Joint Centers of Excellence for Advanced Materials

Development of Higher-Level Building Block Testing Standards

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Development of Higher-Level Building Block Testing Standards

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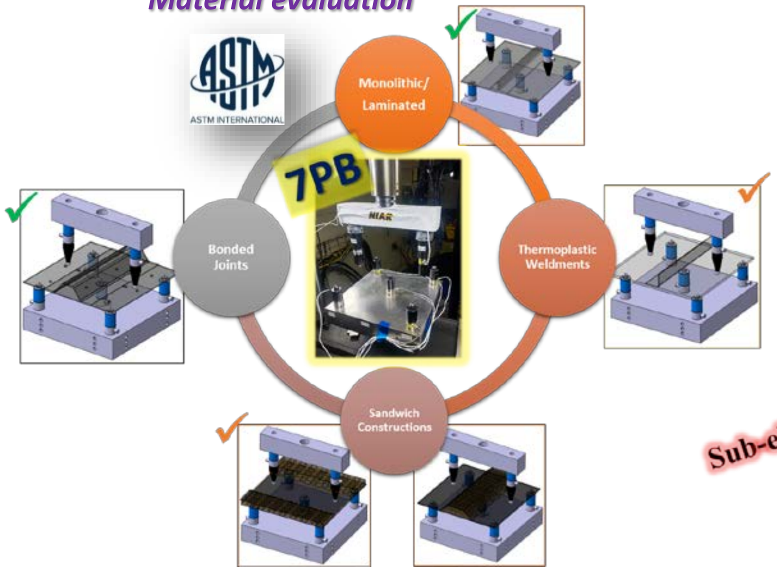
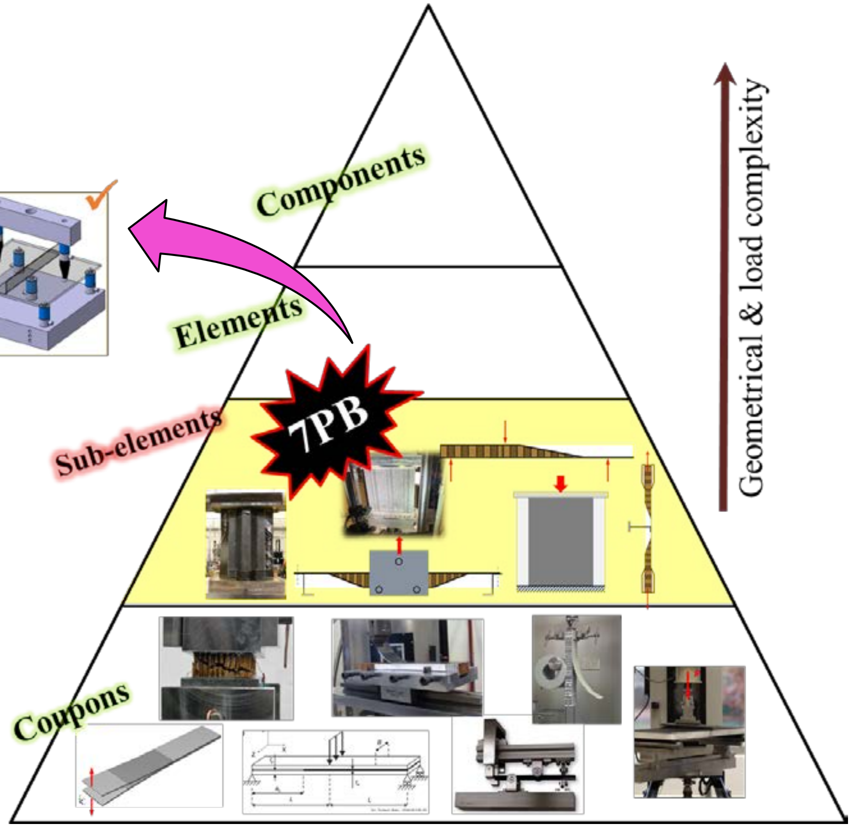
A Higher-Level Building Block Test Standard for Sub-Element level Features

Suited for Design, Geometry, Bondline & Material evaluation

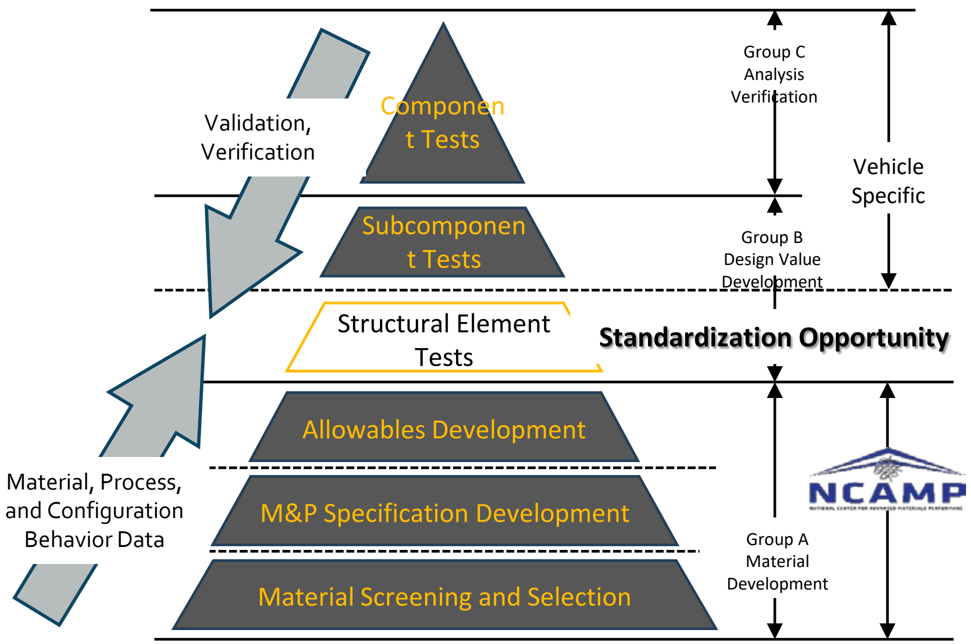




TECHNICAL DESCRIPTION

A unique test methodology aimed at detecting *bonded joints, sandwich designs, attachment features* etc. The methodology aims to bridge the gap between coupon & components level test. Primary goal is to identify *weak designs* using the selected methodology which also introduces complex loading scenario.

Approach



Project Goals

- **Design & Development of sub-element based test methodology for *Monolithic & Bonded Structures***
- ***Evaluate design conservatism in lower-level compared to higher-level Building Block Testing***

Test Findings & Analysis Takeaways

- **Seven Point Bend (7PB) is clearly a mixed-mode test**
- **Easy to install & operate; yet robust enough to introduce complex loading *(long. & transv. bending components)***
- **Developed *Cohesive Zone* based model is able to capture general specimen kinematics & damage growth.**
- **Self-similar crack progression at skin-stringer interface w/ Zero thickness cohesive layer is *robust*.**

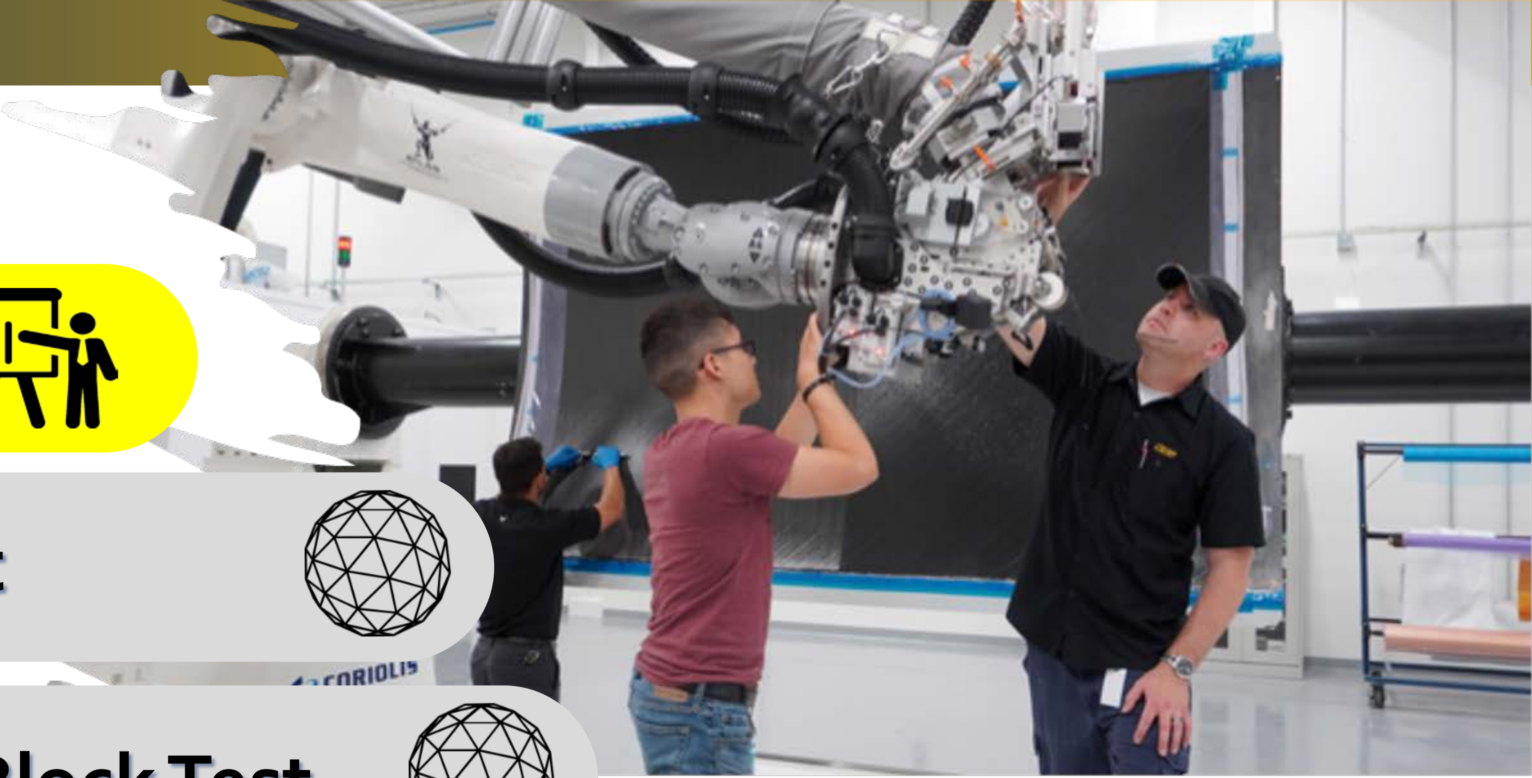
Program Overview

Mid-Level Building Block Test

"Smart" Mid-Level Building Block Test

Test Performance Evaluation

Process & Scaling Effects



Background – M&P Variability

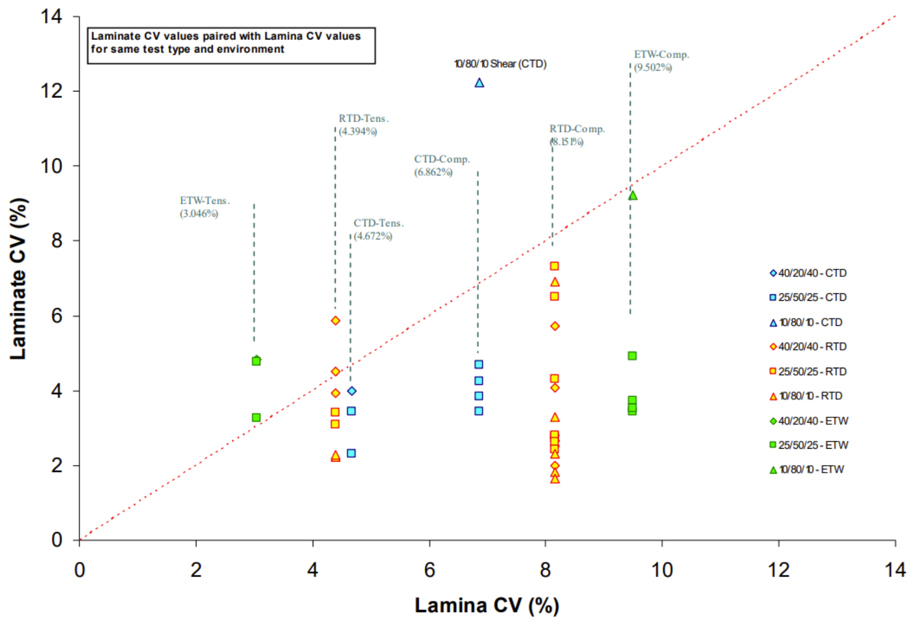


Figure 22. Toray PW Data CV Comparison

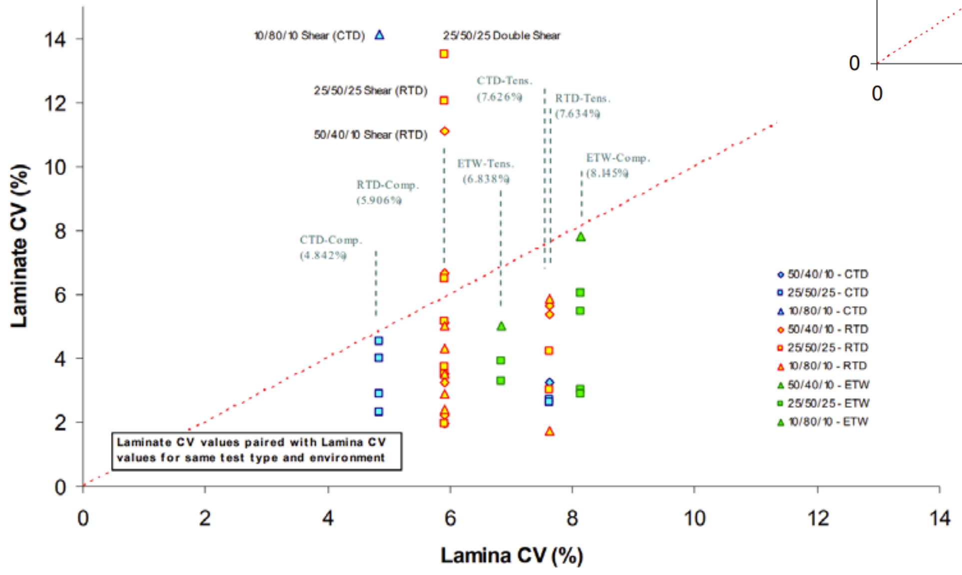
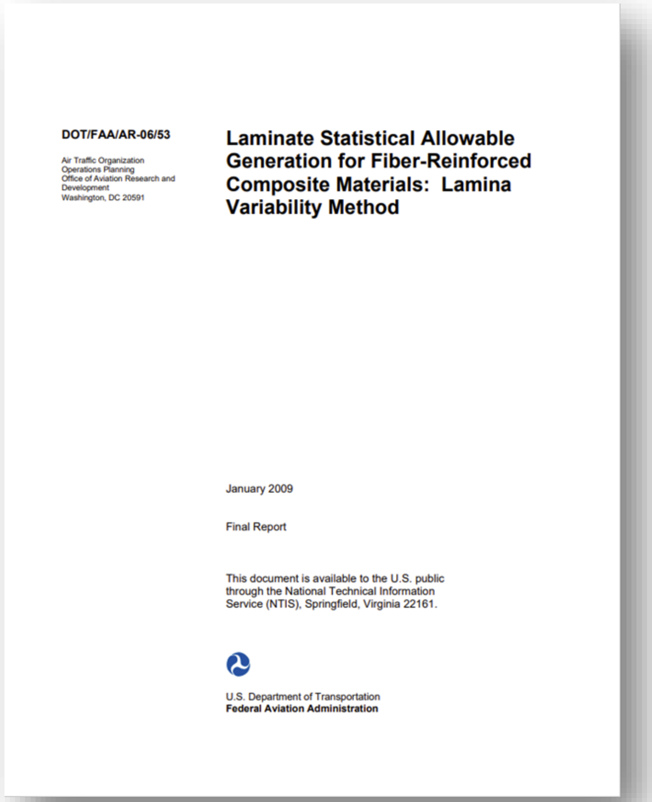
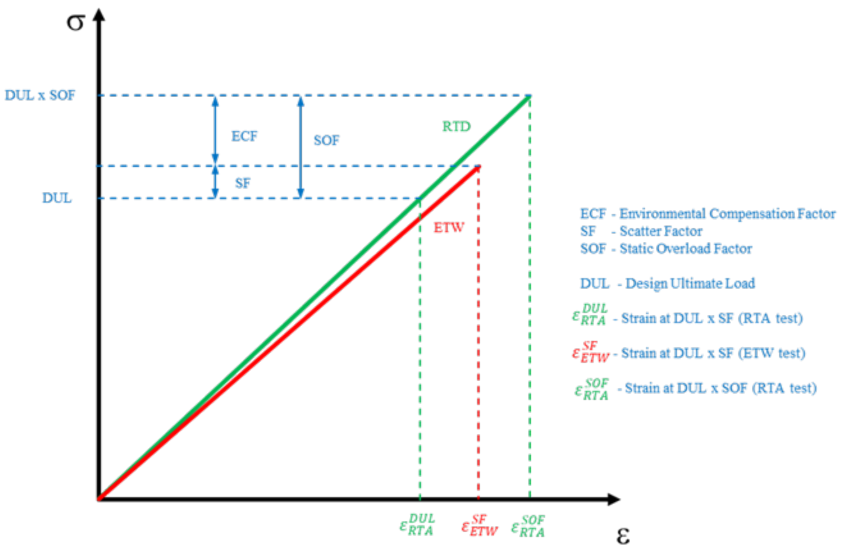


