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CMH-17 COMPOSITE MATERIALS HANDBOOK

Development of Higher Level Building Block Testing Standards

Test Methodologies for Monolithic, Bonded Joints and Sandwich Constructions

JAMS Technical Review
September 30, 2021

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Agenda

- Motivation & Scope
- Sub-element Test Methodologies
- Test Article: Elevator Assessment
- Test Matrix
  - Panel Fabrication
  - Test setup & Instrumentation
- Results & Discussion
- 7PB & m-7PB Discussion
- Conclusions & Outlook

RESEARCH TEAM

FAA

- Larry Ilcewicz, Ph.D.
- Cindy Ashforth
- Ahmet Oztekin, Ph.D. *(Technical Monitor)*

NIAR

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- PI: John Tomblin, Ph.D.
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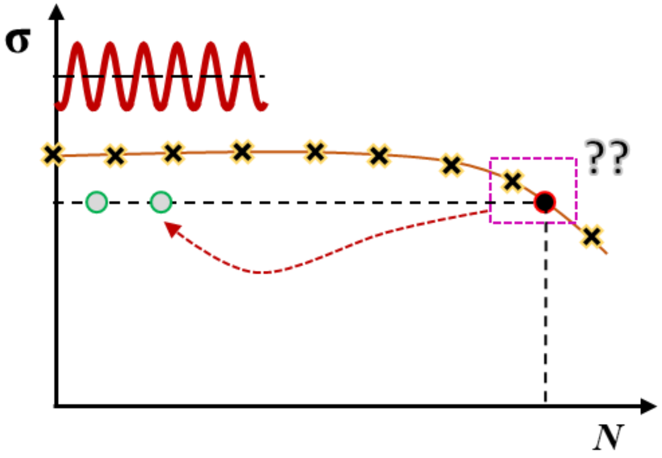
- Mohamed Shafie
- Reomal Vanderwall (Master's student)

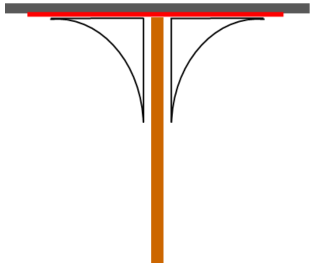
Background

- **Motivation & Key Issues**
  - Lack of reliable test methodology to capture effects of defects, design features & processes
    - Aftermath of manufacturing irregularities (poorly dried core, weak adhesive, failed bond)
    - E.g.: In-service Failure of Main Rotor Blades (MRB)
  - Strength degradation leading to sudden catastrophic failures
  - Fatigue tests w/t embedded artificial cracks do not capture strength degradation

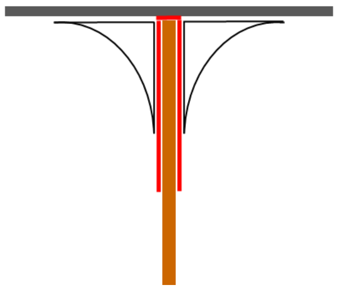


- **Objective and Scope**
  - Objective of this research is to design test methodology to evaluate **Design Features**, **Materials/Processes** & interrogate **Effects of Defects** (detect early in the design phase)
  - Proposed test method must be easy to *install/operate, robust, apply complex (realistic) loading conditions and small enough to expose specimens to conditioning*

Face/Core Interface

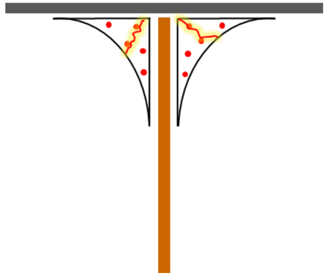


Core Pullout



- **Approach**
  - Identity design critical features in **Monolithic, Bonded & Sandwich Constructions**
  - Compare proposed test methodology w/t existing test methods (SCB & FWT)
  - Perform sensitivity study to understand criticality of defects on the test method *(Effects of Defects)*

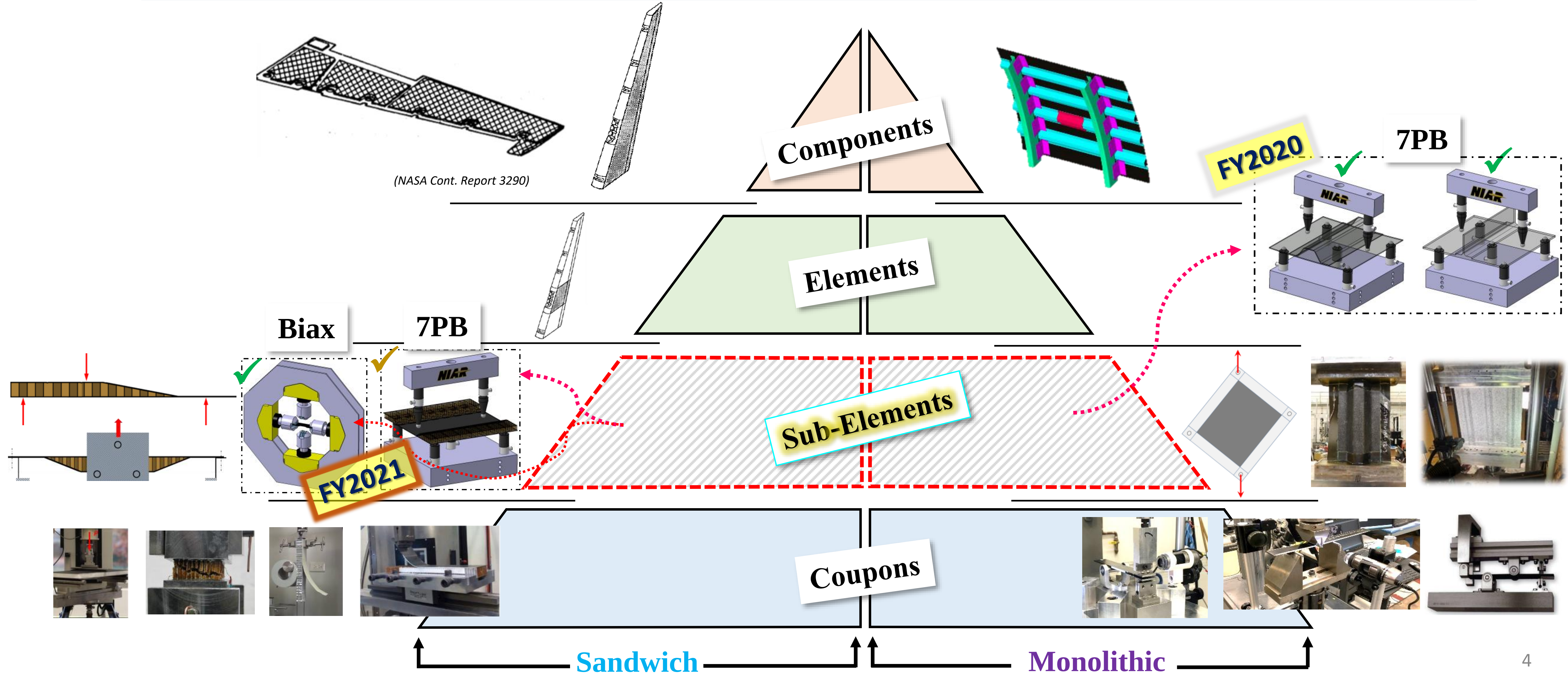
Fillet Fracture



- **Potential Benefits to Aviation / Deliverables**
  - Establish best practice in industry to capture undetectable mfg. defects in the design phase
  - Quantitative knowledge on knock-down (relative damage growth)

