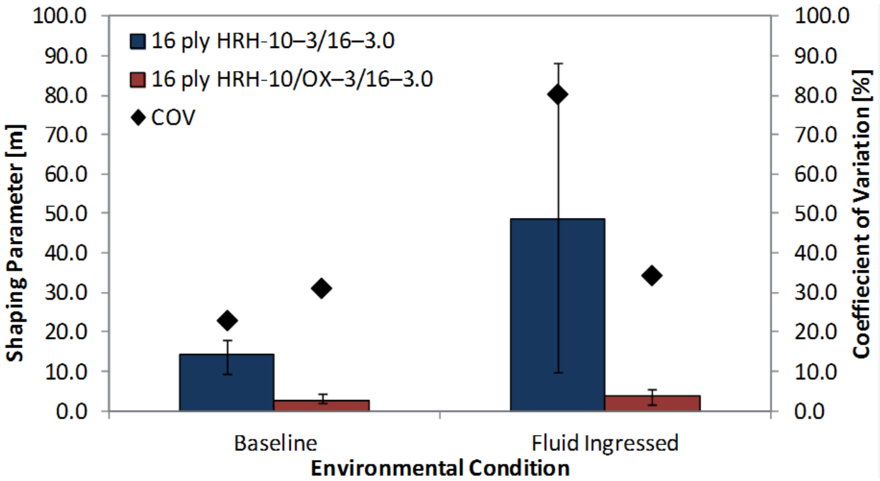
Effects of Fluid Exposure – 4 ply

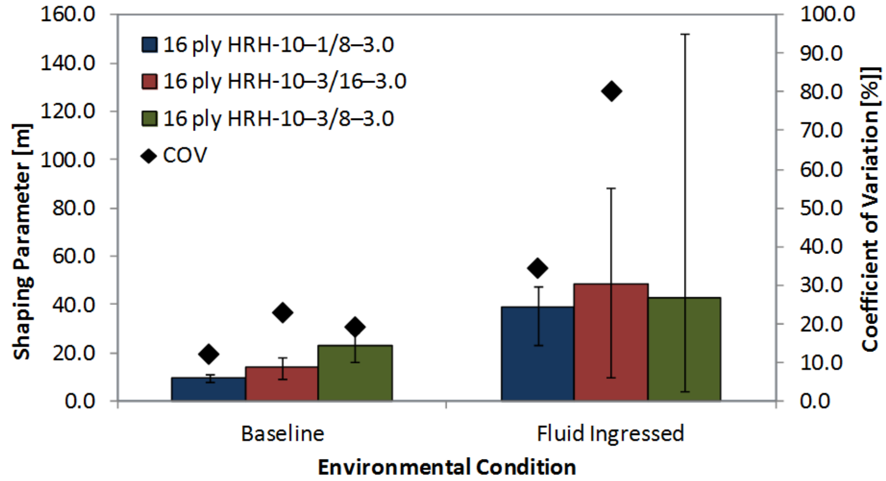


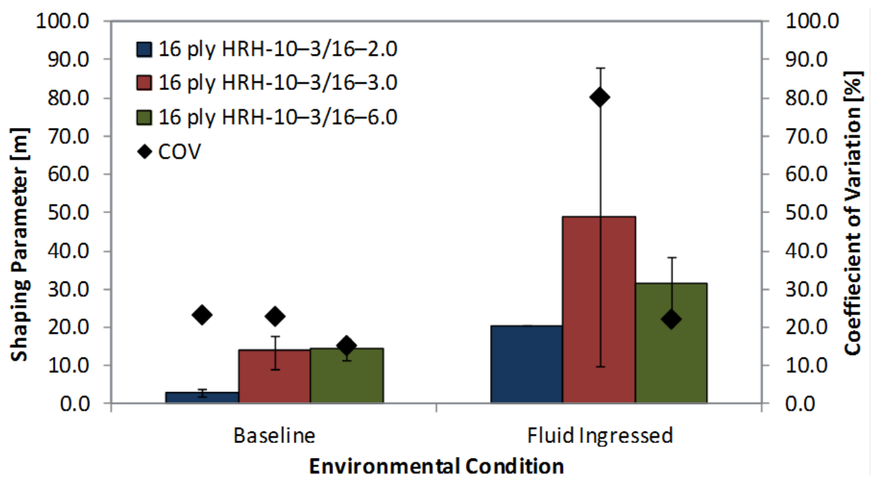




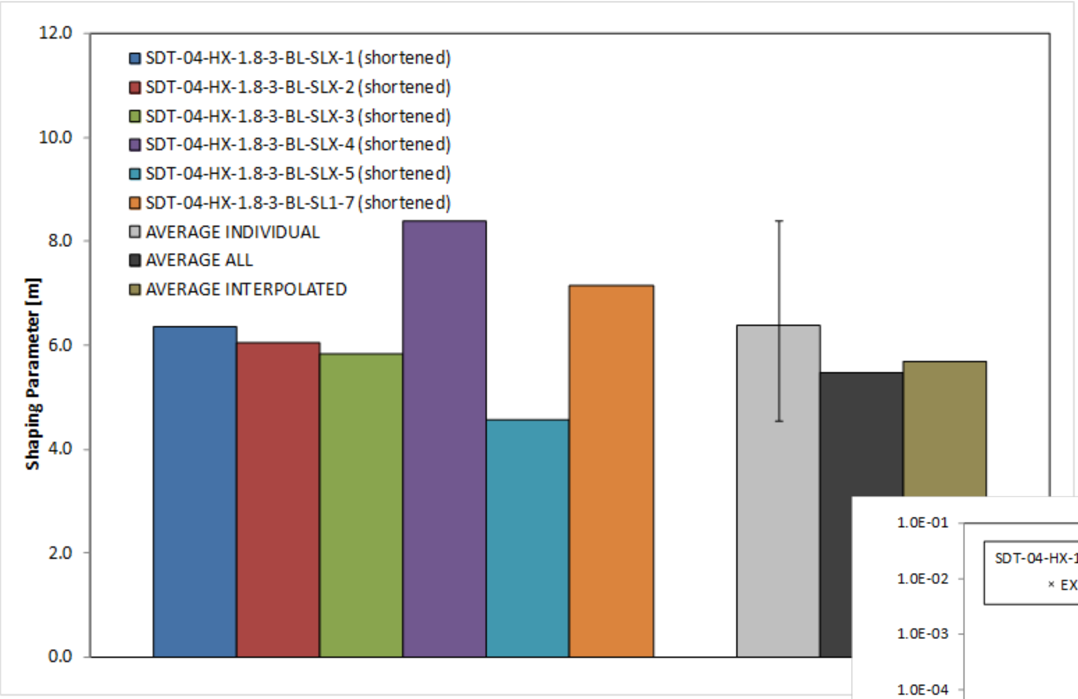
Effects of Fluid Exposure – 16 ply

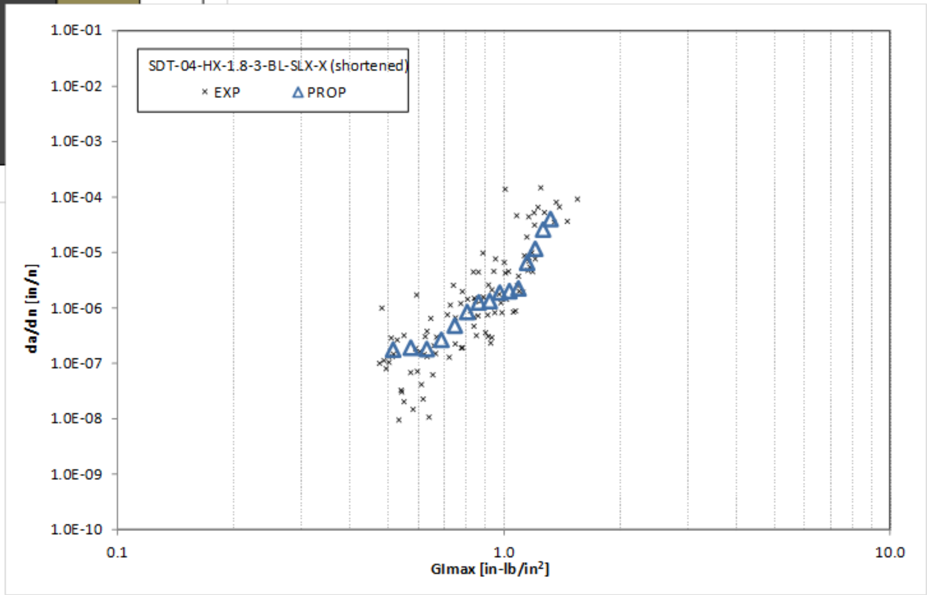






SCB Fatigue Crack Growth Data





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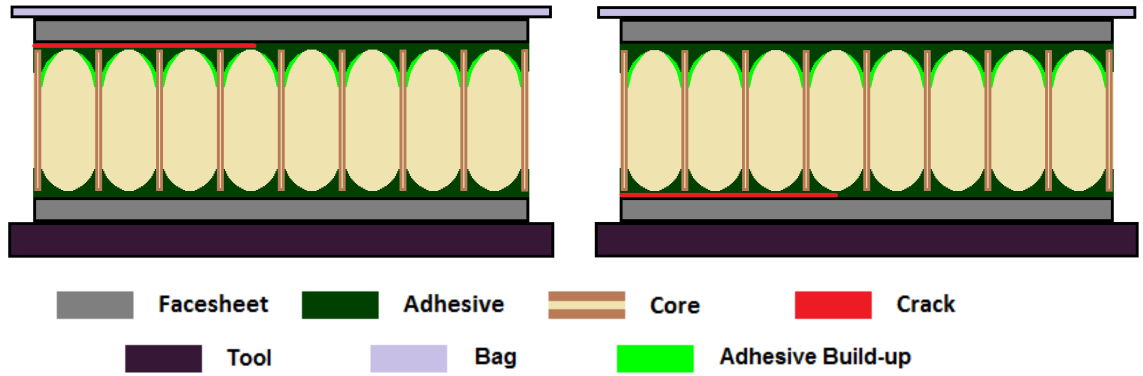
Summary - Fatigue Results

- Core Type
  - Hexagonal core had a larger shaping parameter than over-expanded core
- Cell Size
  - Cell size had varying effects on the shaping parameter and the results seemed to be coupled with both facesheet thickness and environmental conditioning
  - Fillet formation and how it artificially thickens the cell wall could also play a role
- Core Density
  - Core density had an impact on the shaping parameter, with the shaping parameter increasing as core density increased in baseline specimens and increasing then leveling off or decreasing for fluid ingressed specimens.
  - Fillet formation and how it artificially thickens the cell wall could also play a role
- Environmental Condition
  - Fluid ingression altered the crack front through both acid degradation and moisture absorption, the results varied based on facesheet thickness, the baseline specimens typically had a larger shaping parameter in four ply specimens, while the fluid ingressed were typically larger in the sixteen ply specimens