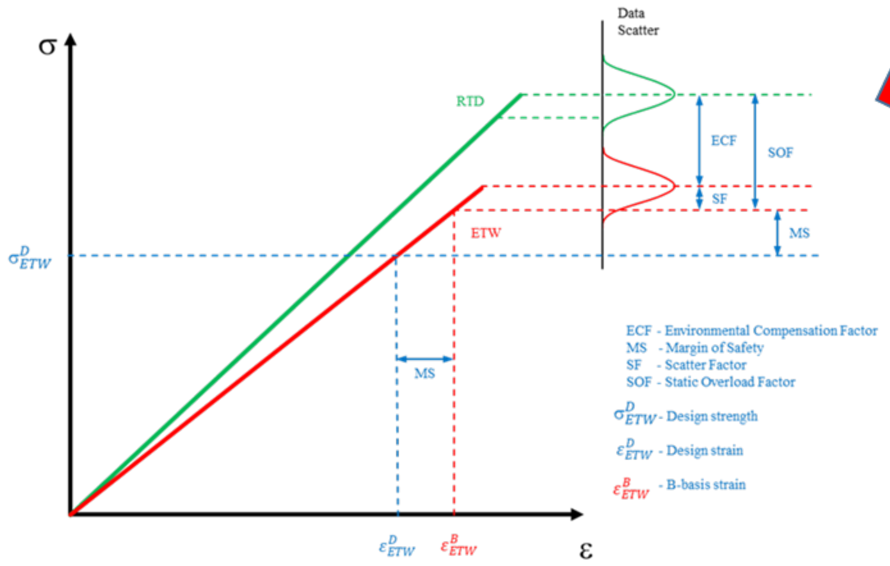
Figure 21. Toray Tape Data CV Comparison

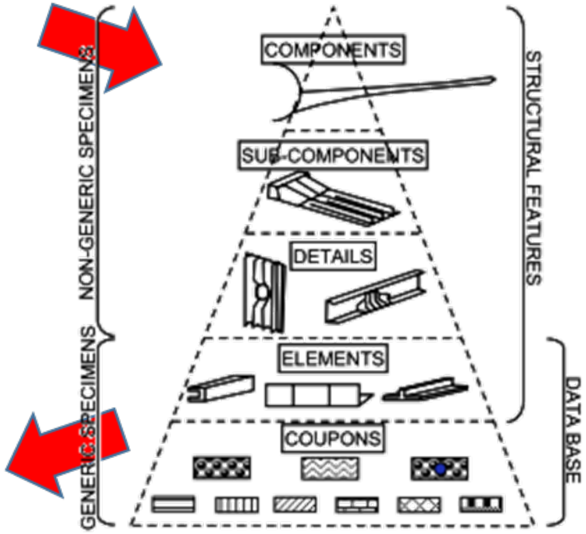


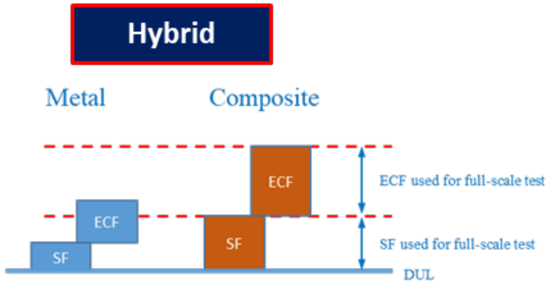
REF: Tomblin, J.S. and Seneviratne, W.P., **Laminate Statistical Allowable Generation for Fiber Reinforced Composite Materials – Lamina Variability Method (LVM),** DOT/FAA/AR-06/53.

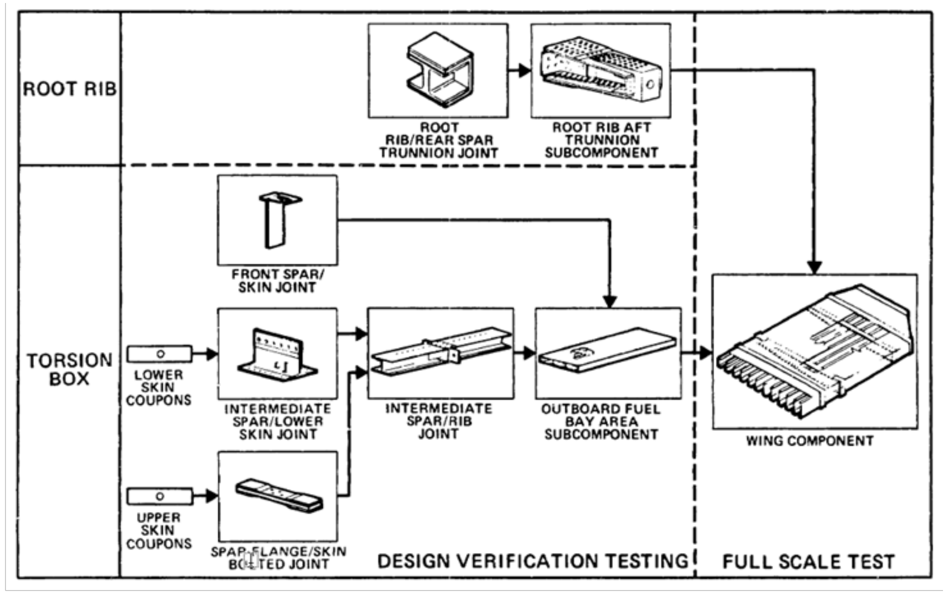
Background - Static Overload Factor (ECF+SF)

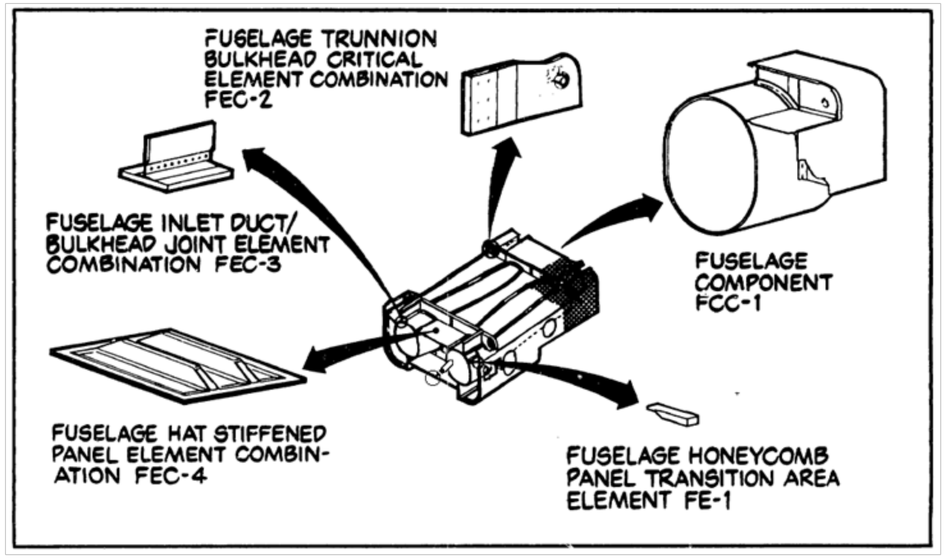












Program Overview

Mid-Level Building Block Test

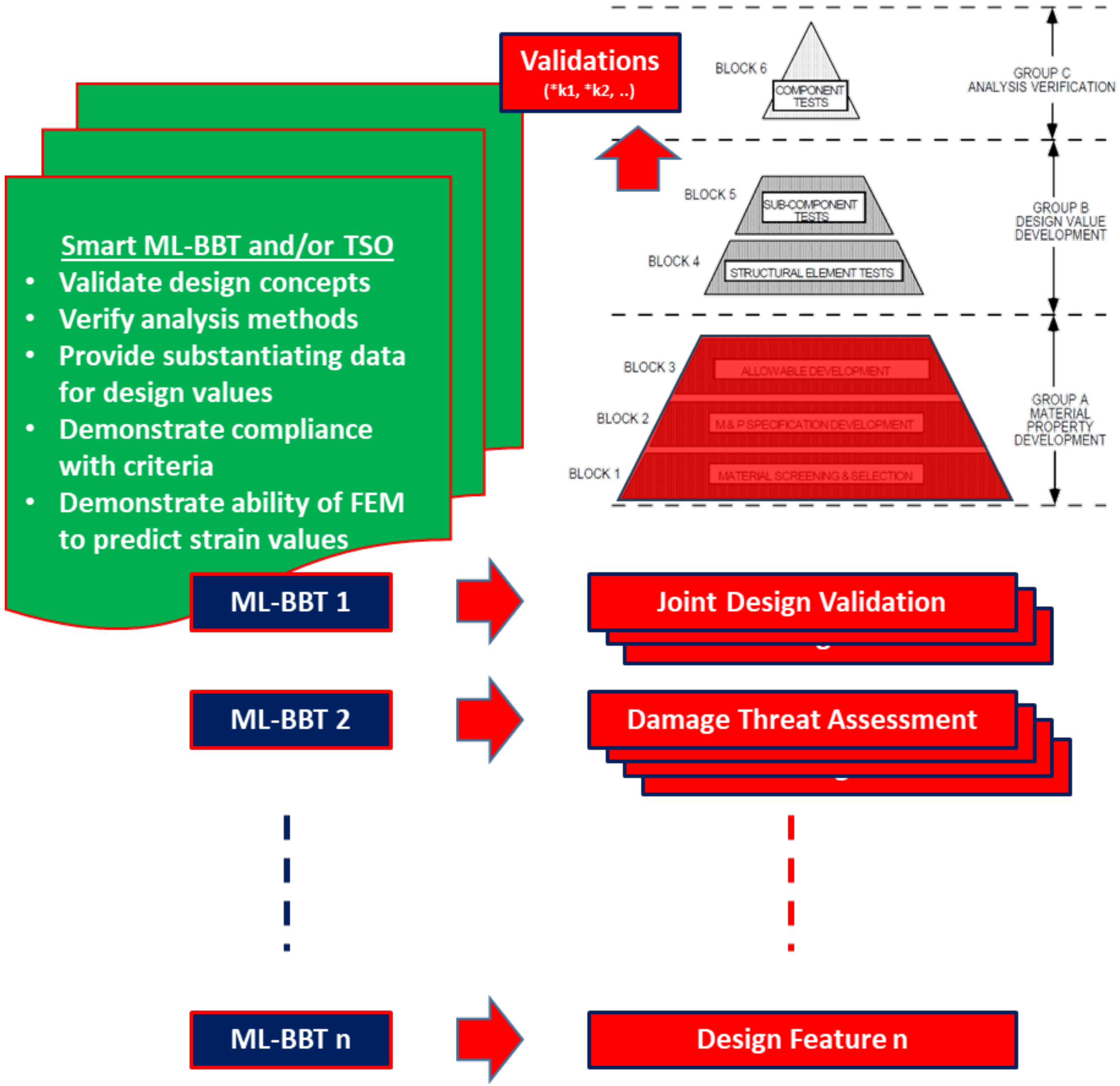
"Smart" Mid-Level Building Block Test

Test Performance Evaluation

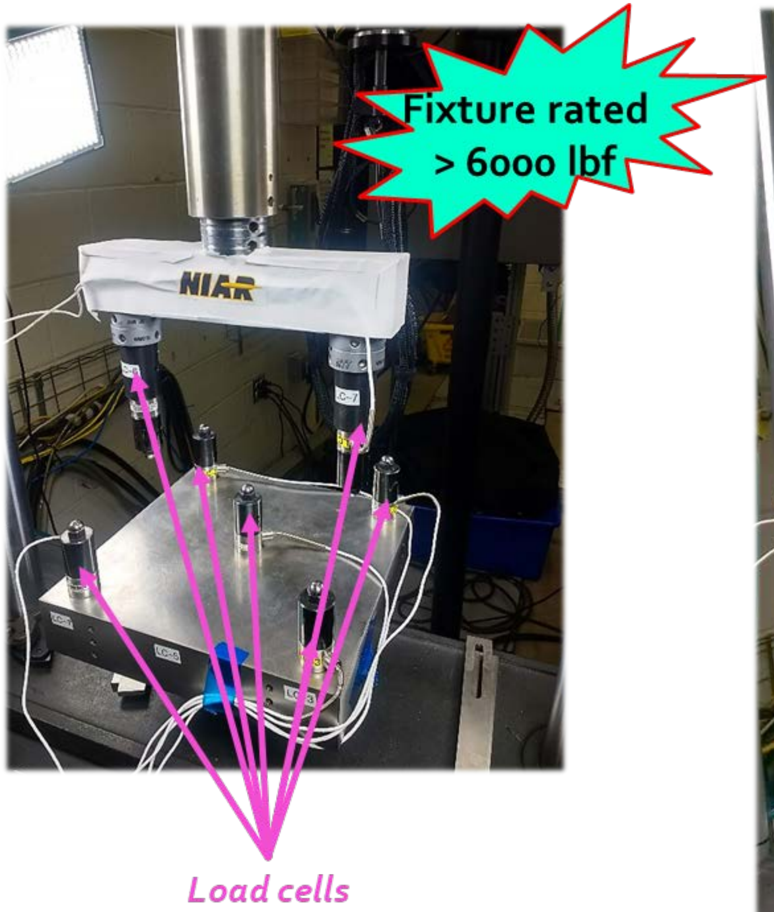
Process & Scaling Effects

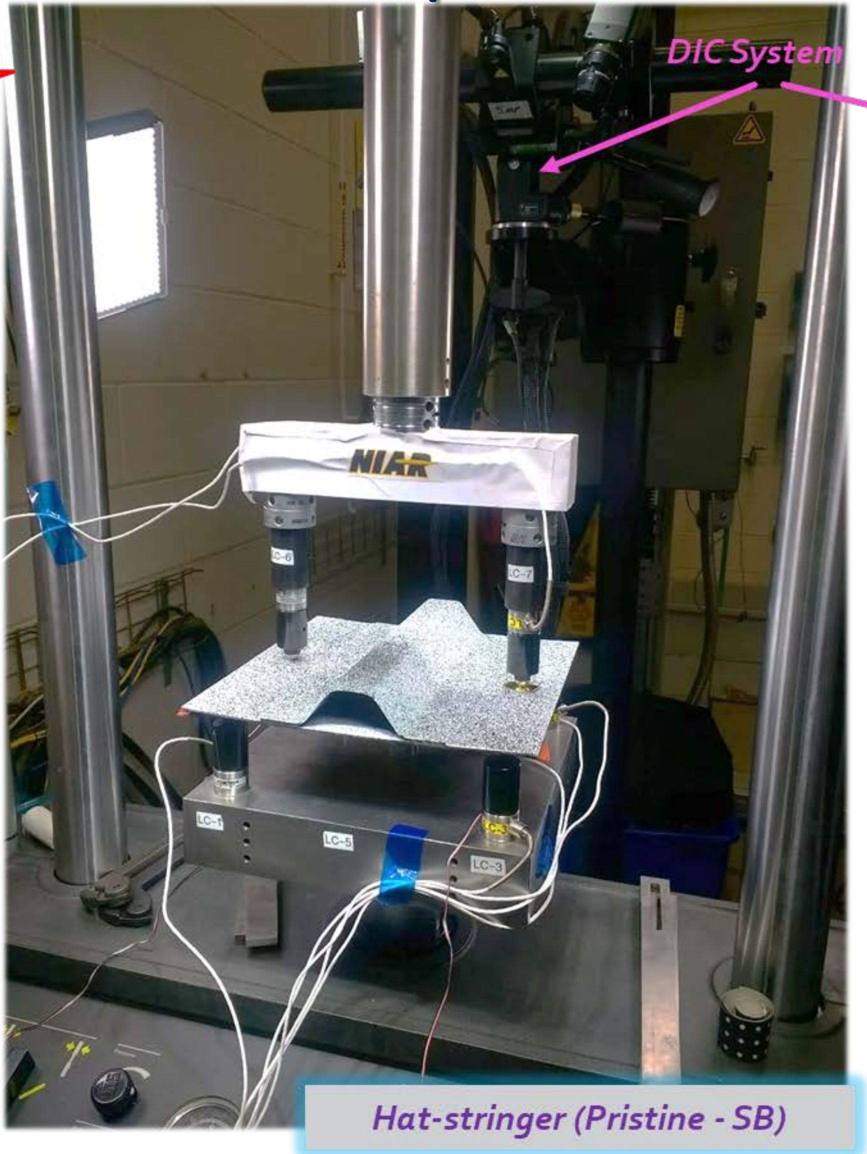
Develop a Set of Mid-Level Building Block Tests

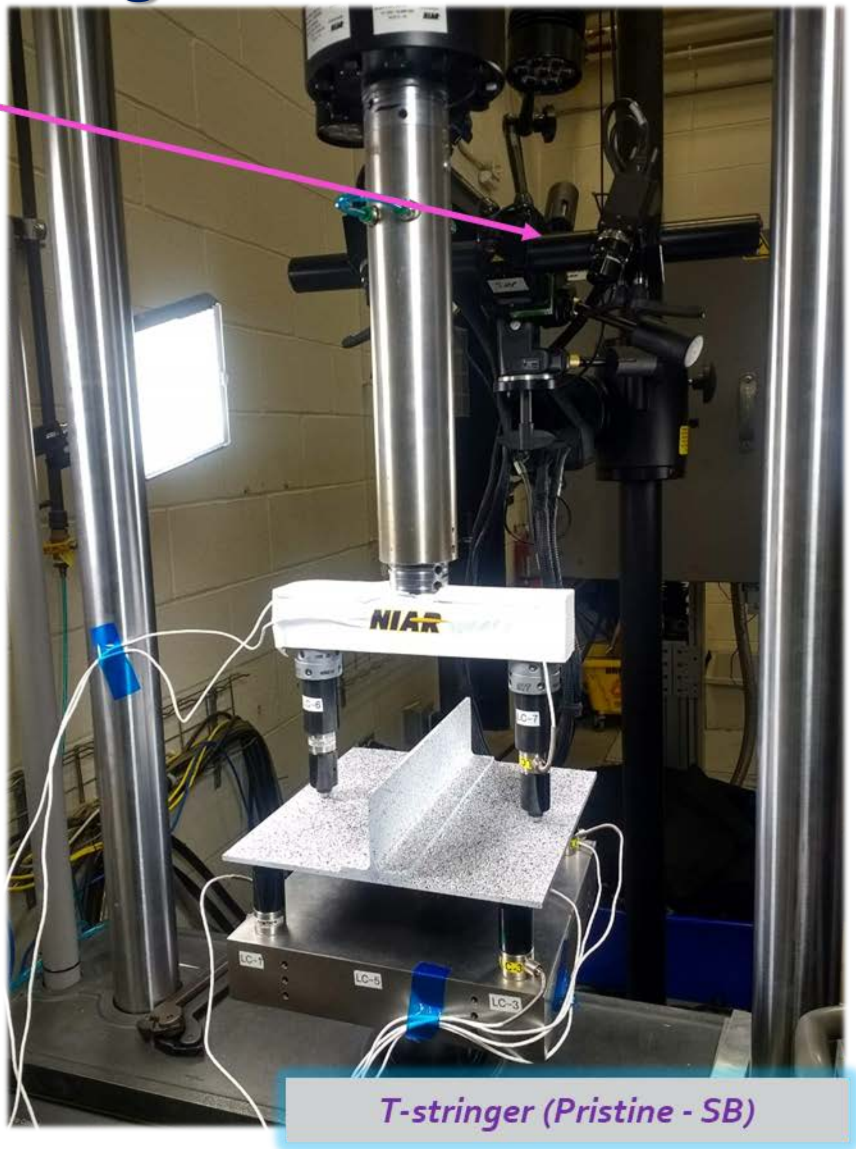
- M&P variability
  - Sensitivity to defects
  - Evaluate process spec limits
- Environmental effects
- Thermoset vs. thermoplastics
- Effectiveness of joints
- Manufacturing defects/features and in-service damages
  - Damage threat assessment
  - Scaling
  - Repair
  - Durability and damage tolerance
    - LEF substantiation *(statistical modal values)*