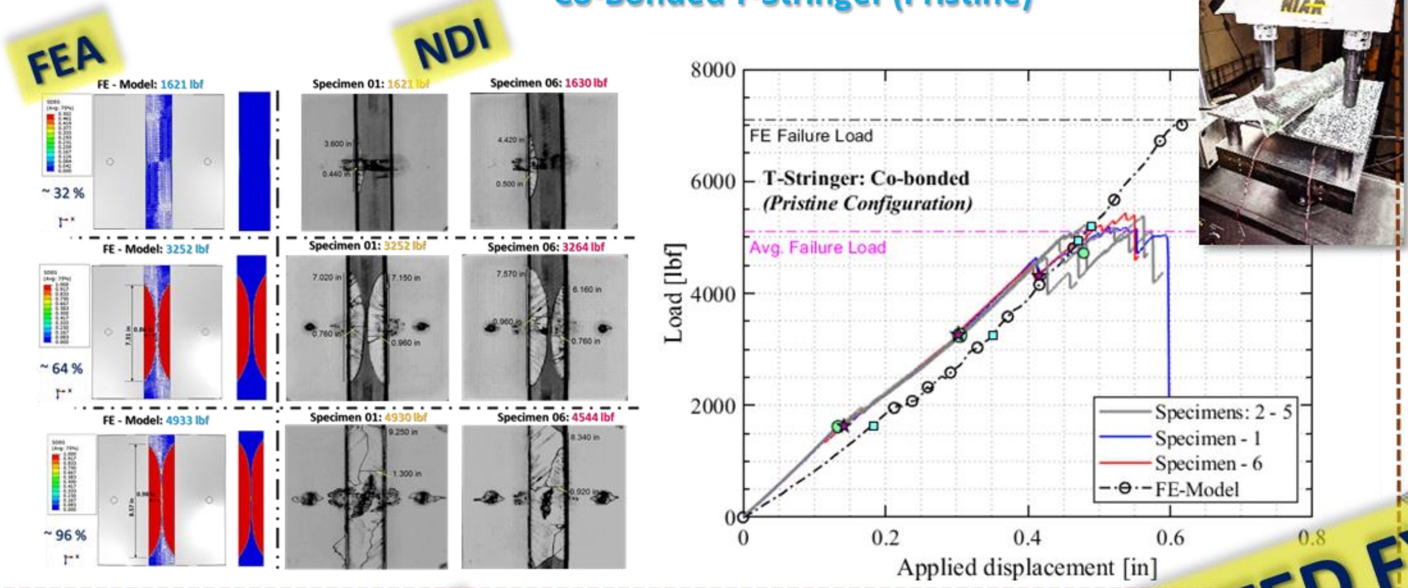
Overview of Current Test Methods: Scope for a Mid-Tier Test Methodology

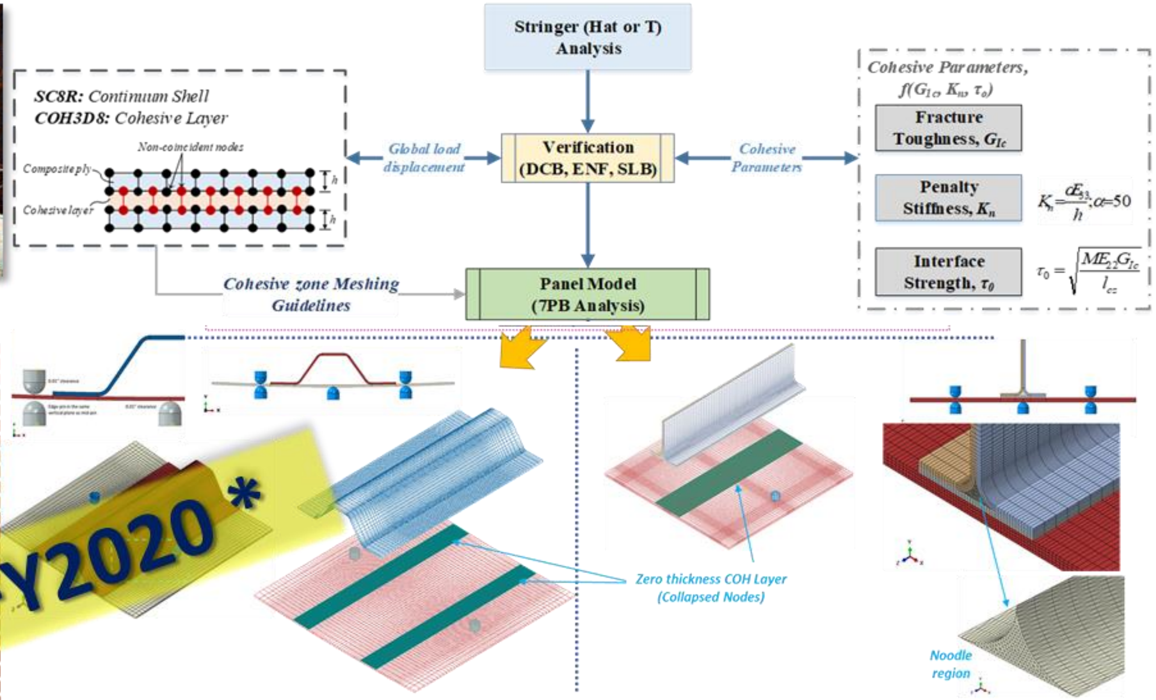
GOAL: *Identify **Weak Design** w/t Aid of selected Test Methodology which introduces **Complex Loading** Scenario (representative of an actual control surface).*