Supplemental SCB Study

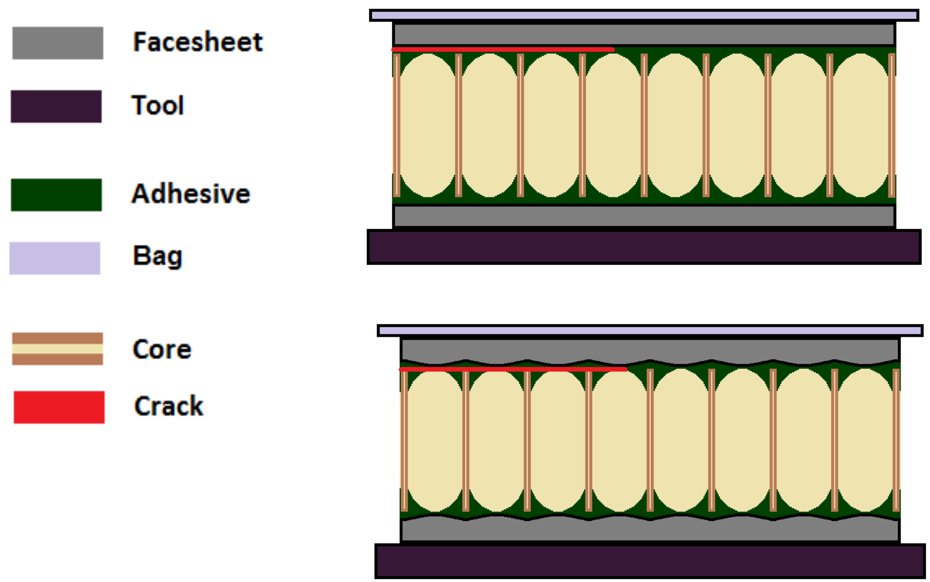
- Disbond Location
  - Top
  - Bottom



	FACE-SHEET	CORE TYPE	CELL SIZE	CELL DENSITY	ENVRON-MENT	DISBOND	CURE	RIBBON	CRACK TIP	PAPER SIZE	TEST	# of Specimens
DISBOND LOCATION [top vs. bottom]	4	HX	1/8	1.8	BL	TOP	PCFS	LONG	CENTER	1.5	SL1	6
	4	HX	1/8	3	BL	TOP	PCFS	LONG	CENTER	2	SL1	6
	4	HX	1/8	6	BL	TOP	PCFS	LONG	CENTER	3	SL1	6
	4	HX	3/16	2	BL	TOP	PCFS	LONG	CENTER	2	SL1	6
	4	HX	3/16	3	BL	TOP	PCFS	LONG	CENTER	2	SL1	6
	4	HX	3/16	6	BL	TOP	PCFS	LONG	CENTER	3 or 4	SL1	6
	4	HX	3/8	2	BL	TOP	PCFS	LONG	CENTER	3	SL1	6
	4	HX	3/8	3	BL	TOP	PCFS	LONG	CENTER	3	SL1	6
	4	OX	3/16	3	BL	TOP	PCFS	LONG	CENTER	NA	SL1	6
	4	HX	1/8	1.8	BL	BOTTOM	PCFS	LONG	CENTER	1.5	SL1	6
	4	HX	1/8	3	BL	BOTTOM	PCFS	LONG	CENTER	2	SL1	6
	4	HX	1/8	6	BL	BOTTOM	PCFS	LONG	CENTER	3	SL1	6
	4	HX	3/16	2	BL	BOTTOM	PCFS	LONG	CENTER	2	SL1	6
	4	HX	3/16	3	BL	BOTTOM	PCFS	LONG	CENTER	2	SL1	6
	4	HX	3/16	6	BL	BOTTOM	PCFS	LONG	CENTER	3 or 4	SL1	6
	4	HX	3/8	2	BL	BOTTOM	PCFS	LONG	CENTER	3	SL1	6
	4	HX	3/8	3	BL	BOTTOM	PCFS	LONG	CENTER	3	SL1	6
	4	OX	3/16	3	BL	BOTTOM	PCFS	LONG	CENTER	NA	SL1	6

Supplemental SCB Study

- Fabrication
  - Co-cured facesheets
  - Pre-cured facesheets



	FACE-SHEET	CORE TYPE	CELL SIZE	CELL DENSITY	ENVRON-MENT	DISBOND	CURE	RIBBON	CRACK TIP	PAPER SIZE	TEST	# of Specimens
FABRICATION [co-cure vs. pre-cure]	4	HX	1/8	3	BL	TOP	PCFS	LONG	CENTER	2	SL1	6
	4	HX	1/8	3	BL	BOTTOM	PCFS	LONG	CENTER	2	SL1	6
	4	HX	3/8	3	BL	TOP	PCFS	LONG	CENTER	3	SL1	6
	4	HX	3/8	3	BL	BOTTOM	PCFS	LONG	CENTER	3	SL1	6
	4	HX	1/8	3	BL	TOP	CCFS	LONG	CENTER	2	SL1	6
	4	HX	1/8	3	BL	BOTTOM	CCFS	LONG	CENTER	2	SL1	6
	4	HX	3/8	3	BL	TOP	CCFS	LONG	CENTER	3	SL1	6
	4	HX	3/8	3	BL	BOTTOM	CCFS	LONG	CENTER	3	SL1	6