NIAR 7PB Test Setup: T & Hat – Stringers



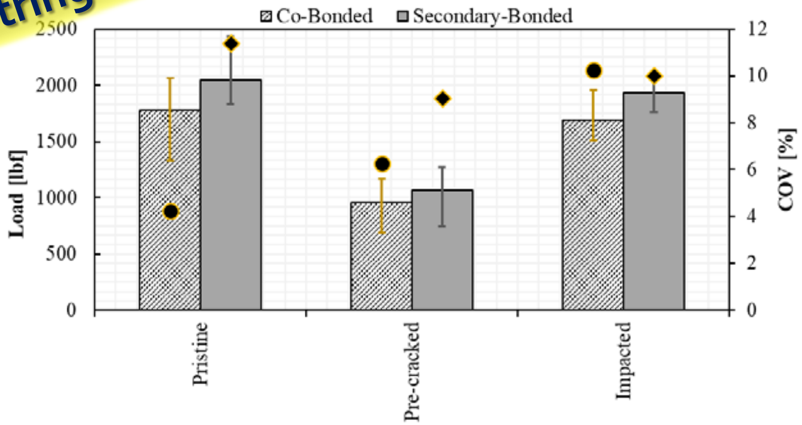


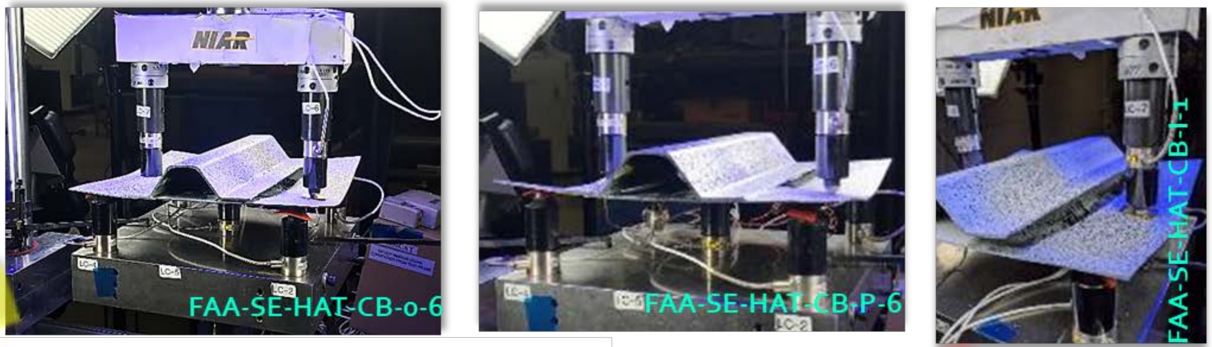


- **DIC Systems –** 2 employed (front & back)
- **Images** are stitched post-test
- **Each** load cell capacity **2050 lbf**
- **Test frame** rating **11 kip**

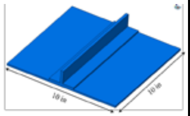
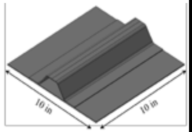
7PB Quasi-Static Tests: Brief Summary

Hat-Stringer

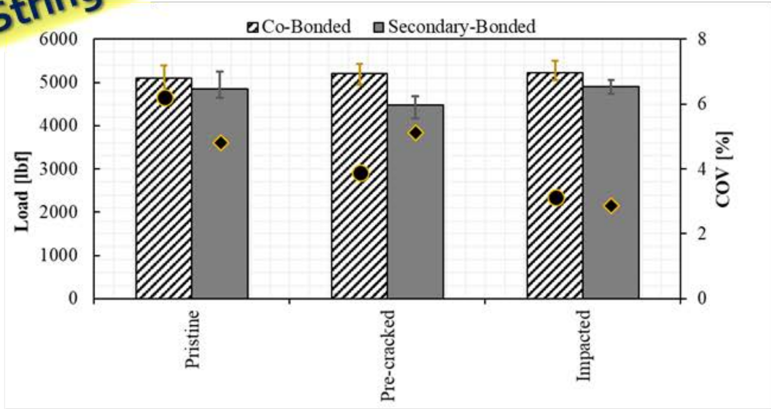


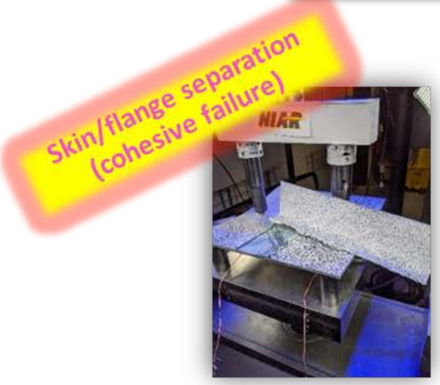


- Fairly Low COV: Highest 11% & lowest of 4%
- Predominantly Cohesive failure observed
- Inter-ply failure by crack migration into fist ply and beyond

Specimen Type	Fab. Process	Specimen Config.	Avg. Failure Load [lbf]	COV [%]
T-Stringer 	Co-bonded	Pristine (Baseline)	5096.4	6.2
		Pre-cracked	5211.1	3.9
		Impacted	5231.2	3.1
	Secondary bonded	Pristine (Baseline)	4856.2	4.8
		Pre-cracked	4478.7	5.1
		Impacted	4910.1	2.9
Hat-Stringer 	Co-bonded	Pristine (Baseline)	1777.1	4.2
		Pre-cracked	957.4	6.3
		Impacted	1691.2	10.3
	Secondary bonded	Pristine (Baseline)	2046.3	11.4
		Pre-cracked	1067.7	9
		Impacted	1934.1	10

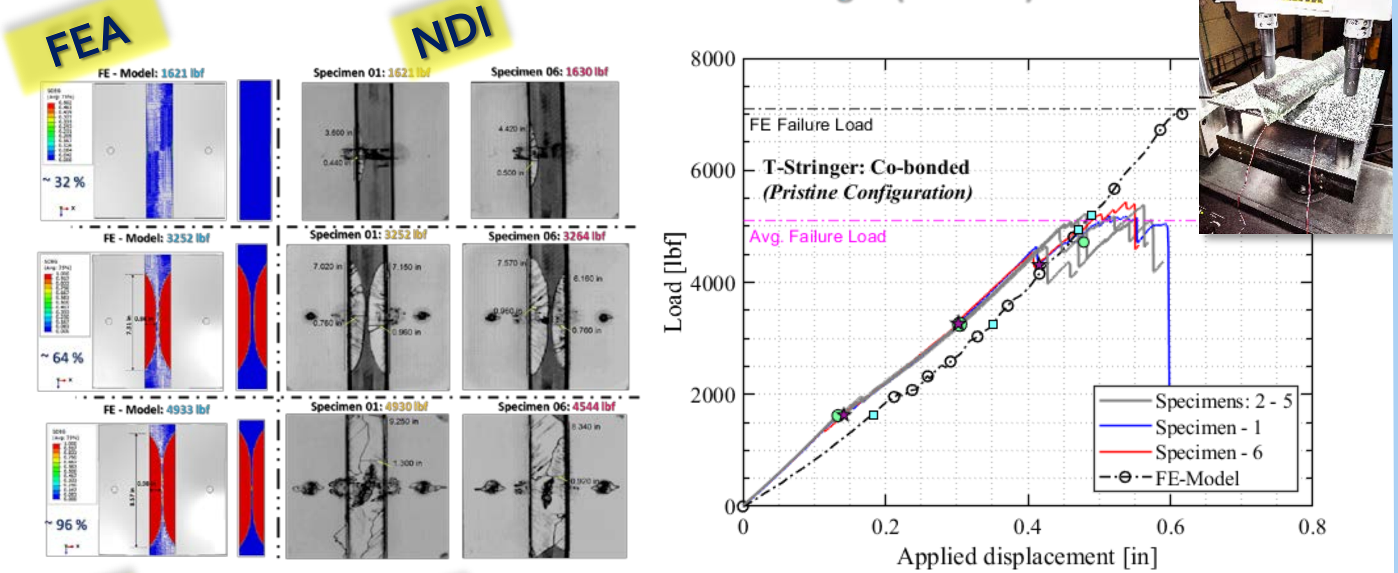
T-Stringer

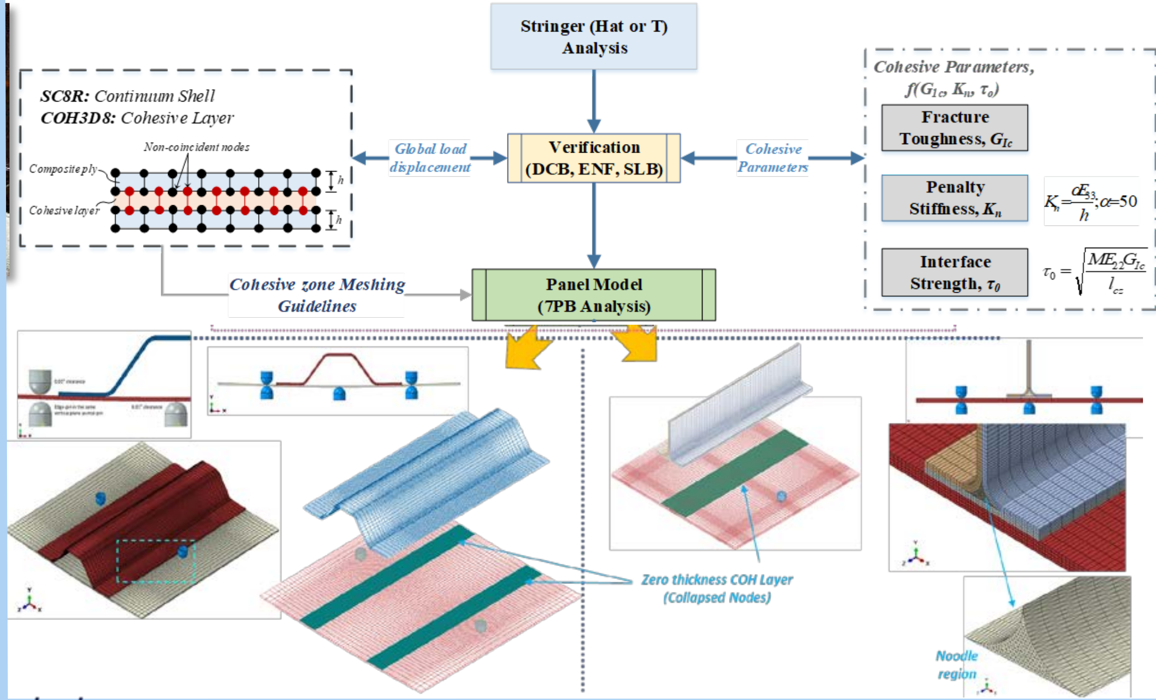




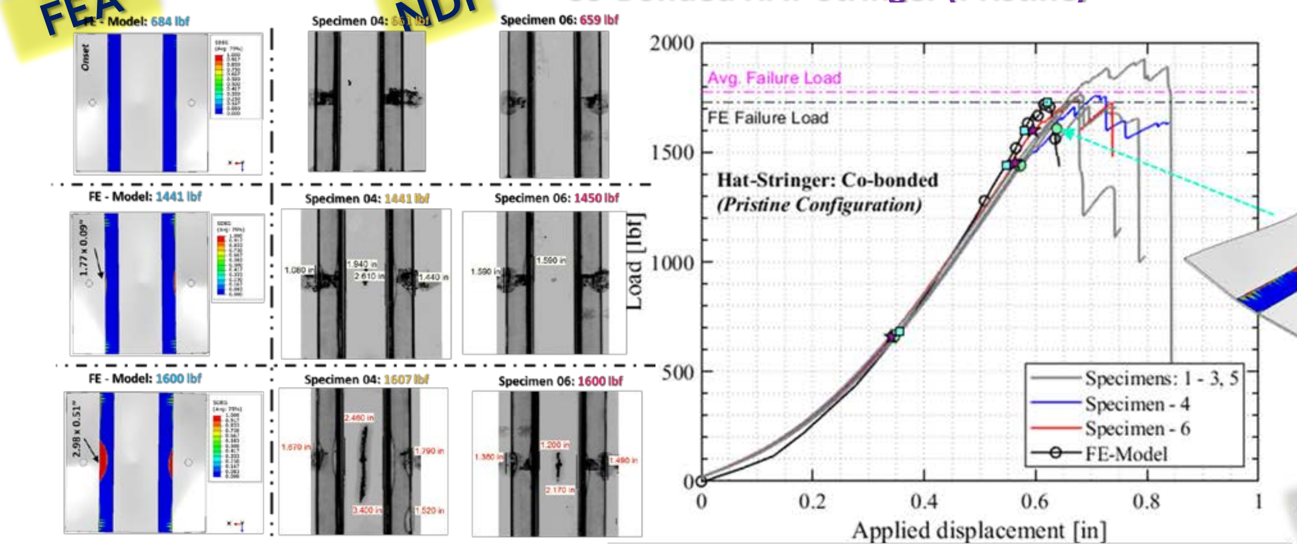
Prediction of Damage Initiation & Evolution in Co-bonded T & Hat-Stringers

Co-Bonded T-Stringer (Pristine)

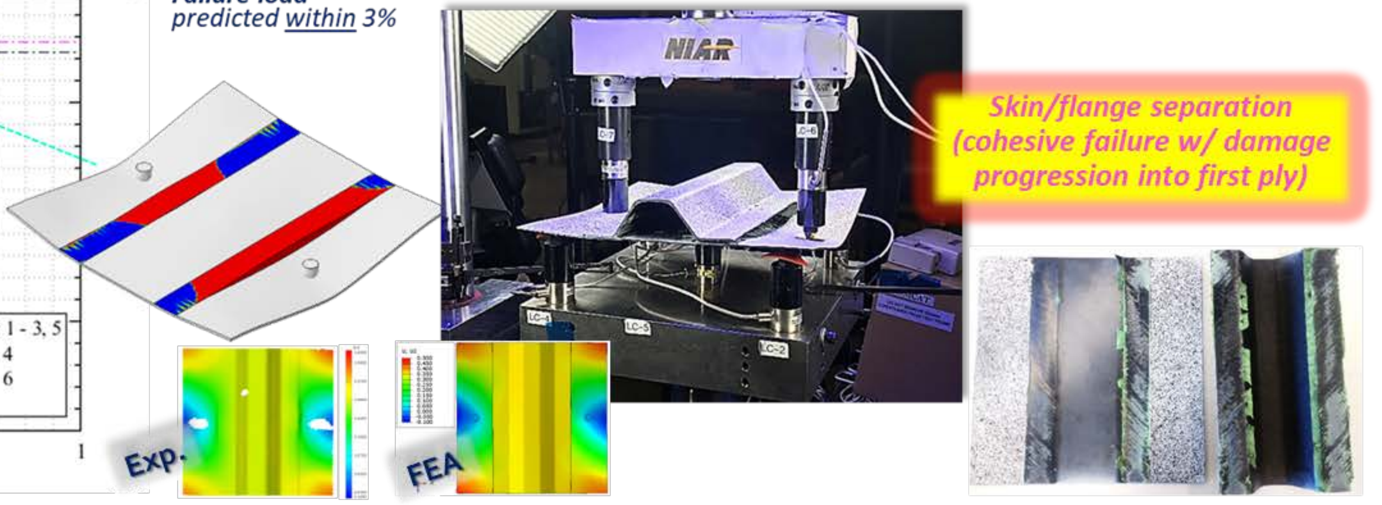




Co-Bonded HAT-Stringer (Pristine)