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

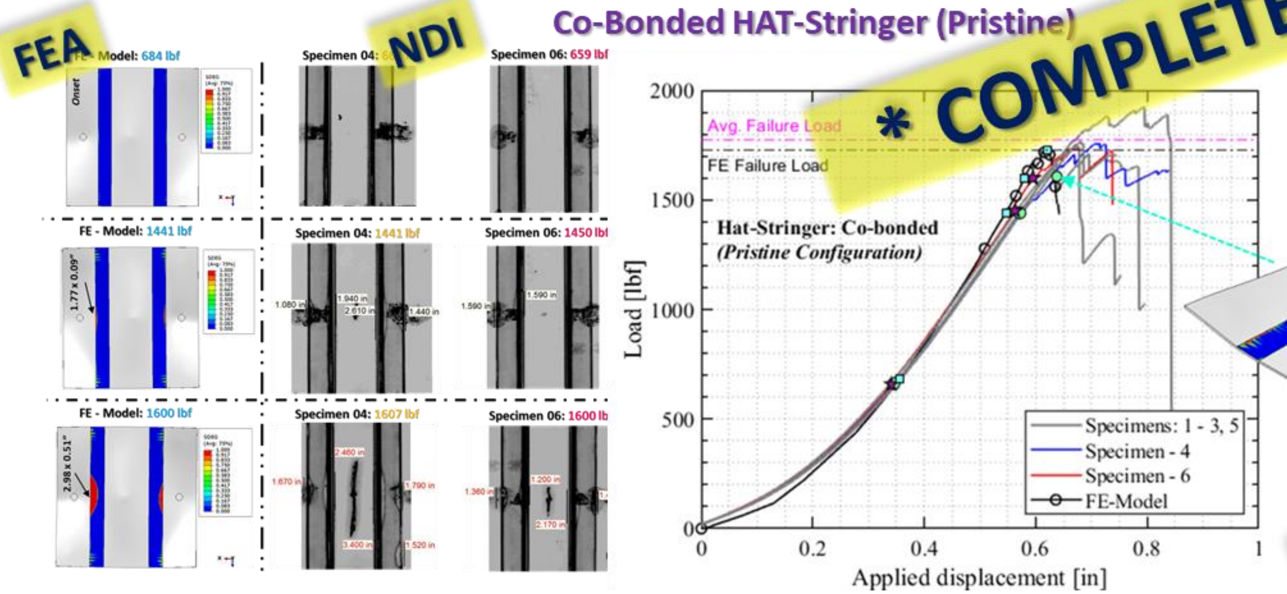
Co-Bonded T-Stringer (Pristine)



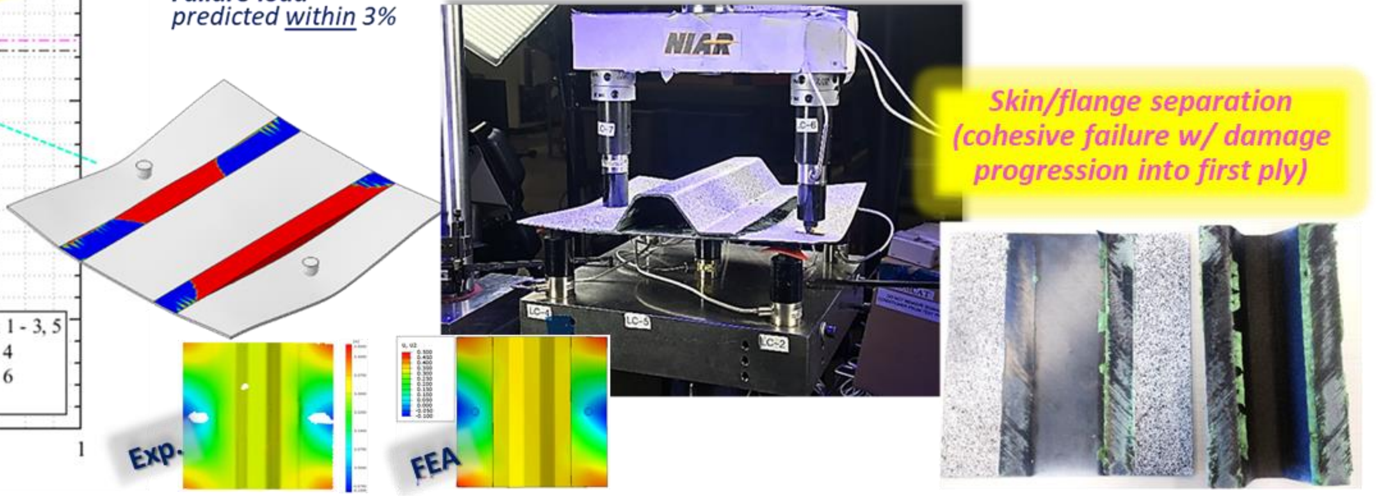


* COMPLETED FY2020 *

Co-Bonded HAT-Stringer (Pristine)



- *Failure load predicted within 3%*

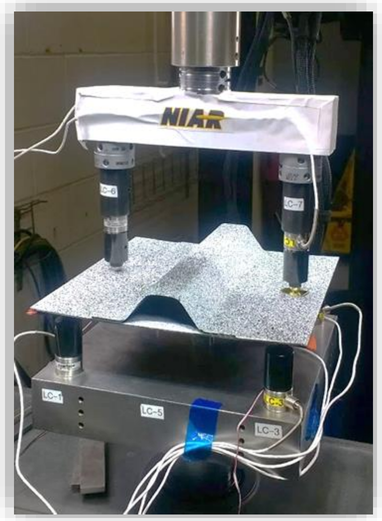


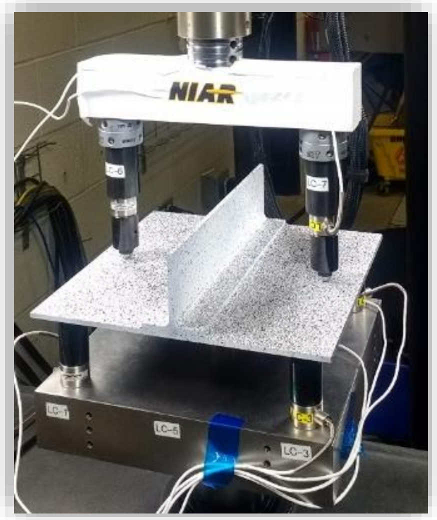
Technical Approach

Phase I | Phase II *(Ongoing)* | Phase III

Monolithic/Bonded Joints

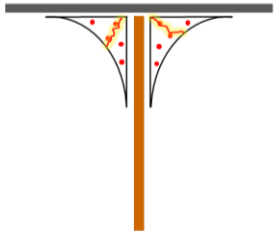
- **Seven-point bend (7PB)** - a case of moment loading about two orthogonal axes
- **Test Articles:** **Hat** & **T-Stringers**
- **Fabrication Procedures:** **Secondary Bonded (SB)** & **Co-Bonded (CB)**
- **Specimen Configuration:** **Pristine** (Baseline), **Pre-cracked** and **Impacted**