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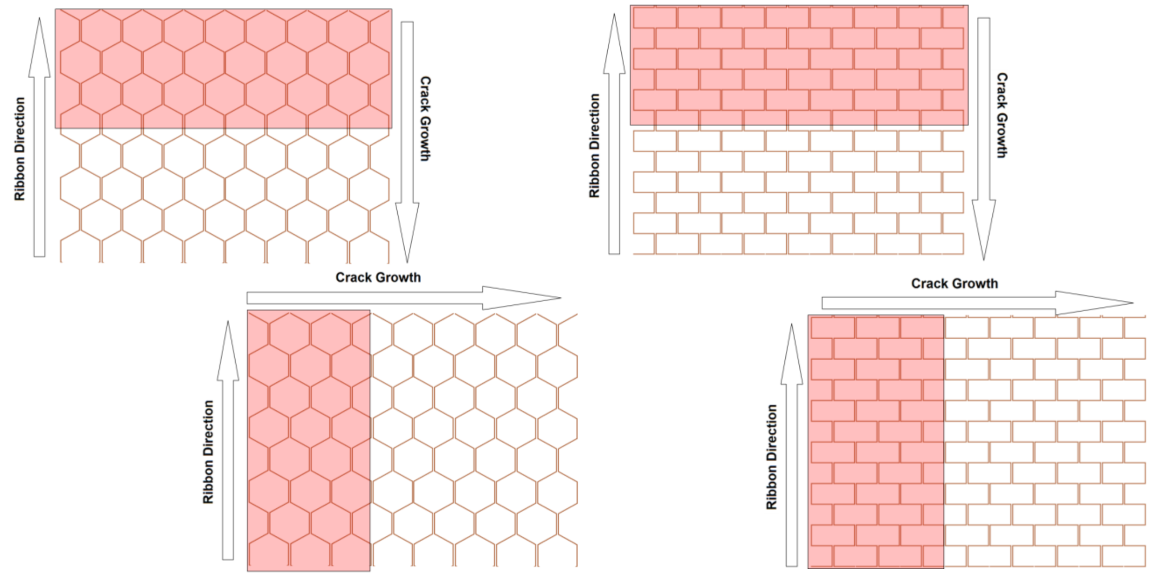
Supplemental SCB Study

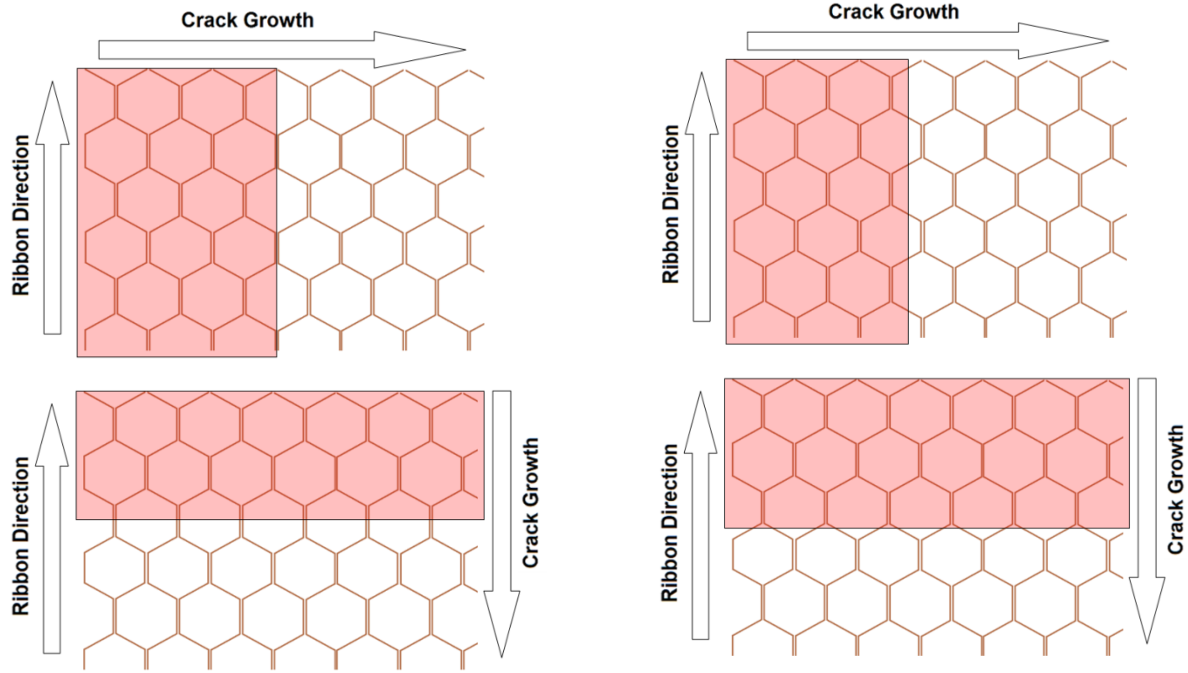
- Ribbon Direction
  - Longitudinal
  - Latitudinal