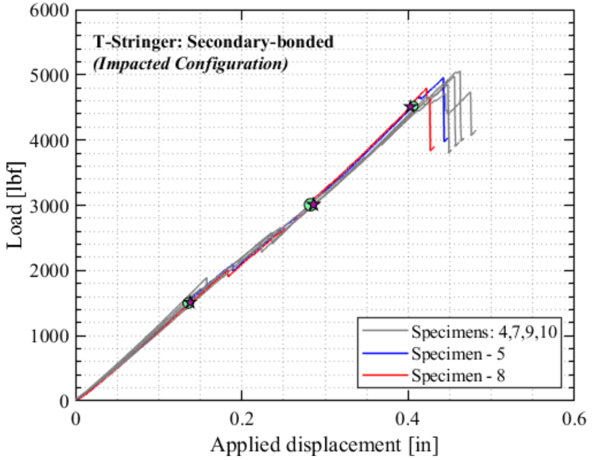


- ***Failure load** predicted within 3%*

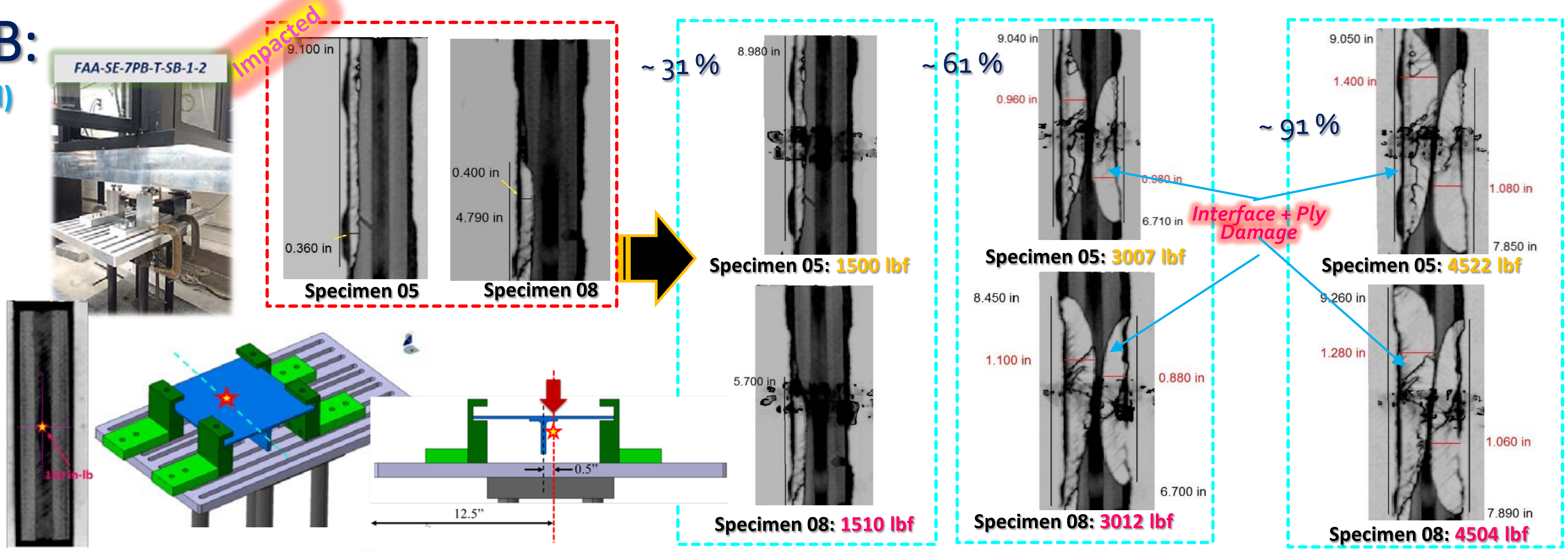


Impact Study w/ 7PB:

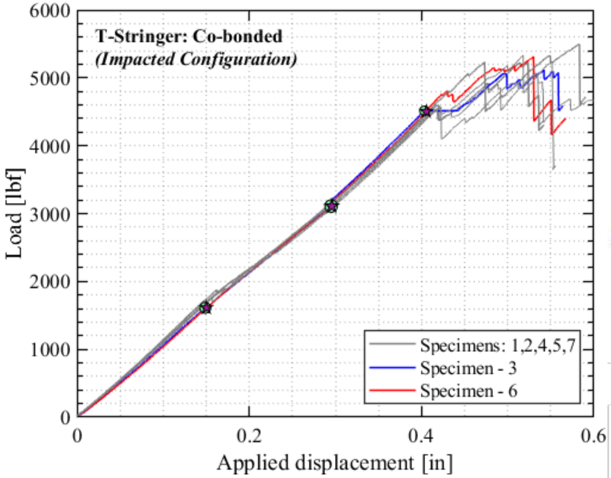
Secondary-Bonded T-Stringer (Impacted)



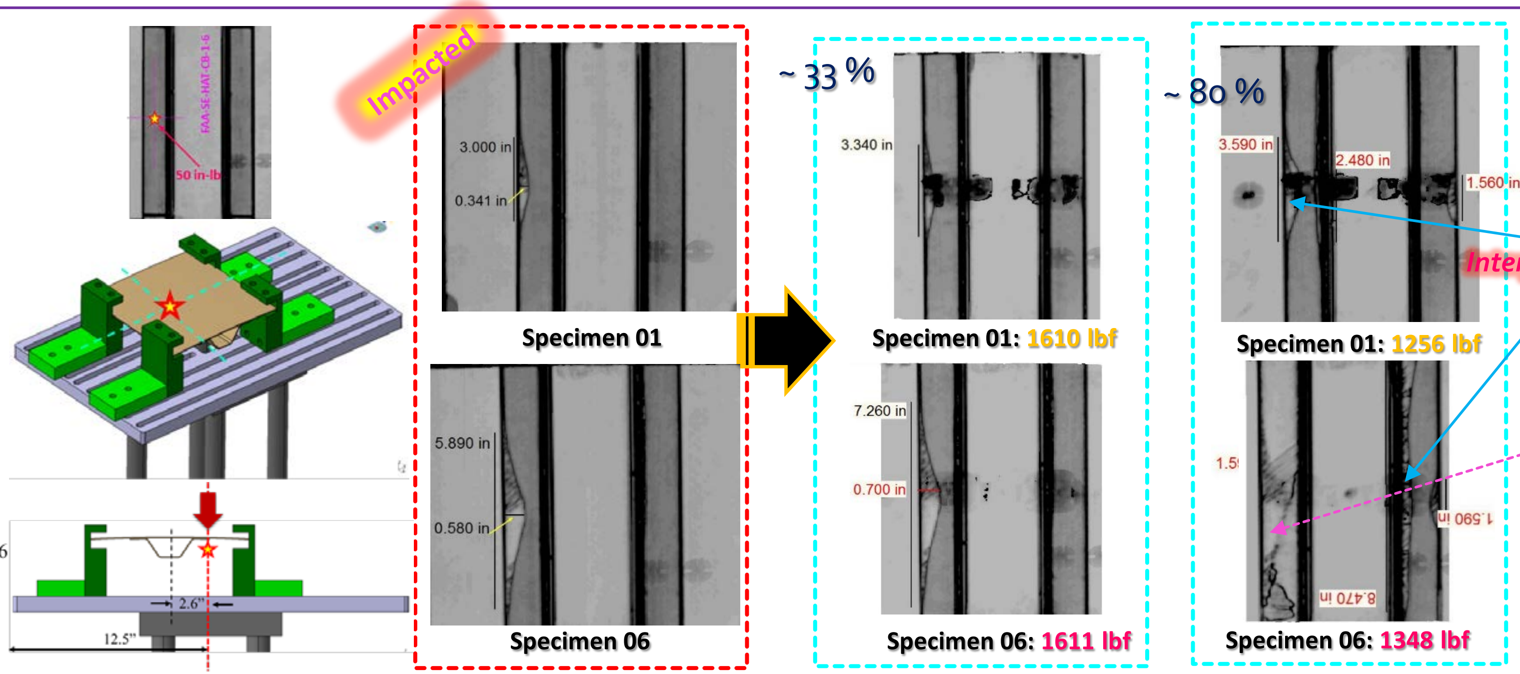
Avg. failure load = 4910.1 lbf

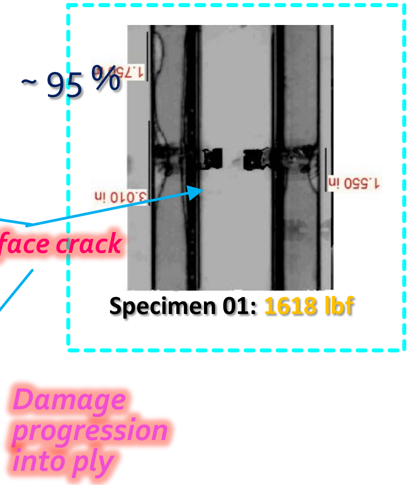


Co-Bonded HAT-Stringer (Impacted)



Avg. failure load = 1691.2 lbf





Study conducted on both ***Secondary-bonded (SB) & Co-bonded (CB)*** *configurations*

Program Overview

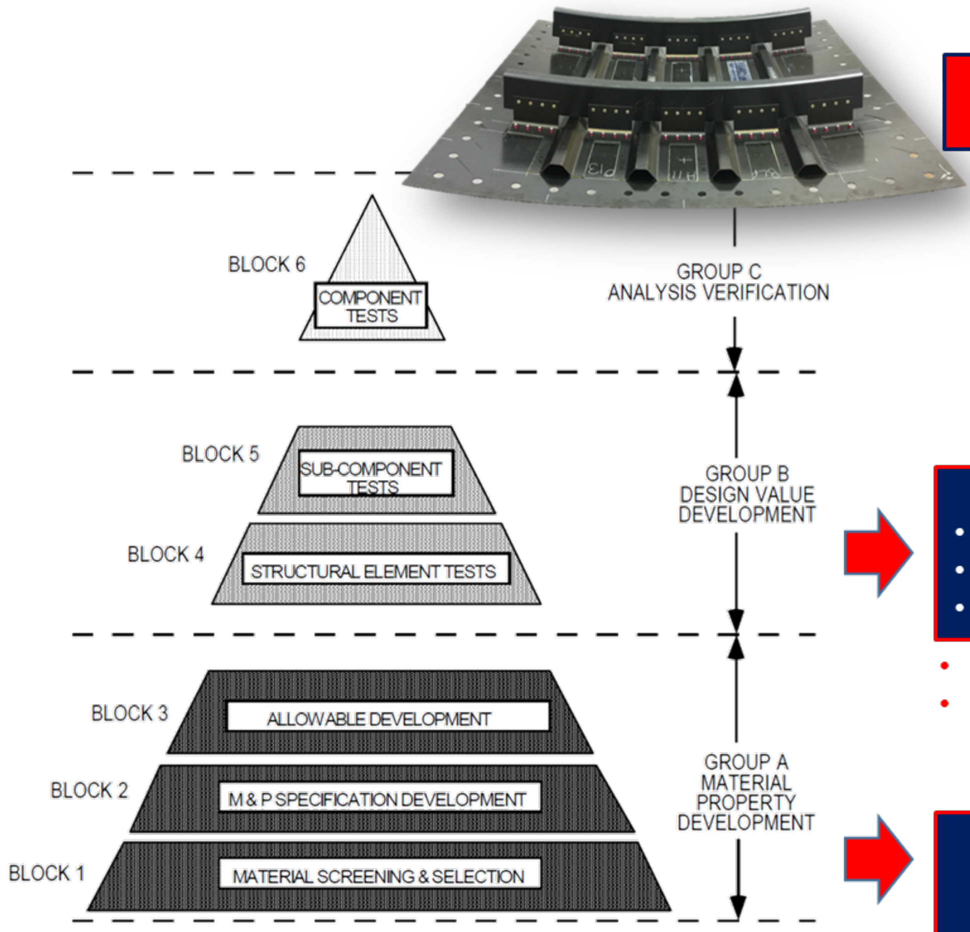
Mid-Level Building Block Test

"Smart" Mid-Level Building Block Test

Test Performance Evaluation

Process & Scaling Effects

"Smart" Mid-Level Building Block Tests



Fragment Testing & Validations (*k1, *k2, ..)

Reevaluate Margins against Mid-level BBT

DT
- Manuf. Defects
- In-service Damage
- Repair

Bonded Repair
- Parent material
- Repair materials
- Adhesive

CACRC

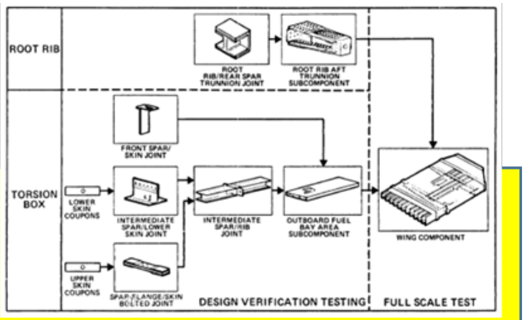
- Non-standard test methods
- Design-specific features/materials/layups, etc.

M&P,
CLT, FEM,
SOF (ECF+SF), LEF

NCAMP

- Standard tests
- Generic layups

AGATE

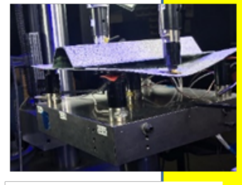


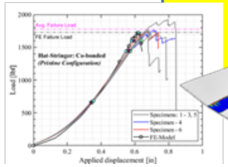
Scaling (*k1, *k2, ..)

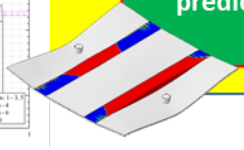
Prior Cert Test Experiences

Development of Mid-Level Building Block Standards

Smart ML-BBT and/or TSO
- Validate design concepts
- Verify analysis methods
- Provide substantiating data for design values
- Demonstrate compliance with criteria
- Demonstrate ability of FEM to predict strain values

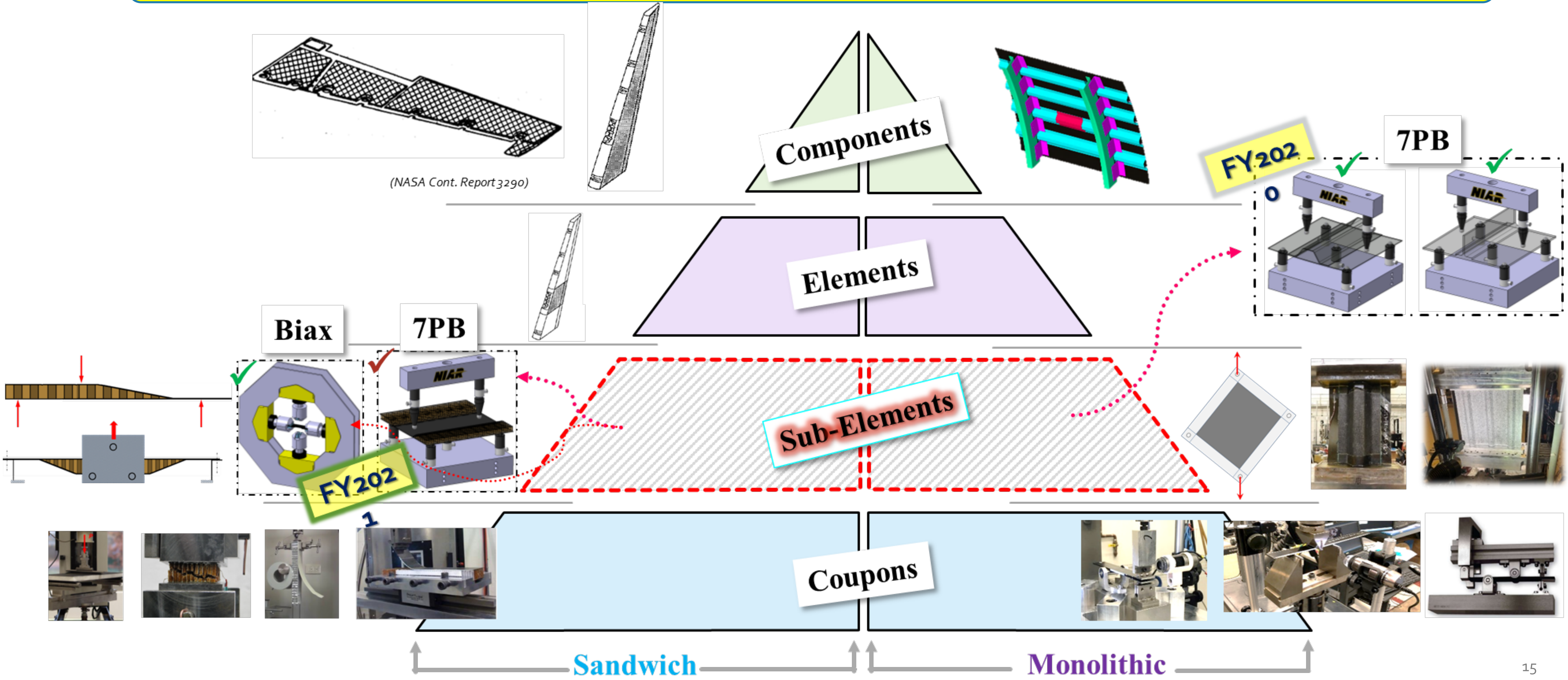






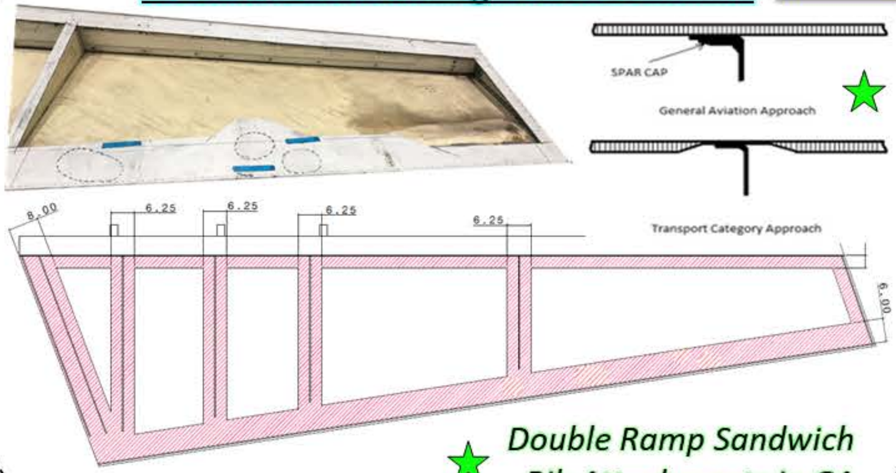
Overview of Current Test Methods: Scope for a Mid-Tier Test Methodology

GOAL: *Identify* ***Weak Design*** *w/t Aid of selected Test Methodology which introduces* ***Complex Loading*** *Scenario (representative of an actual control surface).*