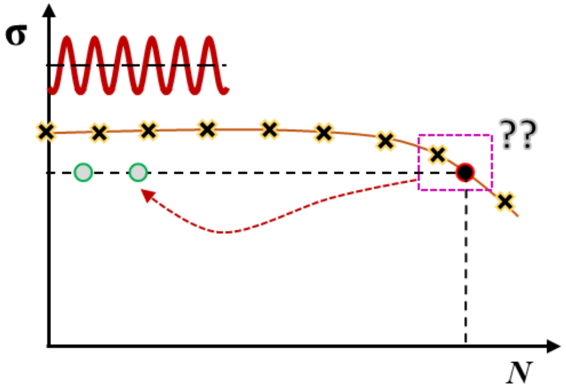


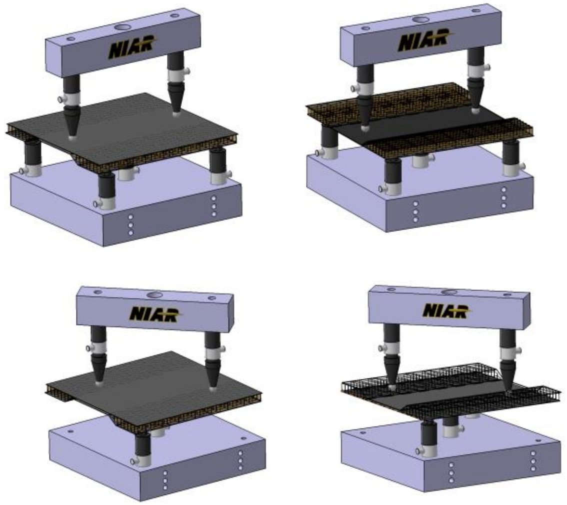


Sandwich Constructions (Effects of Defects)

- Design test method(s) to study effects of defects in sandwich bondline
- Introduce defects at face/core interface (Microporosity)
  - Document using high fidelity X-CT
- Evaluation of selected tests methodology against existing SCB & FWT test methods (Interrogate defects)
- Evaluation of identified test articles (design features)
  - Sandwich mid-ramp configuration identified
- Evaluate sub-element level test method to capture microporosity
  - Effects of Defects w/t complex loading



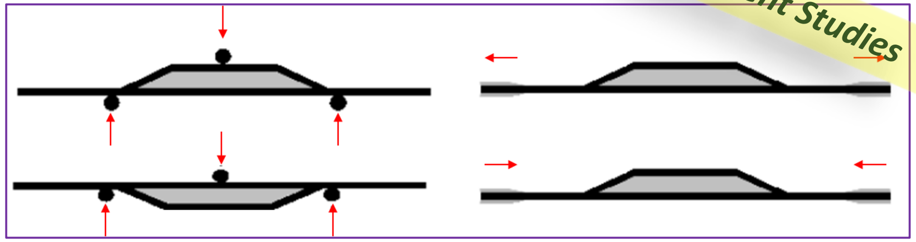


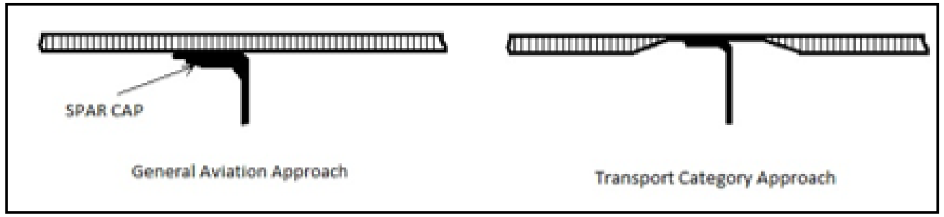


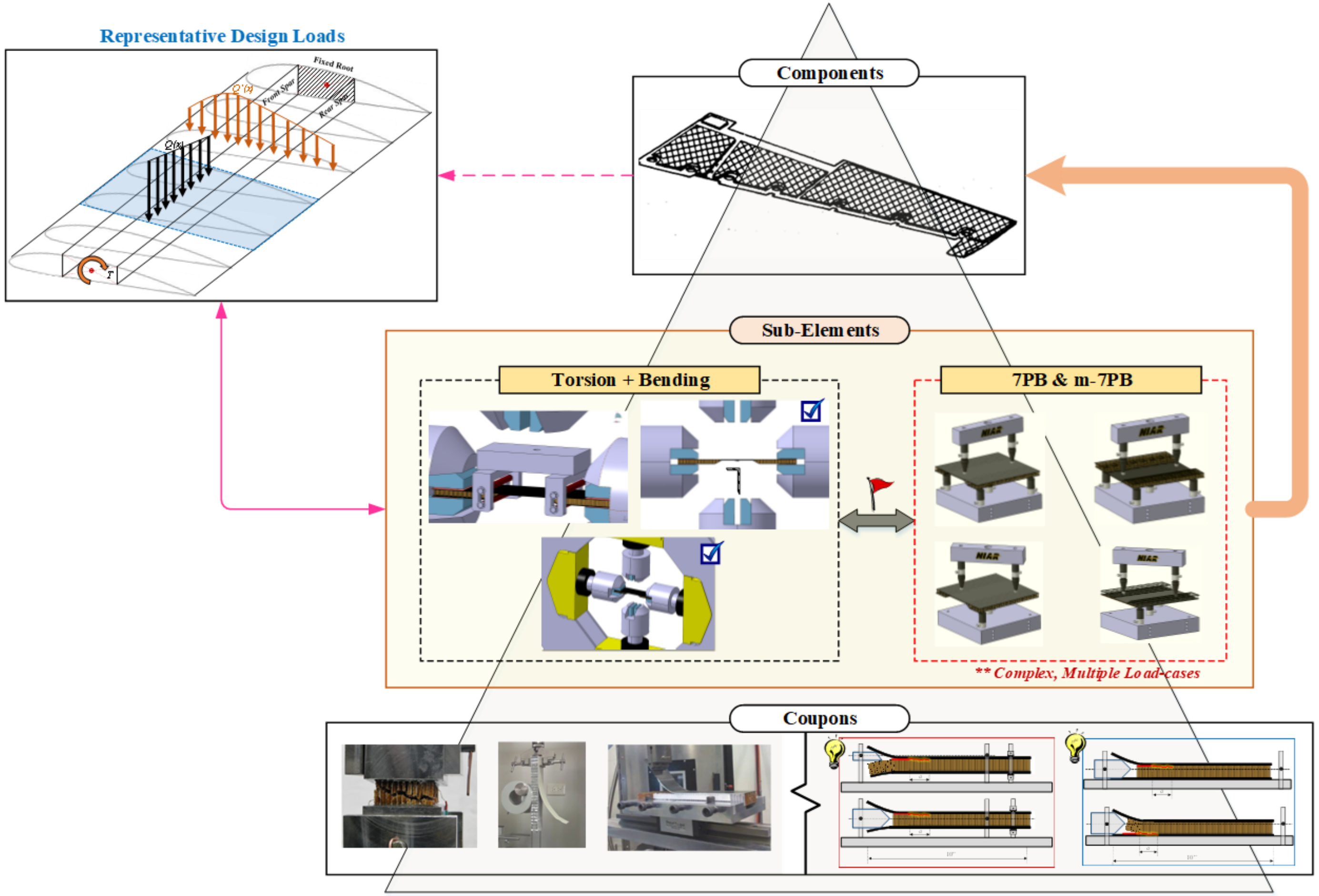
Sandwich Composites Sub-element Test Methodologies