	FACE-SHEET	CORE TYPE	CELL SIZE	CELL DENSITY	ENVRON-MENT	DISBOND	CURE	RIBBON	CRACK TIP	PAPER SIZE	TEST	# of Specimens
RIBBON DIRECTION [longitude vs. latitude]	4	HX	1/8	3	BL	TOP	PCFS	LONG	CENTER	2	SL1	6
	4	HX	1/8	3	BL	BOTTOM	PCFS	LONG	CENTER	2	SL1	6
	4	HX	3/16	3	BL	TOP	PCFS	LONG	CENTER	2	SL1	6
	4	HX	3/16	3	BL	BOTTOM	PCFS	LONG	CENTER	2	SL1	6
	4	HX	3/8	3	BL	TOP	PCFS	LONG	CENTER	3	SL1	6
	4	HX	3/8	3	BL	BOTTOM	PCFS	LONG	CENTER	3	SL1	6
	4	OX	3/16	3	BL	TOP	PCFS	LONG	CENTER	NA	SL1	6
	4	OX	3/16	3	BL	BOTTOM	PCFS	LONG	CENTER	NA	SL1	6
	4	HX	1/8	3	BL	TOP	PCFS	LAT	CENTER	2	SL1	6
	4	HX	1/8	3	BL	BOTTOM	PCFS	LAT	CENTER	2	SL1	6
	4	HX	3/16	3	BL	TOP	PCFS	LAT	CENTER	2	SL1	6
	4	HX	3/16	3	BL	BOTTOM	PCFS	LAT	CENTER	2	SL1	6
	3	HX	3/8	3	BL	TOP	PCFS	LAT	CENTER	3	SL1	6
	4	HX	3/8	3	BL	BOTTOM	PCFS	LAT	CENTER	3	SL1	6
	4	OX	3/16	3	BL	TOP	PCFS	LAT	CENTER	NA	SL1	6
	4	OX	3/16	3	BL	BOTTOM	PCFS	LAT	CENTER	NA	SL1	6

Supplemental SCB Study

- Crack Tip Location
  - Center
  - Edge



	FACE-SHEET	CORE TYPE	CELL SIZE	CELL DENSITY	ENVRON-MENT	DISBOND	CURE	RIBBON	CRACK TIP	PAPER SIZE	TEST	# of Specimens
CRACK TIP LOCATION [edge vs. center]	4	HX	1/8	3	BL	BOTTOM	PCFS	LAT	CENTER	2	SL1	6
	4	HX	1/8	3	BL	BOTTOM	PCFS	LONG	CENTER	2	SL1	6
	4	HX	3/8	3	BL	BOTTOM	PCFS	LAT	CENTER	3	SL1	6
	4	HX	3/8	3	BL	BOTTOM	PCFS	LONG	CENTER	3	SL1	6
	4	HX	1/8	3	BL	BOTTOM	PCFS	LAT	EDGE	2	SL1	6
	4	HX	1/8	3	BL	BOTTOM	PCFS	LONG	EDGE	2	SL1	6
	4	HX	3/8	3	BL	BOTTOM	PCFS	LAT	EDGE	3	SL1	6
	4	HX	3/8	3	BL	BOTTOM	PCFS	LONG	EDGE	3	SL1	6

Summary

- Core Type
  - Hexagonal core had a larger shaping parameter than over-expanded core
- Cell Size
  - Cell size had varying effects on the shaping parameter and the results seemed to be coupled with both facesheet thickness and environmental conditioning
  - Fillet formation and how it artificially thickens the cell wall could also play a role
- Core Density
  - Core density had an impact on the shaping parameter, with the shaping parameter increasing as core density increased in baseline specimens and increasing then leveling off or decreasing for fluid ingressed specimens.
  - Fillet formation and how it artificially thickens the cell wall could also play a role
- Environmental Condition
  - Fluid ingression altered the crack front through both acid degradation and moisture absorption, the results varied based on facesheet thickness, the baseline specimens typically had a larger shaping parameter in four ply specimens, while the fluid ingressed were typically larger in the sixteen ply specimens
- FAA final reports
  - Damage Growth in Sandwich Structures (Vol. I)
  - Fatigue Damage Growth Rate in Sandwich Structures (Vol. II)

Looking Forward

- **Benefit to Aviation**
  - Guidelines for substantiating sandwich structures
    - Fluid ingression phenomenon
    - GAG effects on damage growth
    - Effects of geometry and sandwich parameters on fracture toughness and damage growth rates
- **Future needs**
  - Field history data related to sandwich data growth phenomenon
  - Analytical methods
  - Standardized test procedures

End of Presentation.

Thank you.

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