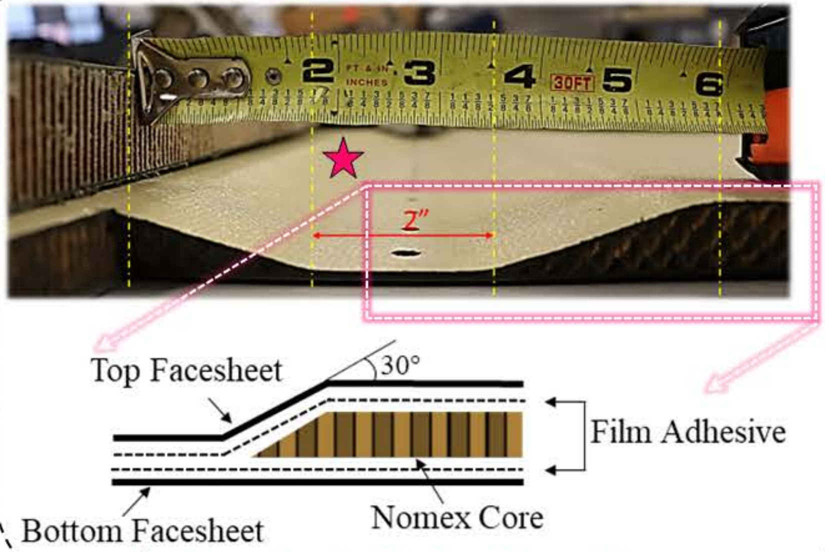
Analysis for Design Considerations in Sandwich Constructions

A. Structural Design Assessment



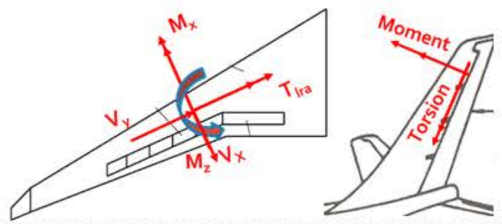
★ Double Ramp Sandwich Rib Attachments in GA

B. Critical Design Features

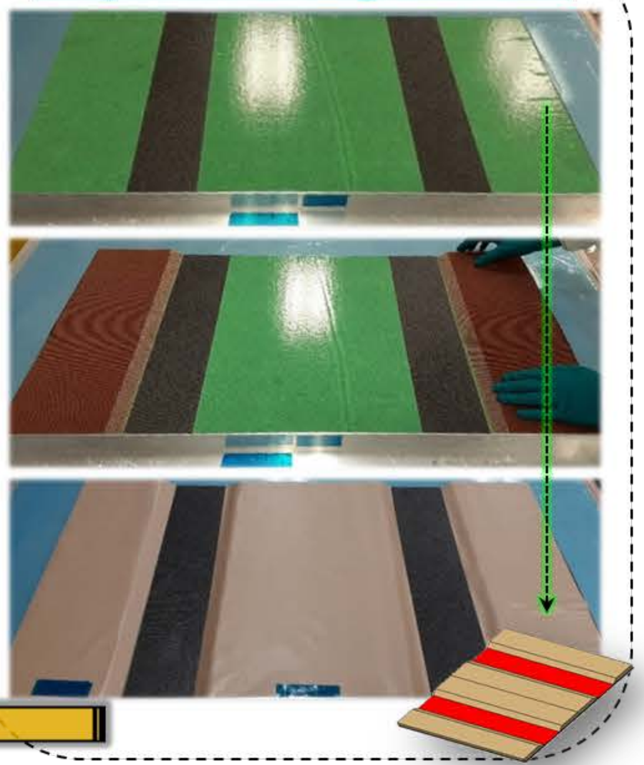


★ Ramp Angle, Radius, Materials, etc.

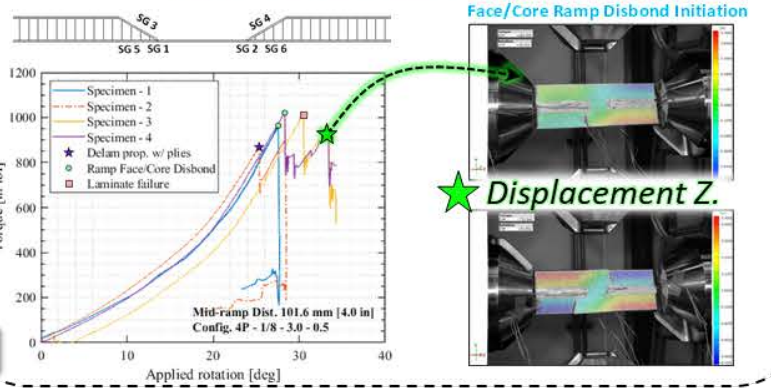
C. Loading Considerations



D. Specimen Design and Fab

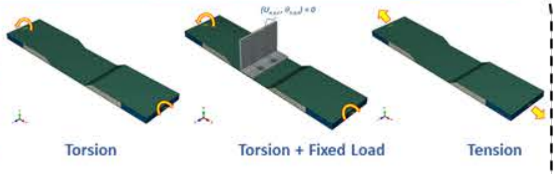


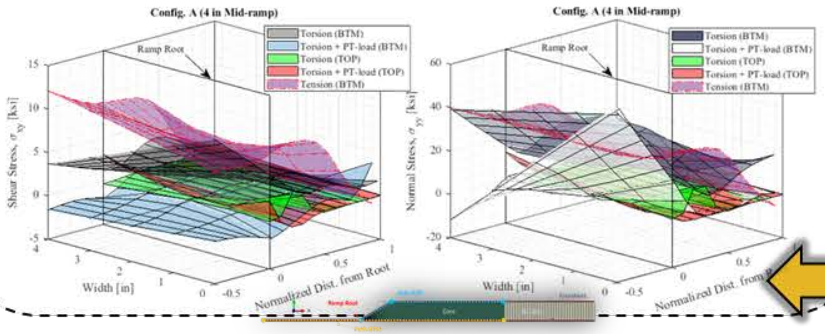
E. Mechanical Testing



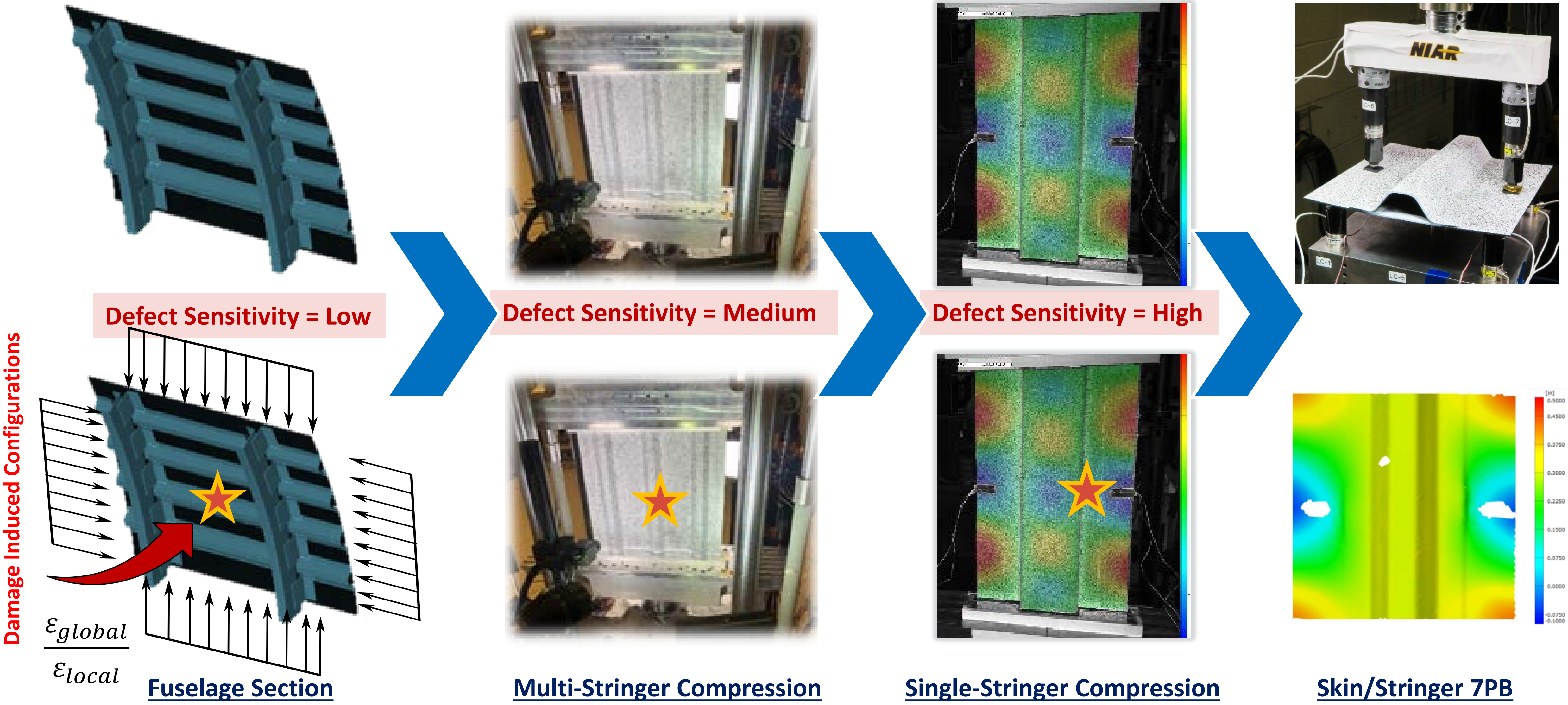
F. Interface Shear & Normal Stress Compared

★ High asymmetrical shear and normal stresses in Torsion & Torsion + Pt.Load Case



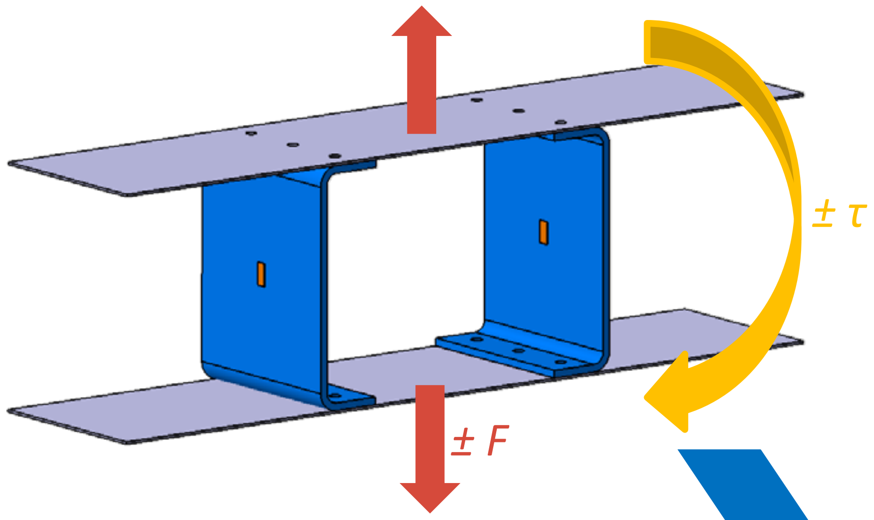


Evaluation of Fuselage Section: Top-Down Fragmented Testing



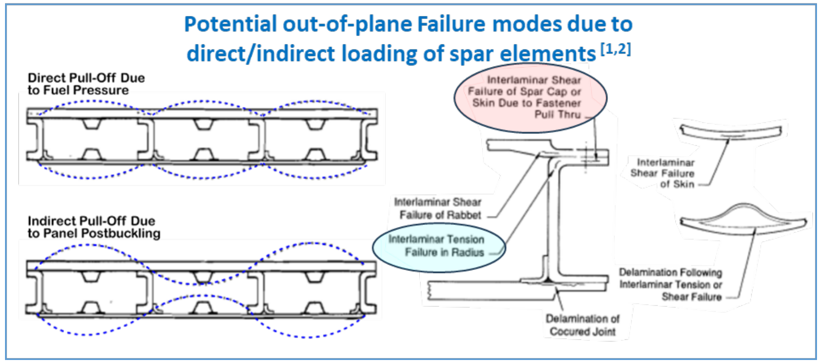
Conservatism in design based on lower-level allowable vs higher-level building block testing

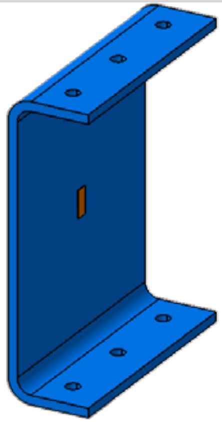
Evaluation of Wing-Box Structure| Top-Down Fragmented Testing

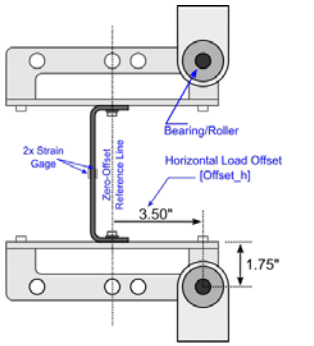


Defect Sensitivity = Low

- Less Web Bending
- Complex/realistic loading



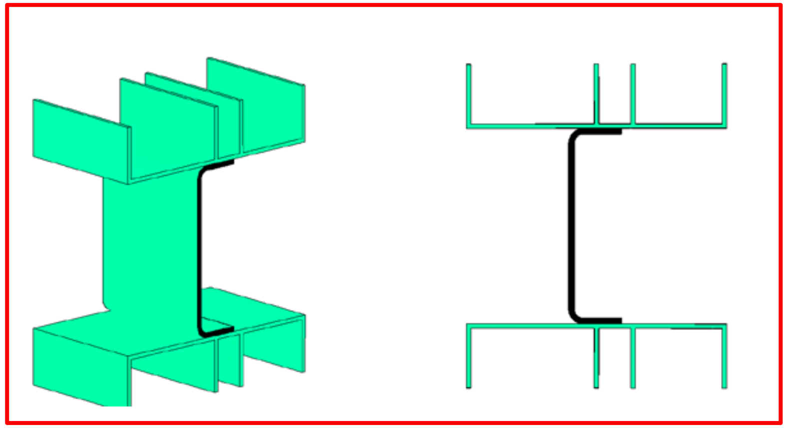




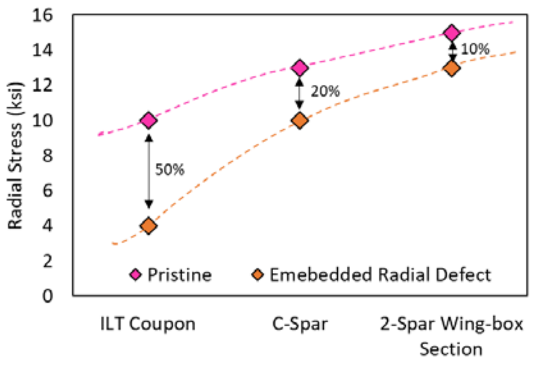
Material System	Horizontal Load Offset, Offset_h (in)			
IM7/5320-1	0.0"	1.0"	3.5"	-3.5"
IM7/5250-4	0.0"	1.0"	3.5"	N/A

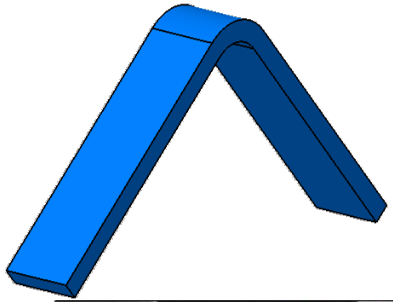
Defect Sensitivity = Medium

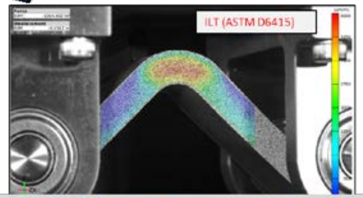
- Excessive Web Bending!