Current Studies

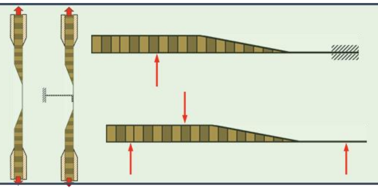
- **Design Feature Evaluation:** Ramp region
- **Biaxial-based** testing (can't employed on a standard lab setting)
- **Mid-ramp** length (>2x radius) selected to avoid load-end effects
- **7PB:** Both top & bottom loading considered



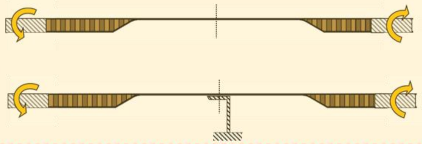




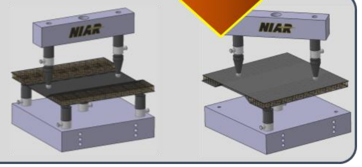
- Cantilever
- Three-Point Bend (3PB)
- Tension
- Tension + Point-load



- Torsion
- Torsion + Point-Load

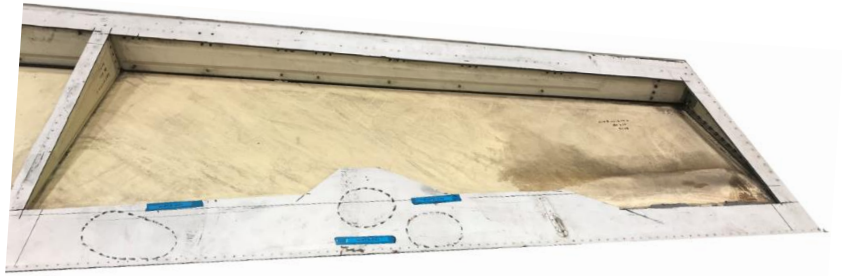


- Sandwich 7PB *(Top & Bottom Load)*
- Sandwich m-7PB *(Top & Bottom Load)*

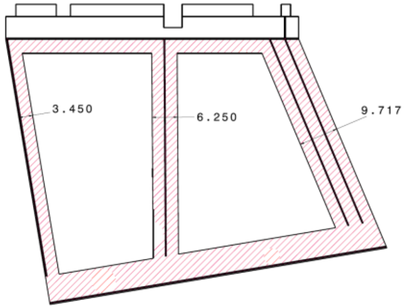


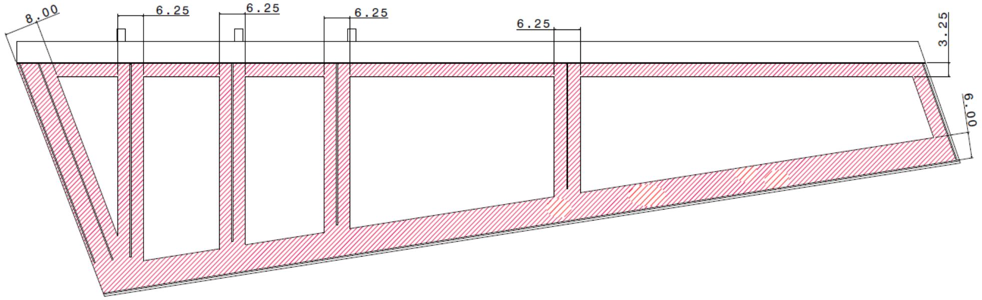
Sandwich Ramp Area: Elevator Assessment

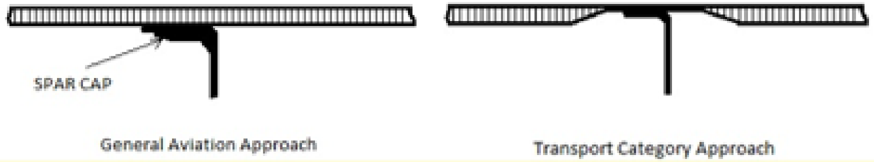
Component #12
Right IB Elevator



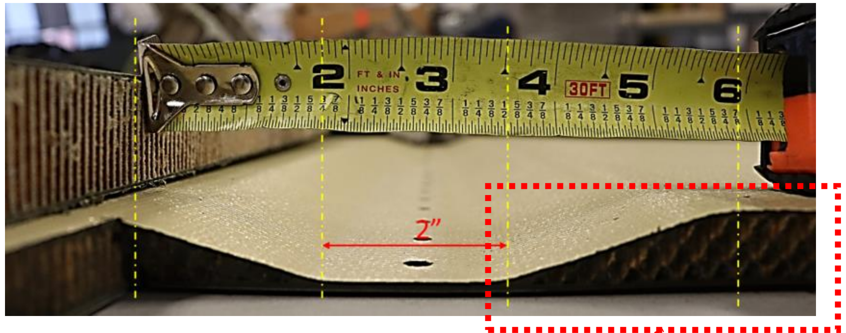
Component #9
Right OB Elevator

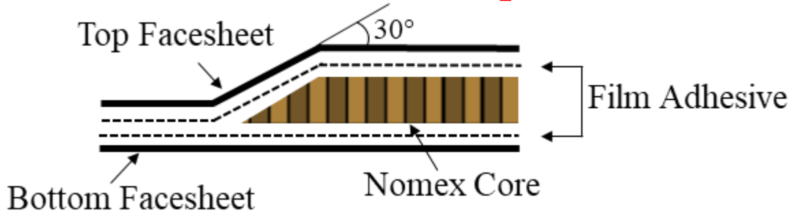




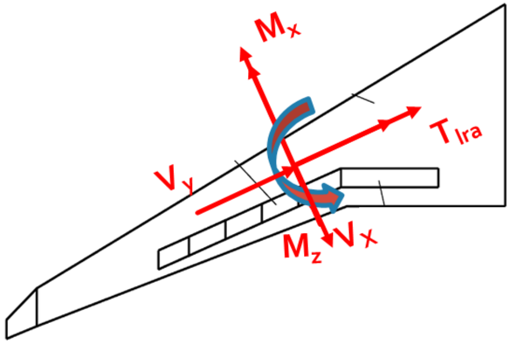


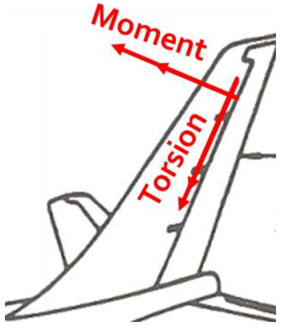
Sandwich Double ramp sandwich - rib attachments in general aviation

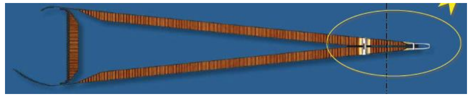


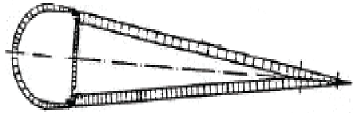


Force & Moment Components









(2016) Chantal Fualdes

- **Critical Area Targeted:** Ramp region
- **Load:** Torsion + Bending component
- **Sandwich ramp** area Assessment: Ramp angle, radius, materials etc.

Test Matrix, Materials & Conditioning (Ongoing)

- **Side Study** to establish microporosity conditions at the face/core interface
- **Thermal Cycling:** To evaluate test candidates by damage characteristics

Facesheet & Core Materials

Facesheet (T650/5320-1 PW)	
No. of Plies	Layup Sequence CPT = 0.0073 in.
4	[(±45)/(0/90)/(0/90)/(±45)]

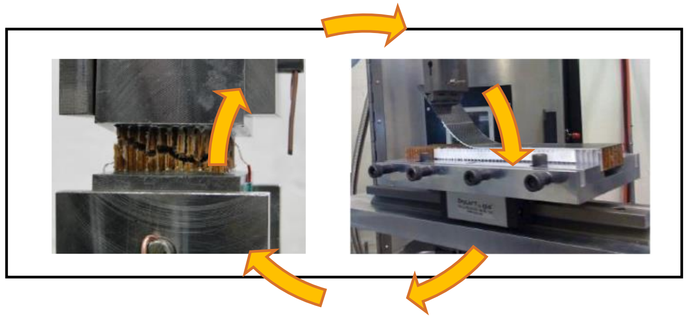
Core (Nomex® HRH-10)		
Density [pcf]	Cell-size [in.]	Thickness [in.]
3	1/8	0.5

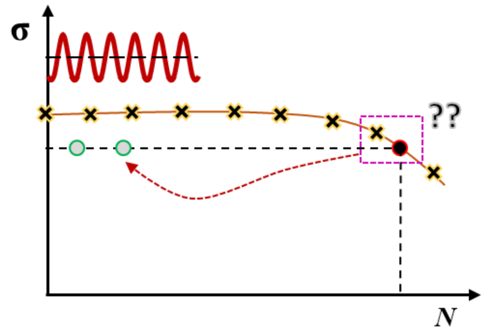
Thermal Cycle Test Matrix

Test Method	N = 0 (Baseline)		No. of Coupons
	Pristine	Microporosity	
FWT			3 + 3
SCB			3 + 3
7PB m-7PB			3 + 3 3 + 3
		Total No. Coupons	24

Test Method	Thermal Cycle		No. of Coupons
	Pristine	Microporosity	
FWT			3 + 3
SCB			3 + 3
7PB m-7PB			3 + 3 3 + 3
		Total No. Coupons	24

By inducing Thermal Cyclic loads the interface (both pristine & microporous coupons) will weaken & thus damage characteristics will be distinguishable across various test methods





Side Study - Microporosity

Trial Test Matrix to introduce Microporosity				
Core Pre-Fab Condition	Co-Cured (CC)	Co-Bonded (CB)	Secondary-Bonded (SB)	Panel Size
Pristine				12 x 5 in
Untreated				
Proces/Treatment				

Test Matrix: Sandwich Coupons

Specimen Type	Specimen Config.	Mid-Ramp Dist.	Loading	Number
Sandwich - **7PB**	* Pristine	4.0 in.	Top Load	4
			Bottom Load	3
Sandwich - **m7PB**	* Pristine	4.0 in.	Top Load	4
			Bottom Load	3
Sandwich - **Biaxial (Torsion)**	✓ Pristine	4.0 in.	Torsion only	4
	Impacted			3
	✓ Pristine	6.5 in.	Torsion only	4
	Impacted			3
Sandwich - **Biaxial (Torsion + PT-Load)**	✓ Pristine	4.0 in.	Torsion + Point-load	4
	Impacted			3
	✓ Pristine	6.5 in.	Torsion + Point-load	4
	Impacted			3

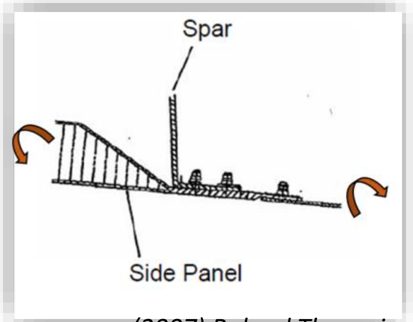
* Fabricated ✓ Test Completed **Total No. of Specimens:** 42

Facesheet & Core Materials

Facesheet (T650/5320-1 PW)	
No. of Plies	Layup Sequence CPT = 0.0073 in.
4	[(±45)/(0/90)/(0/90)/(±45)]

CPT = 0.0073" [0.185 mm]

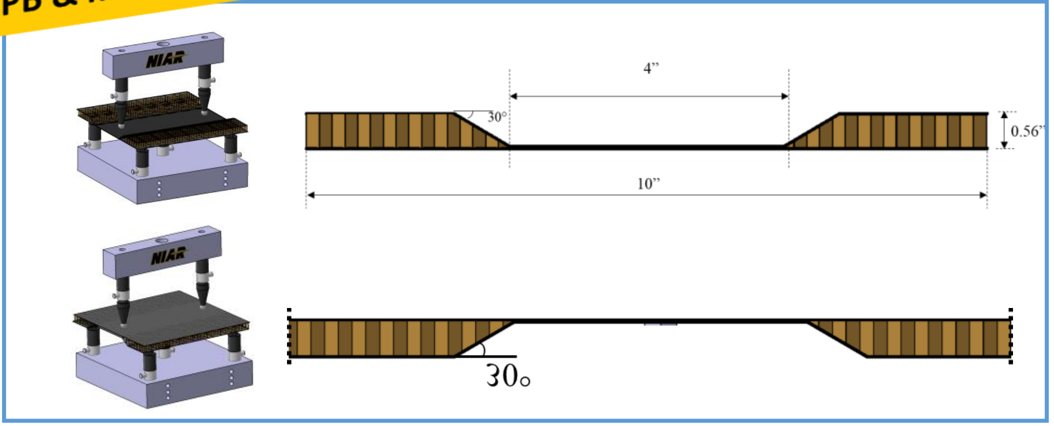
Core (Nomex® HRH-10)		
Density [pcf]	Cell-size [in.]	Thickness [in.]
3	1/8	0.5