Vertical Displacement & Induced Rotation

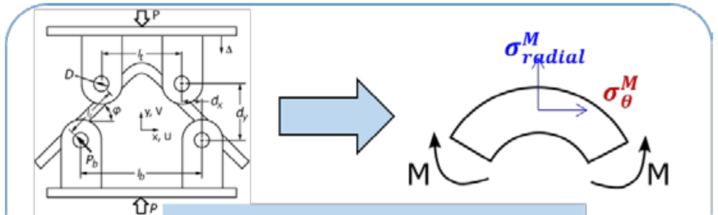




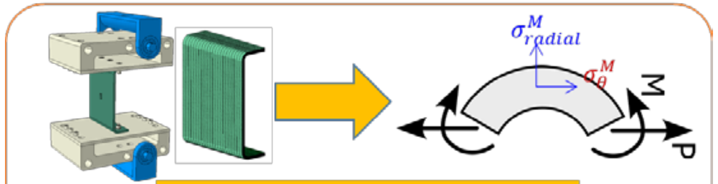


Uniform Strain distribution in typical ILT Specimen under bending. Centrally aligning peak ~ 30% though thickness (Hard Layup IM7/5250-4)

Defect Sensitivity = High

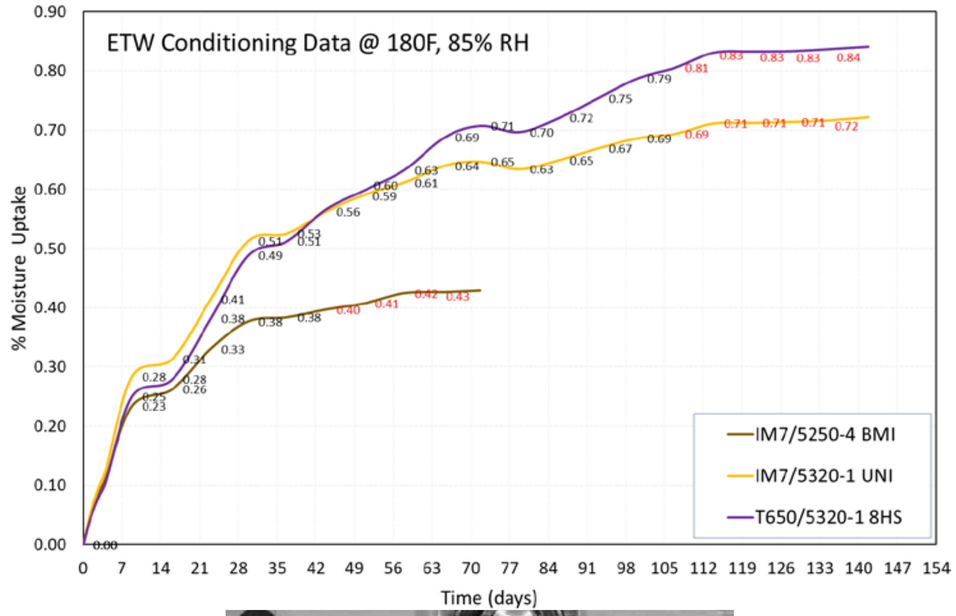


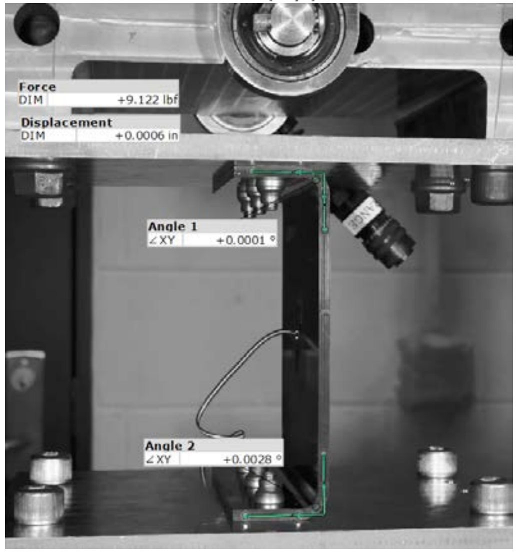
ASTM D6415 ILT under PURE BENDING

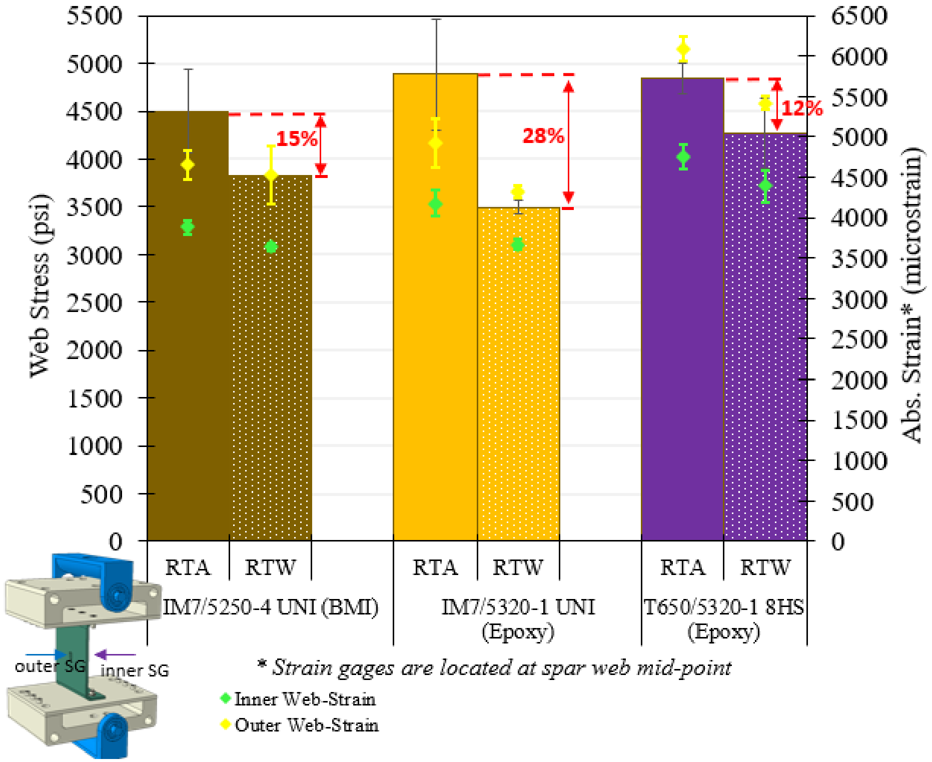


C-Spar under BENDING + END FORCE

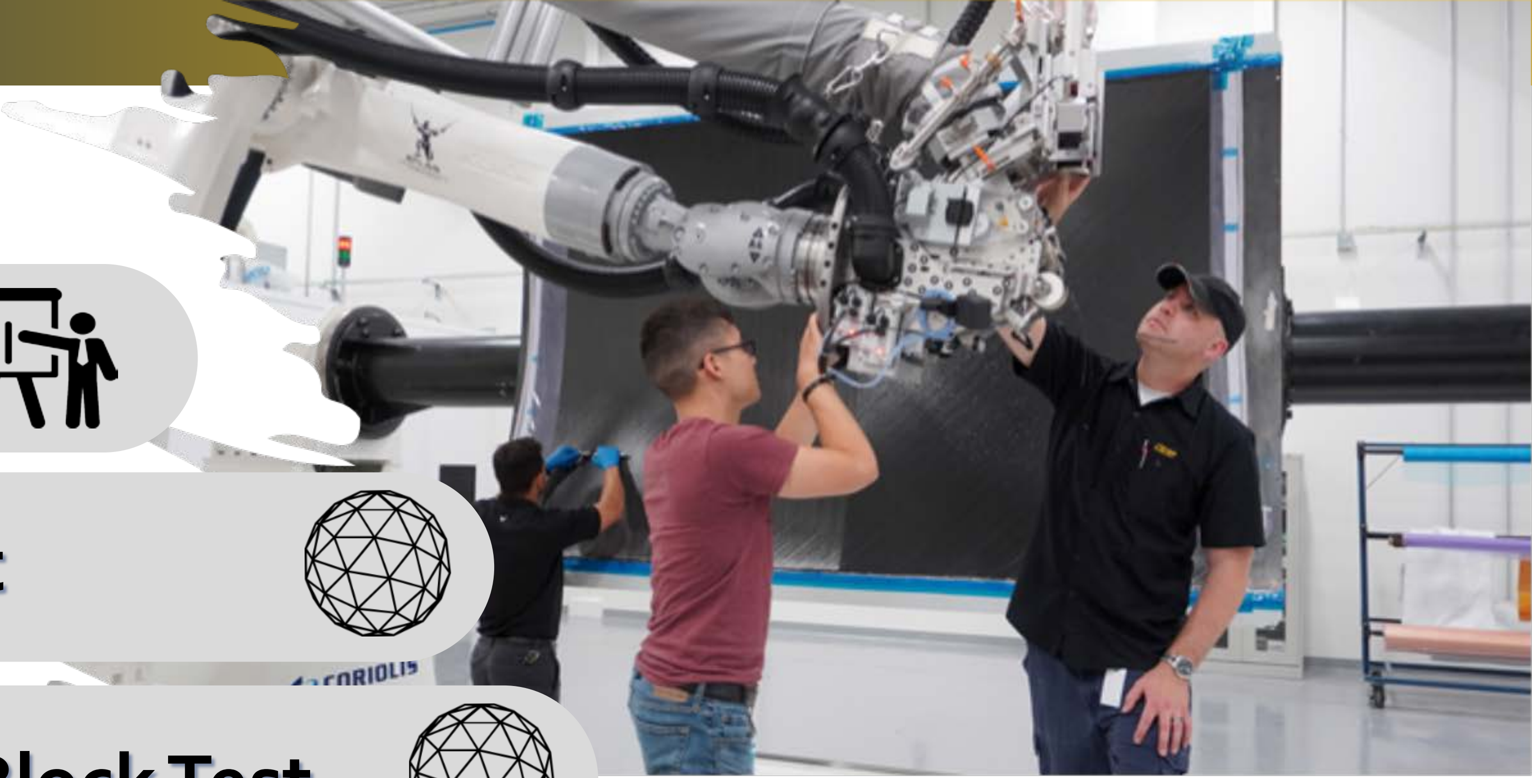
C-Spar Static – Environmental Conditioned and Tested @ RTA [RTW]







C-spars were preconditioned at 180°F, 85% RH and tested at room temp. Additionally, testing will be conducted at elevated temp. (220F) condition.



- Program Overview
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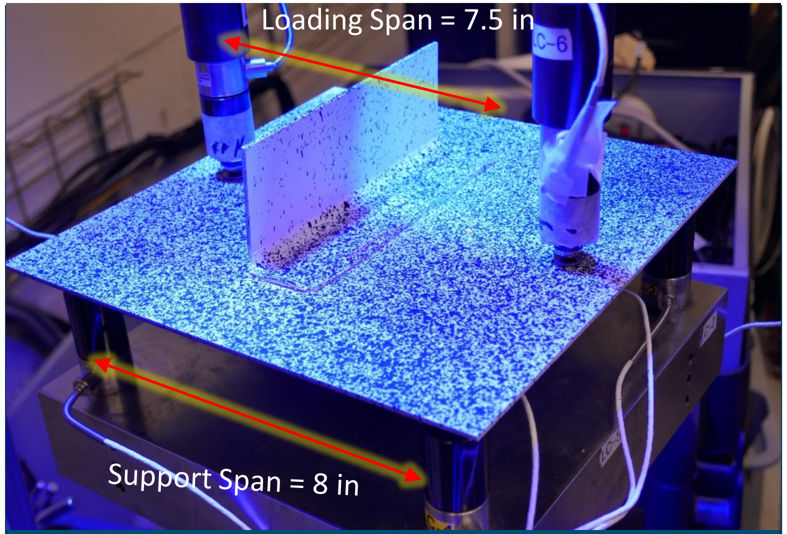
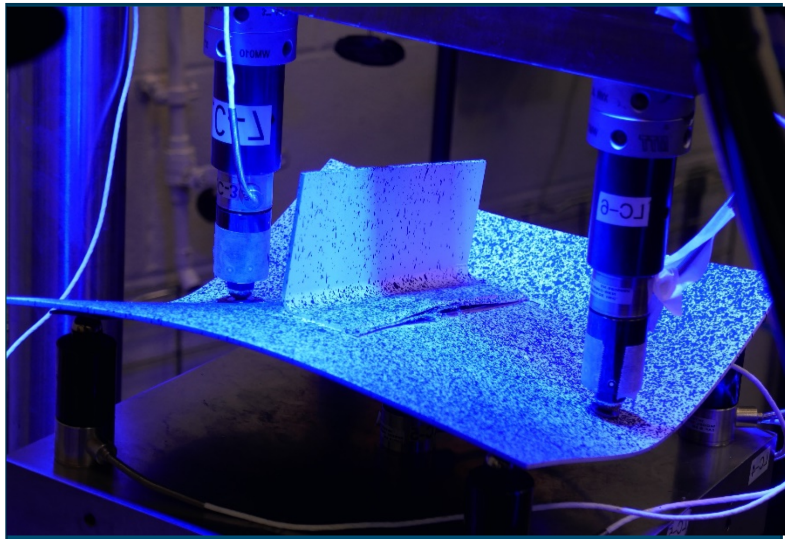
7-Point Bend L-Shear Tie Configuration [TC1225/T700]

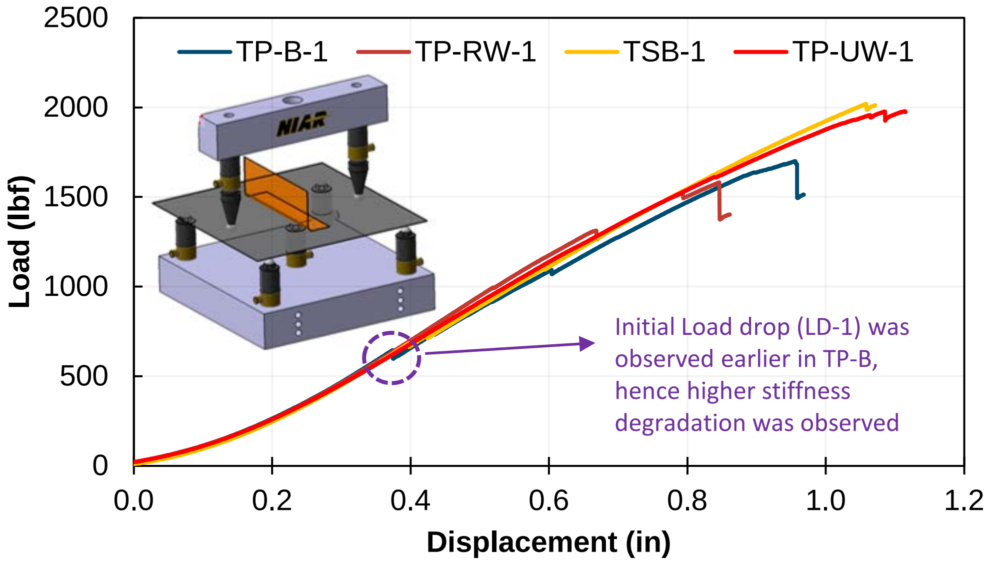


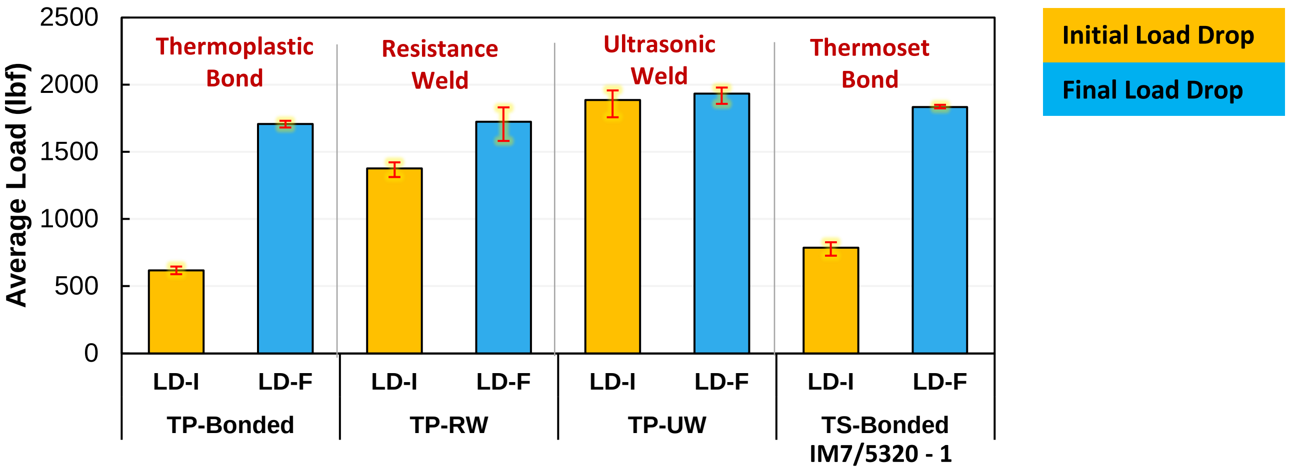
7-point bend L-shear tie Test Setup



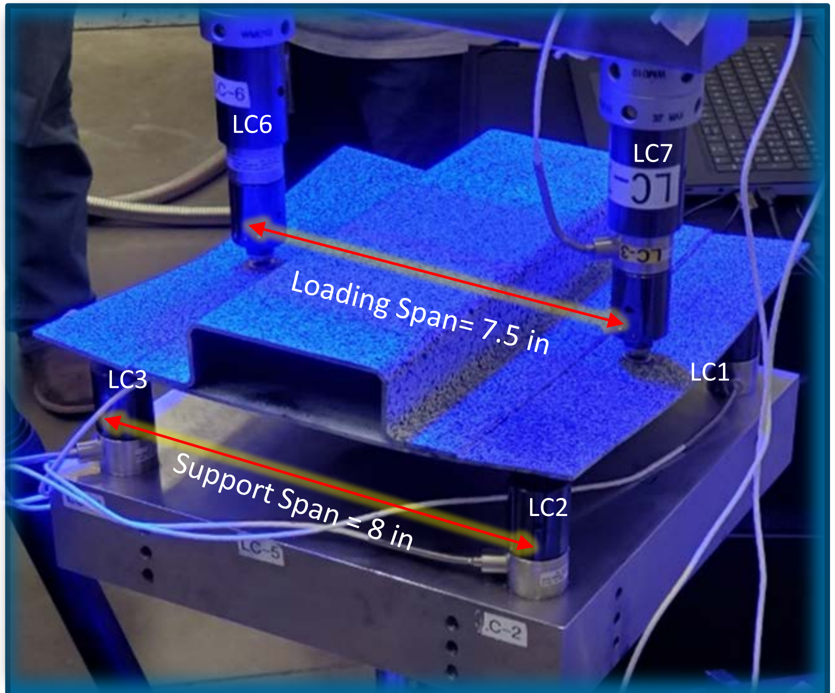
Failure Mode / Out-of-Plane Deformation

- 7PB replicates buckling modes akin to skin/stiffener compression via out-of-plane displacements
- Initial Load Drop was **higher** for Thermoplastic Weldment (TPW) than both TP and TS-Bonded
- Final Load Drop was similar for both TPW and TPB

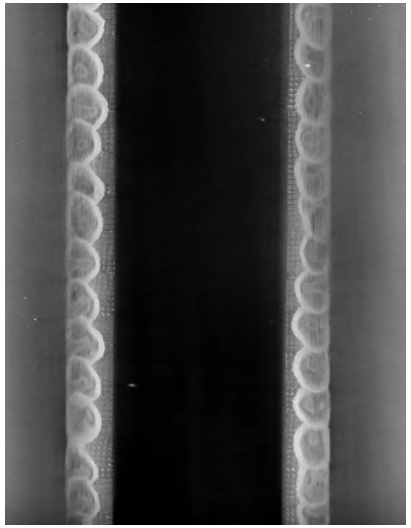


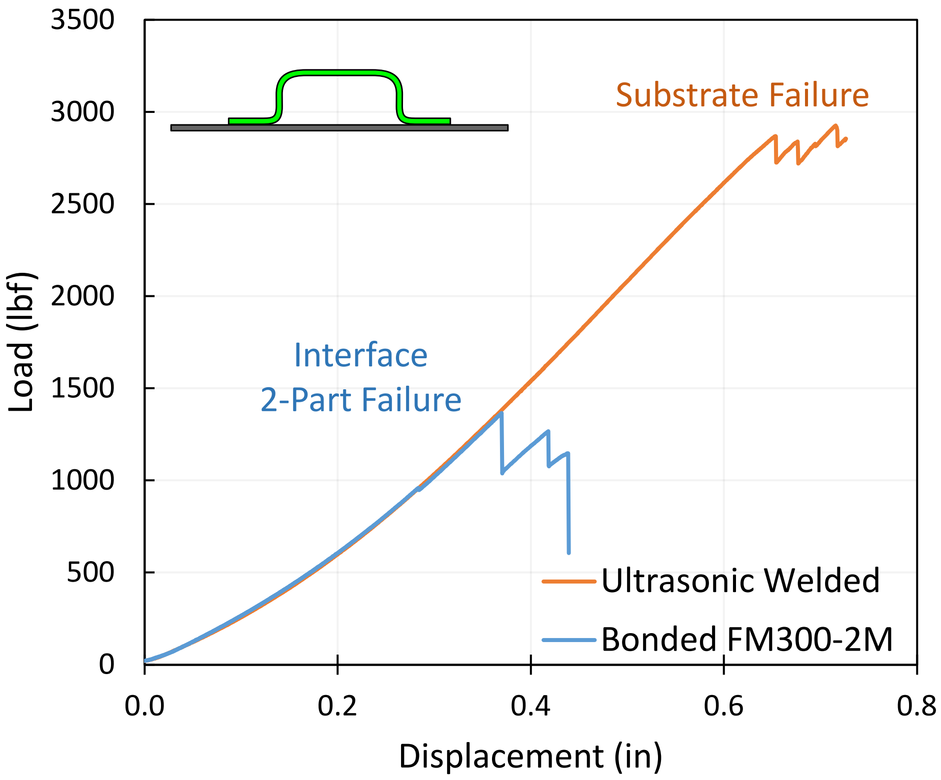


7-Point Bend Rectangular-Hat Stringer [APC/AS4D]



7-point bend Rect.-hat stringer test setup


XCT image of sequentially welded R-hat stringer stiffened skin at the interface



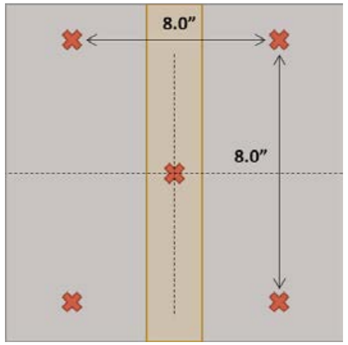
➢ **TP-UW** failed at **50% higher load** than TP-Bonded.

7PB Testing Configurations

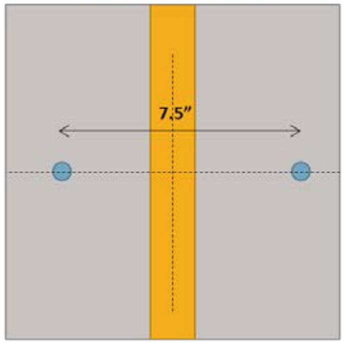
TP – B : [FM300-2] Thermoplastic Adhesive Bond
TS – B : [EA7000] Thermoset Adhesive Bond
Secondary bonded unless specified as Co-bonded (Co)

RW : Resistance Weld (TP)
UW : Ultrasonic Weld (TP)

BOTTOM SUPPORTS (x5)

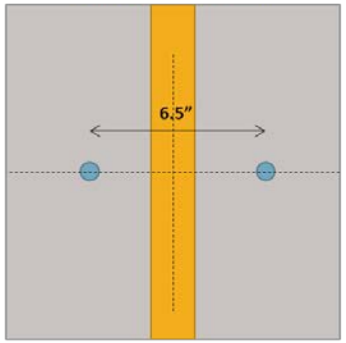


TOP LOAD PINS (x2)
Config 1: 7.5” Load Span

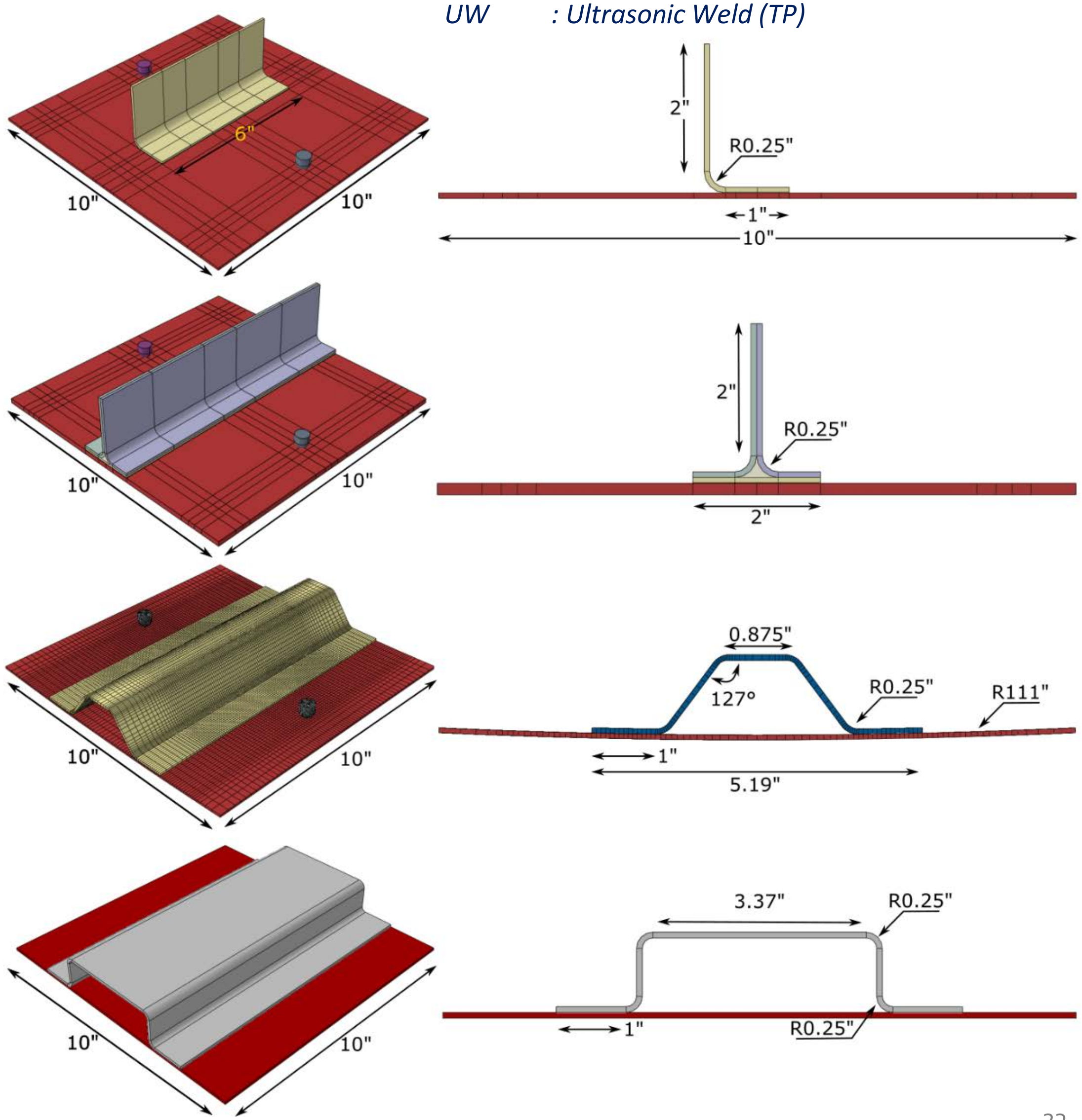


- Hat(trapezoidal) Stringer [Thermoset]
- Hat(rectangular) Stringer [Thermoplastic]
- L-Stiffener/Shear-Tie [Thermoplastic]

TOP LOAD PINS (x2)
Config 2: 6.5” Load Span



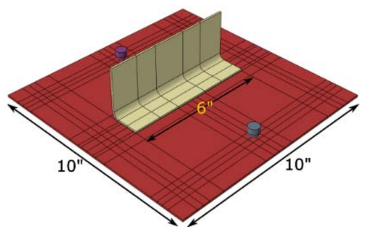
- T-Stringer [Thermoset]
- L-Stiffener (Fatigue) [Thermoplastic]



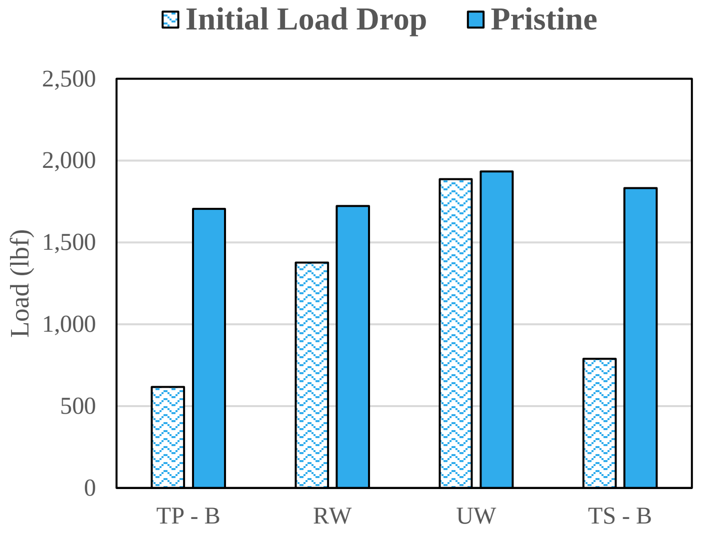
Configuration	Material	Interface	Adhesive	Static		
				Pristine	Pre-Crack	Impacted
T-Stiffener	Thermoset [T800/3900-2]	Co-Bonded	EA 7000	X	X	X
		Secondary-Bonded		X	X	X
Hat-Stiffener with curved Skin (Omega Hat Configuration)		Co-Bonded		X	X	X
		Secondary-Bonded		X	X	X
L-Stiffener/Shear Tie	Thermoplastic [APC/AS4D] [TC1225/T700]	Bonded	FM 300-2	X		
		Fusion by Weldment		X		
Hat-Stiffener (Flat/Rectangular Configuration)		Bonded	FM 300-2	X		
		Fusion by Weldment		X		

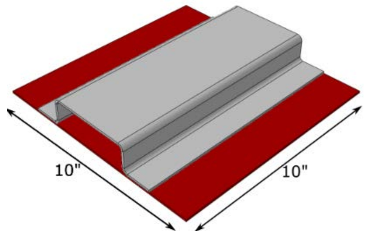
***** Pre-Crack = 2” x 1” Disbond Region Centrally on Each Flange***

7PB Performance – Materials, Configurations & Joining Methods

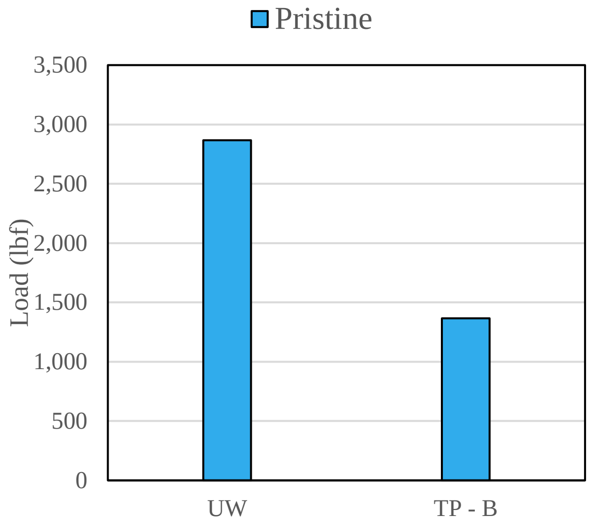


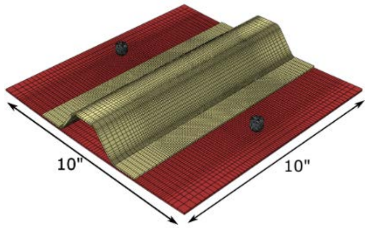
Layup / Ply	**16 QI**
Material	TC1225/T700 IM7/5320-1
Adhesive	FM300-2M
Load Distance	7.5”



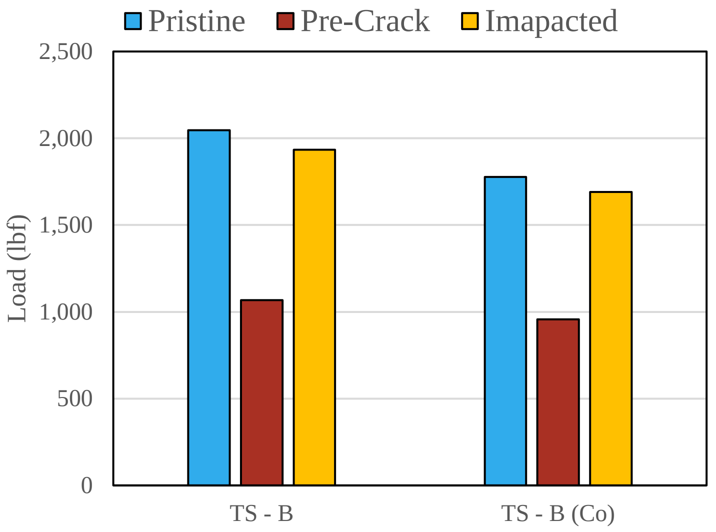


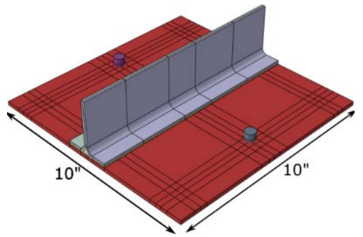
Layup / Ply	**16 QI**
Material	APC/AS4D
Adhesive	FM300-2M
Load Distance	7.5”



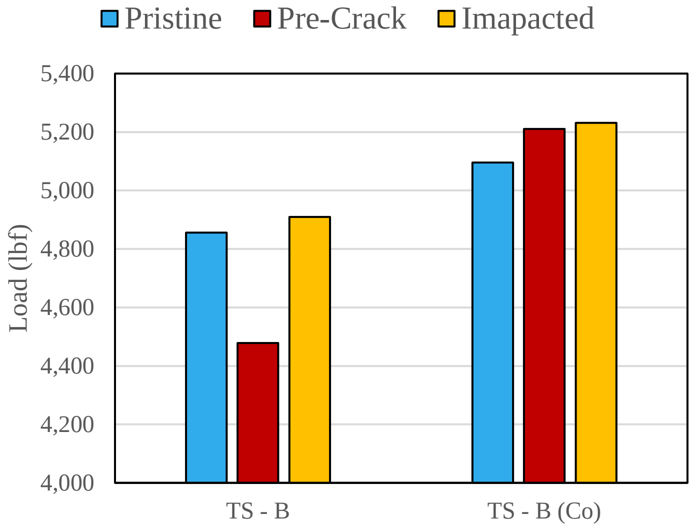


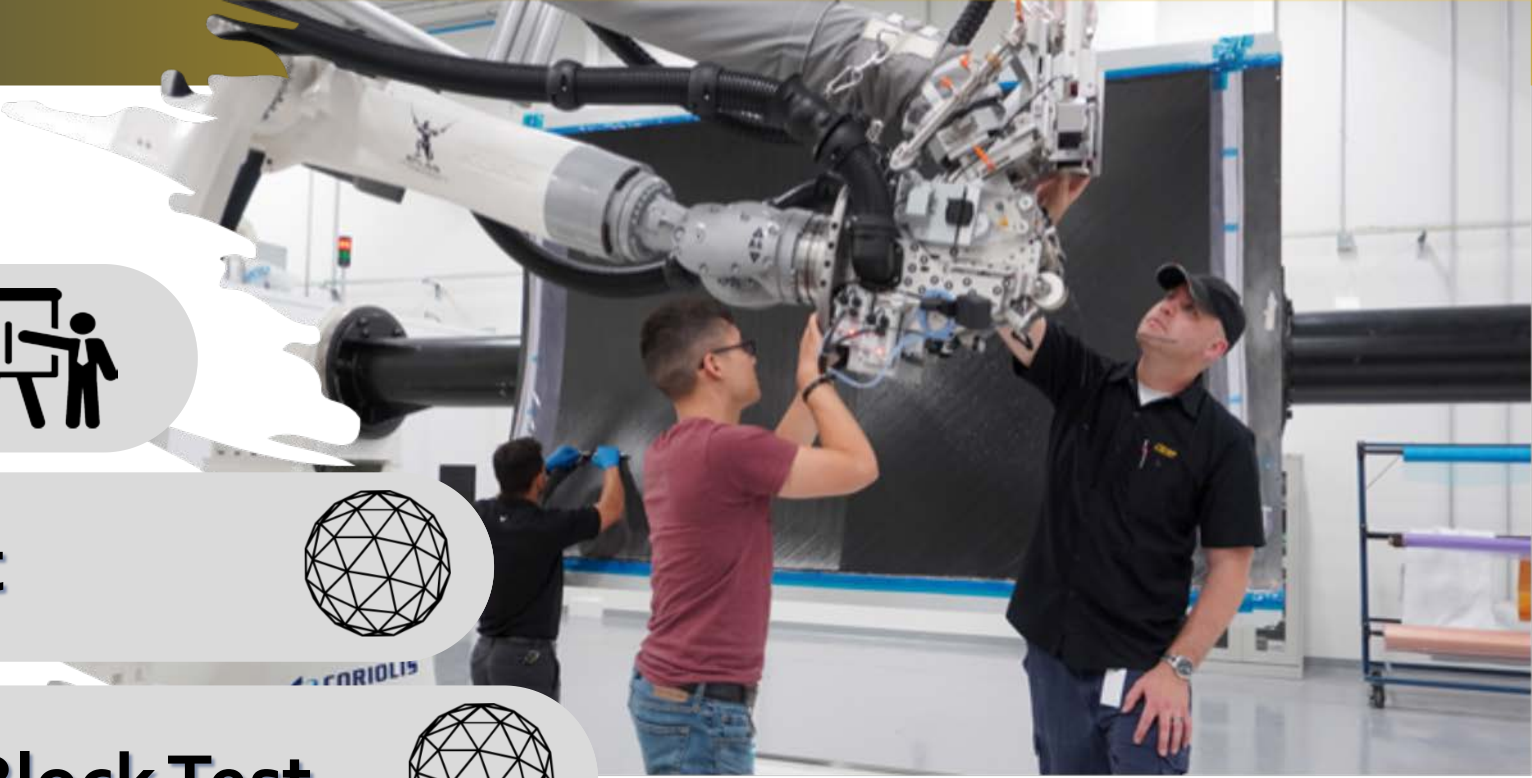
Layup / Ply	**10/11 Plies**
Material	T800/3900-2
Adhesive	EA7000
Load Distance	7.5”