(2007) Roland Thevenin

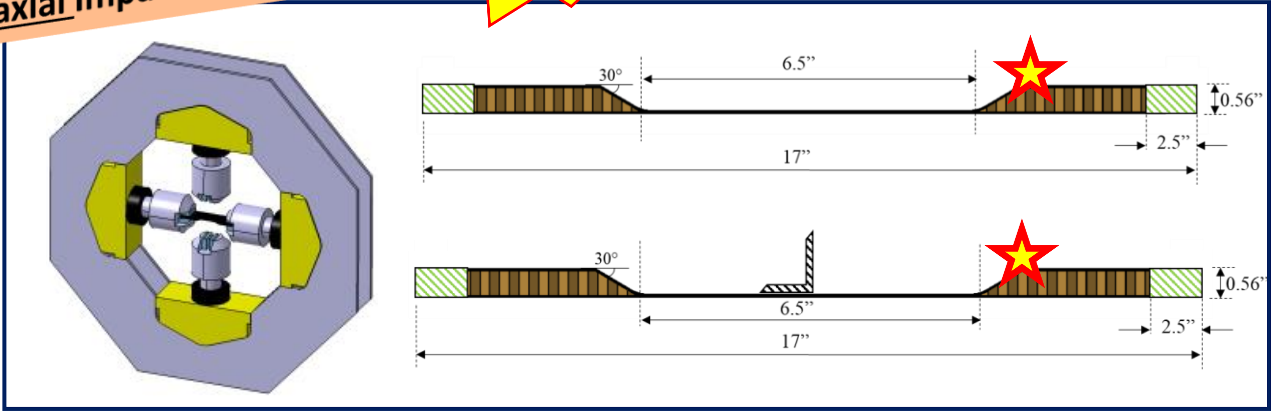
Impact on ramp location

7PB & m-7PB Coupons



Sandwich double ramp (7PB Coupon)

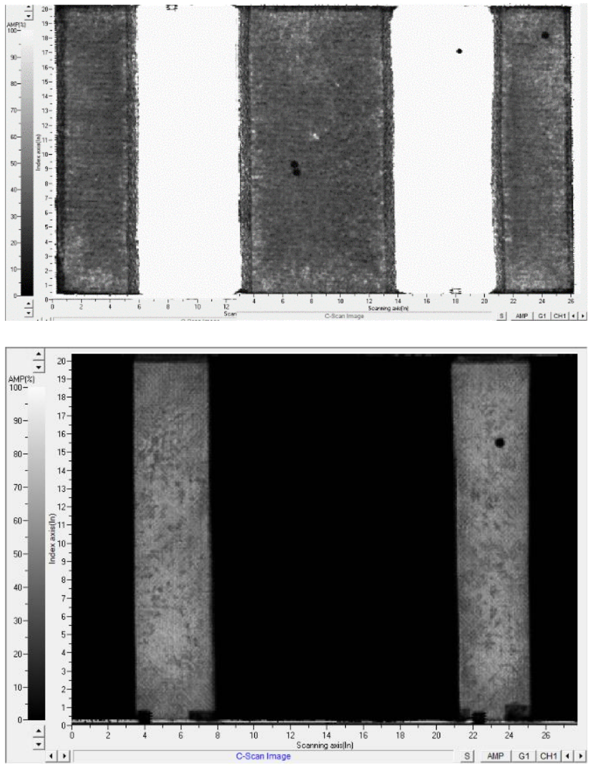
Biaxial Impact Locations



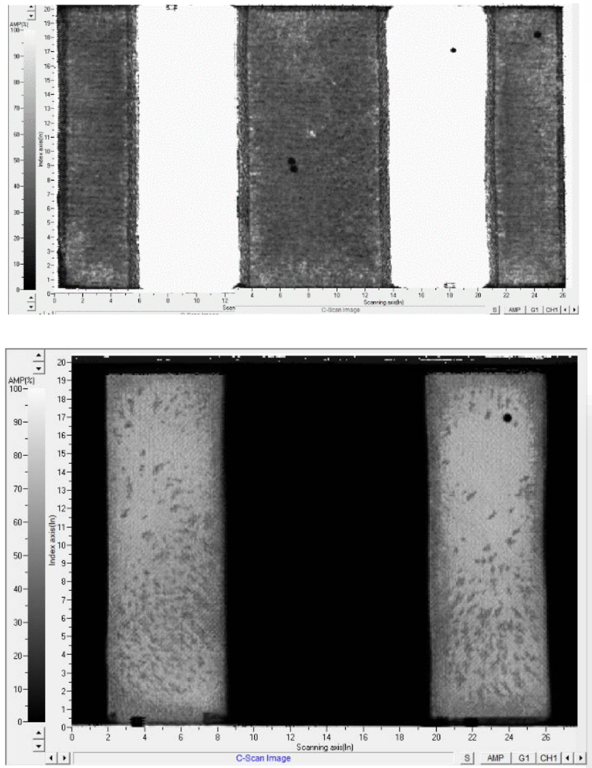
Sandwich double ramp (Biaxial Coupon)