Layup / Ply	**24 QI**
Material	T800/3900-2
Adhesive	EA7000
Load Distance	6.5”





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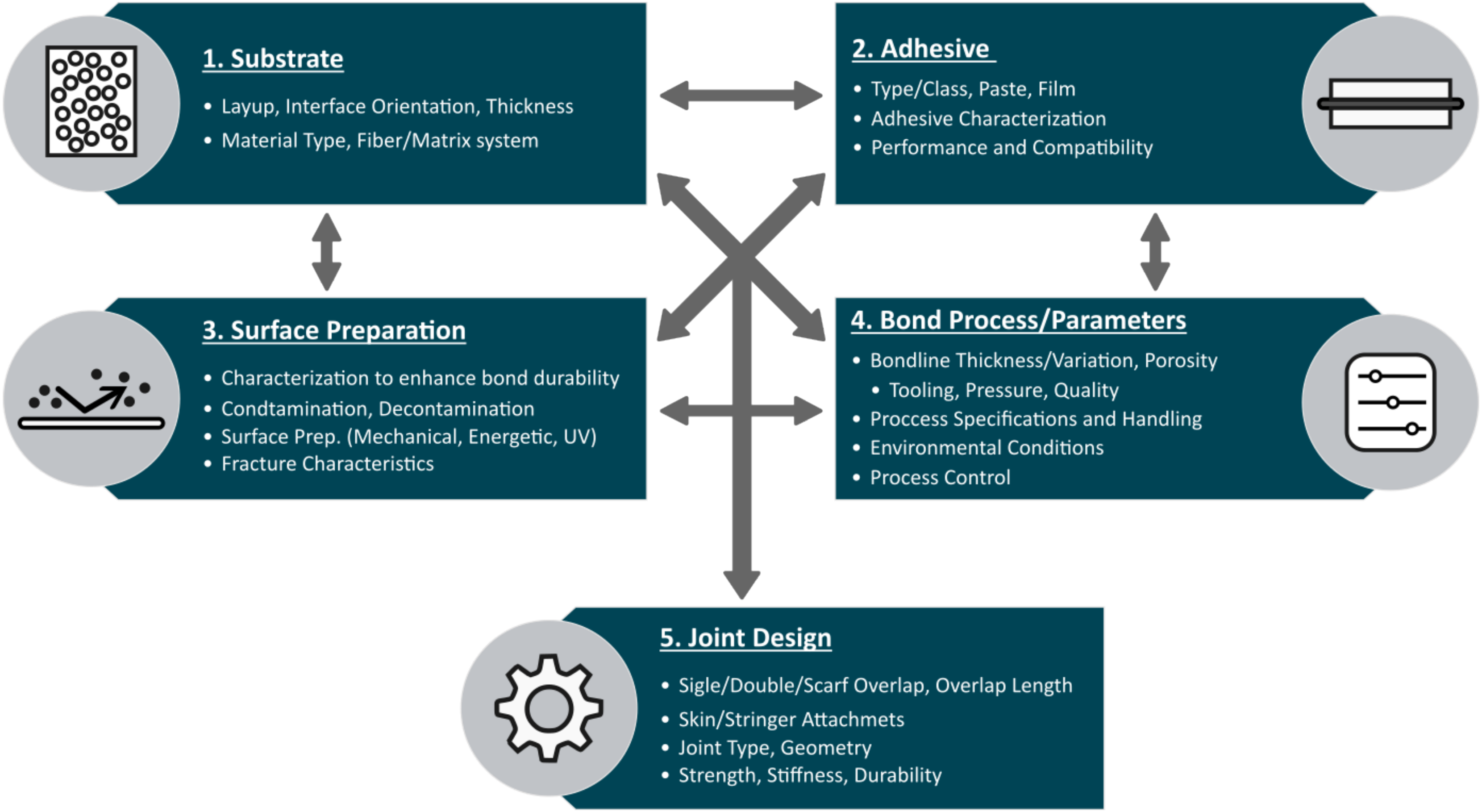
- **Process & Scaling Effects**

Adhesive Joints as a System

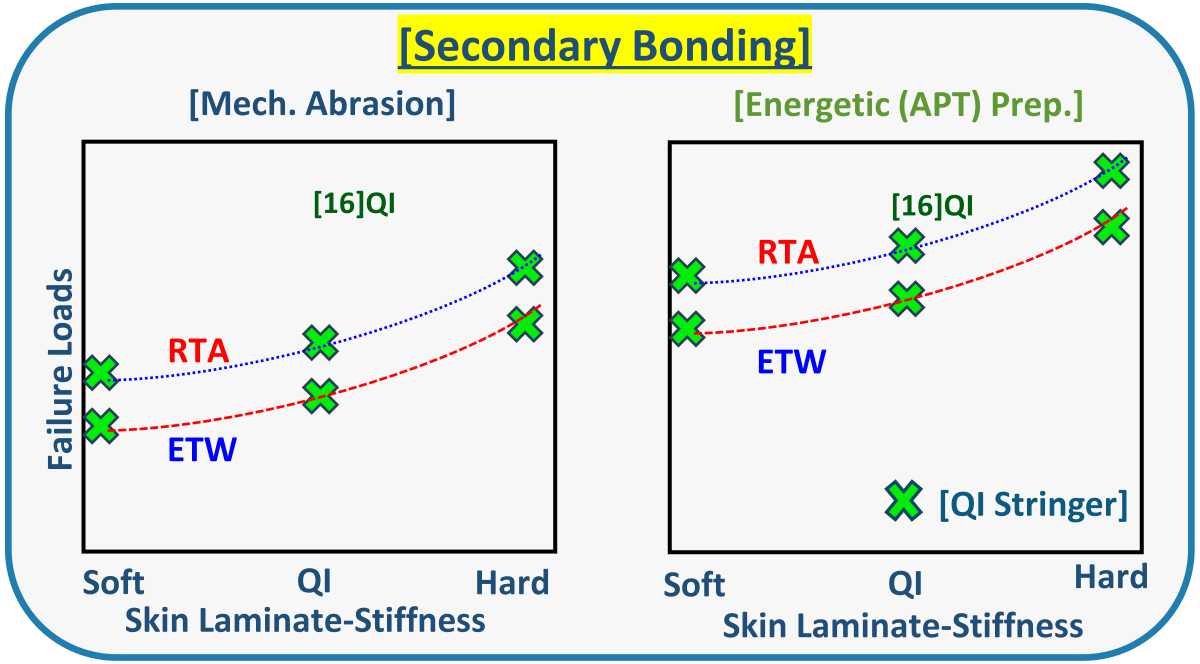


Key Characters for Joint System

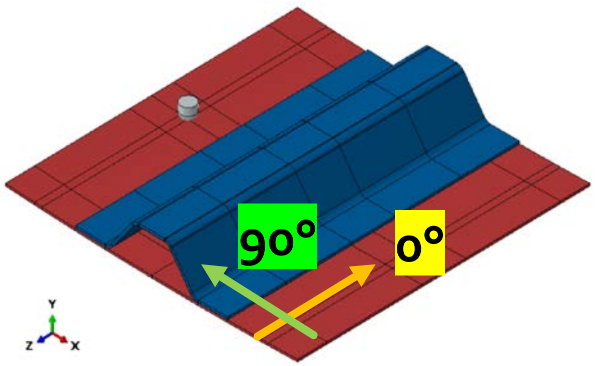
- Substrate Material/Configuration
- Adhesive Type and Compatibility
- Surface Preparation Methods
- Surface Contaminants
- De-contamination Methods
- Environmental Conditions
- Mfg. Procedure (Co/Sec. Bond)
- Joint Design, Load Cases/Intensity, Mode Mixity Ratios

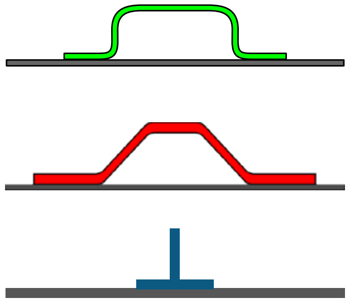
Bond Process Qualification at Scale – 7 pt Bend Test

Joint-System	Key Parameters	#1	#2	#3
1. Substrate	Substrate Material	IM7/5320-1	Thermoplastic	
	Substrate Config.	Soft	QI/Custom	Hard
2. Adhesive/Interface	Adhesive	FM300-2 (film)	EA9394 (paste)	
3. Surface Preparation	Surface Preparation	Mech. Abrasion	Energetic (APT)	UV Ablation
	Surface Contamination	Pristine	Contaminant	
4. Bond Process	Process	Co-Bonding	Secondary Bonding	
5. Design Feature	Joint Desing	Hat-Stiffener (Omega)	T-Stiffener	
Conditioning	Test Environment	RTA	ETW/Moisture	

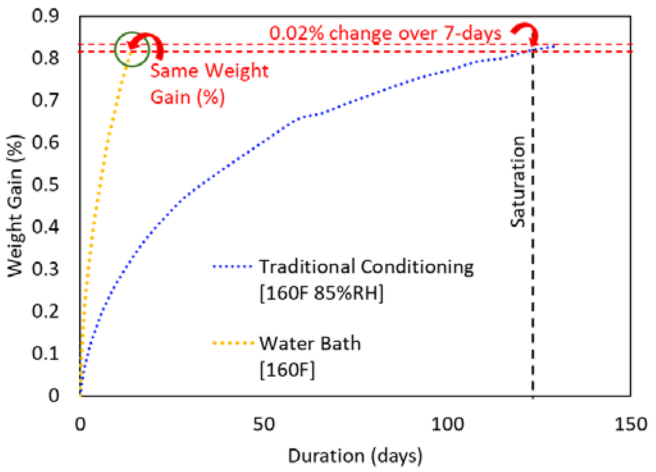


Config.	Layup	Stack-up	Distribution
Hard	[45/0/-45/0/90/0/45/0]_S	16	50% | 38% | 13%
QI	[45/0/-45/90]_2S	16	25% | 50% |25%
Soft	[45/-45/0/45/-45/45/-45/90]_S	16	13% | 75% | 13%





Environmental Conditioning (Moisture Saturation)



Moisture Saturations for Environmental Testing

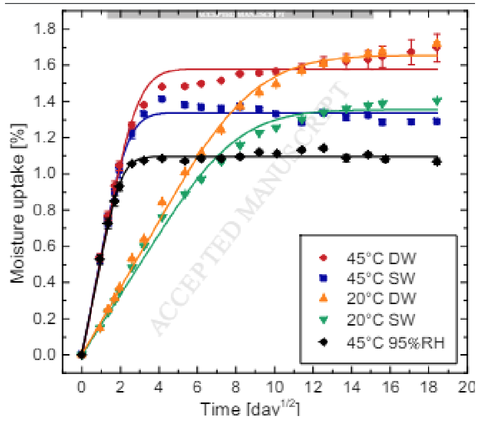
- Effects due to moisture ingression
- Challenges with conditioning time for larger test articles
  - Bondline region saturation
- Evaluation of **Accelerated** Conditioning Approach
  - Humidity/Temperature dependance
  - Water Immersion

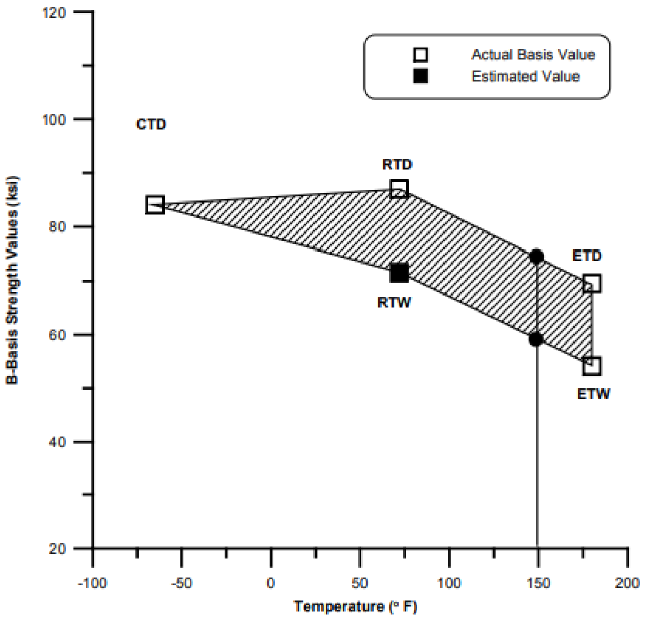
ASTM D5229 - Moisture Absorption Properties & Equilibrium Conditioning of PMC

5.5 Vapor-exposure testing shall be used to condition the specimen when the in-service environmental condition is a vapor such as humid air. Immersion in a liquid bath should be used to simulate vapor exposure only when *apparent* absorption properties are desired for qualitative purposes. Properties determined in the latter manner shall be reported as *apparent* properties.

Traveler Coupons from bonded flange region to evaluate saturation rate during environmental conditioning

Traveler mass ≈ 10 g





Tomblin, J., et al. 2001, B – Basis Design Allowables for Epoxy – Based Prepreg, Faberite 8-Harness Graphite FabricT650 3k-135-8H / 7740
https://agate.niar.wichita.edu/Materials/WP3.3-033051-102.pdf

Tomblin, J., et al. 2002, A – Basis and B – Basis Design Allowables for Epoxy – Based Prepreg,
www.niar.wichita.edu/agate/Documents/Materials/WP 3.3-033051-136 Rev. 1.pdf

Heshmati, M., Haghani, R., & Al-Emrani, M. (2016). Effects of moisture on the long-term performance of adhesively bonded FRP/steel joints used in bridges. Composites Part B: Engineering, 92, 447–462.

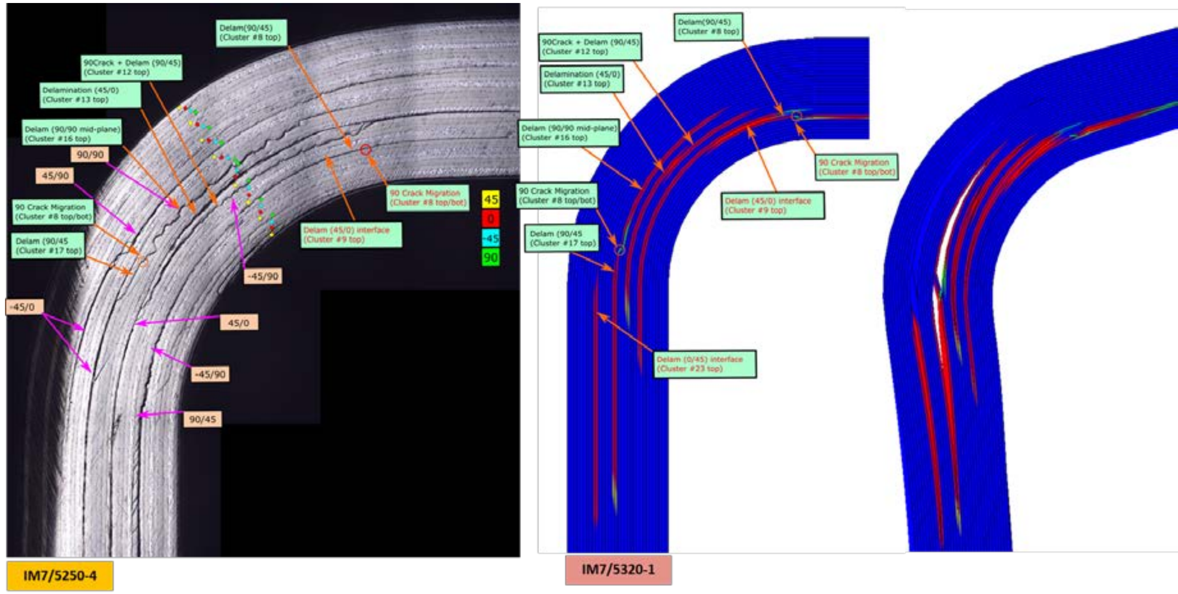
Summary

Testing & Evaluation

- The 7PB test methodology was showcased as robust & reliable test method for evaluation of monolithic/bonded joints (Findings were presented to the ASTM D30 sub-committee on March 2021)
- Development of 7-point bend test as a (ASTM) standard for evaluating the sensitivity of design features and material/processes for manufacturing defects and potential aging threats at early stages of design with sufficient load complexity without the use of costly & time-consuming structural tests
- Top-Down approach to evaluate design conservatism when based on lower-level allowables

Analysis Validations

- Expand the continuum damage modeling and validations for **structural details** (secondary bonds, co-bonds, and co-cured hat- and T-stiffeners)
- Discrete damage modeling using regularized extended finite element analysis (ReFEM) for investigating competing failure modes and crack migration.



Looking Forward / Future Work

- Benefit to Aviation
  - Development of a test methodology to evaluate various design aspects at early stages of the design and manufacturing process to mitigate risks
  - Understanding of scaling effects and design factors (scatter factor, environmental compensation factors)
- Next Steps:
  - Complete 7-point bend testing of bonded and welded thermoplastic joints (bond process qualification at scale)
  - Experimental evaluation of component-level fuselage section and fragmented testing
  - Continued discussions with ASTM D30 about the possibility of standardizing 7-point bend testing