Panel Fabrication & NDI

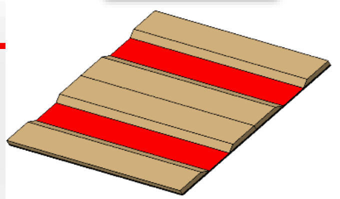
Mid-ramp Distance – 4 in



Mid-ramp Distance – 6.5 in

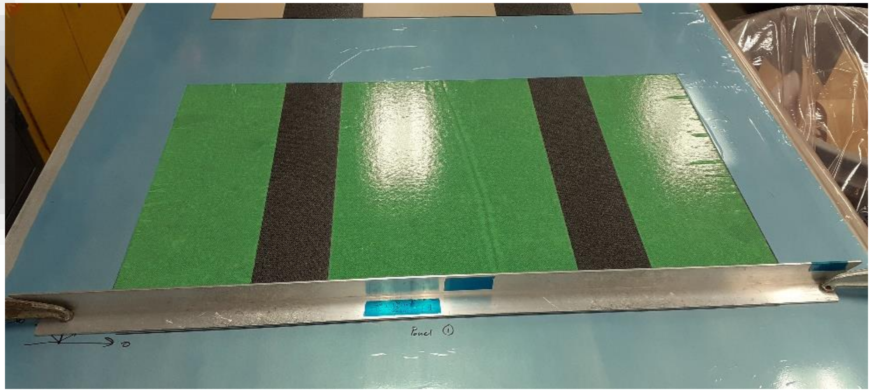


Layout

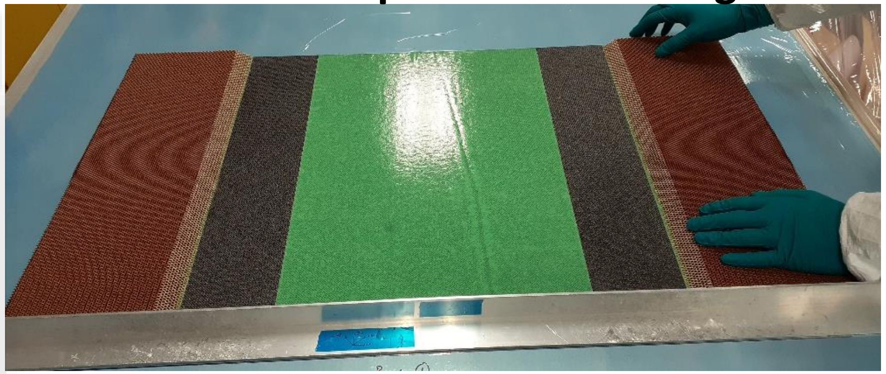


Fabricated Panel

Bottom Facesheet & Adhesive Layup



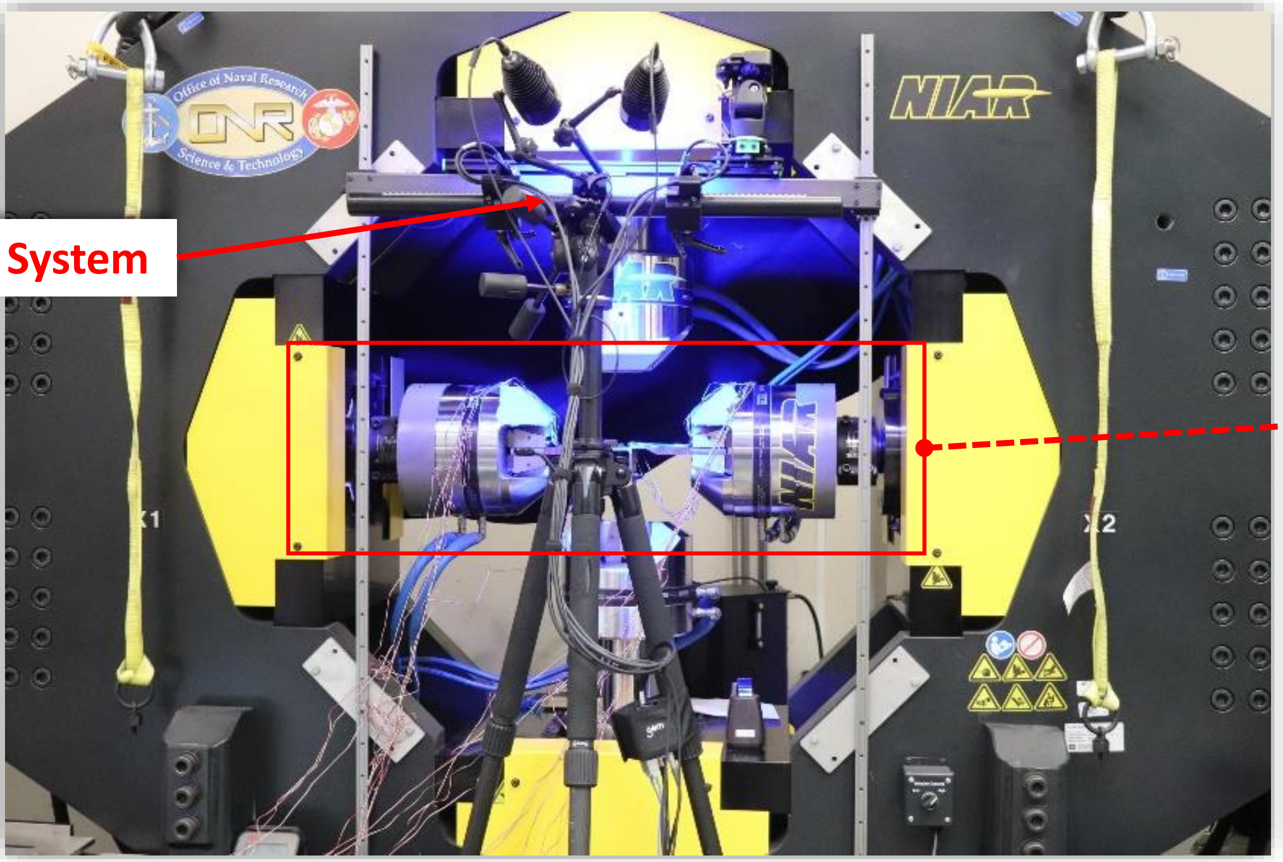
Double Ramp Core Positioning



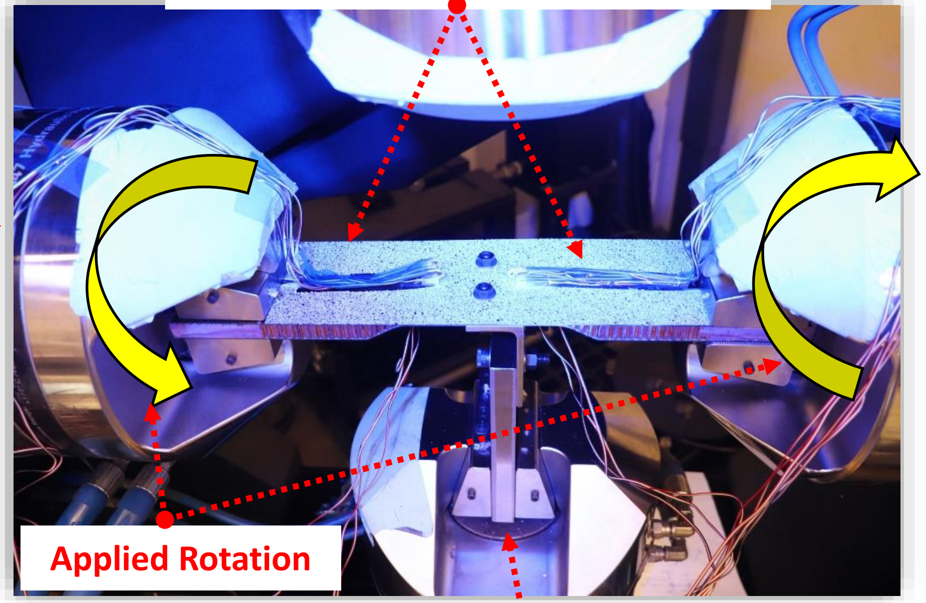
Prep. for Top Adhesive Layer

- No pressure (Vacuum only); good consolidation, no caul plates used
- **Two-step cure:** 250 °F 2hr and 350 °F for 2hr (post-cure)
- MRCC for 5320-1/T650 PW, EA7000 compatible w/ both 250 & 350
- TTU NDI conducted post-fabrication

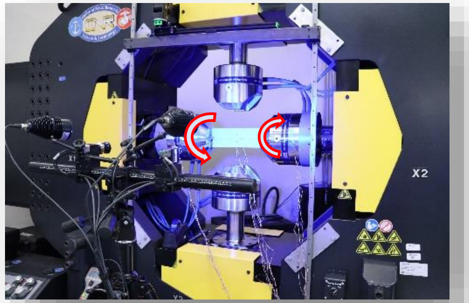
Instrumentation & Test Setup (Applied Rotation & BCs)



** *Horizontal Actuators rotated by 90 deg*



Torsion Only *test setup: Horizontal Actuators in Original Position*

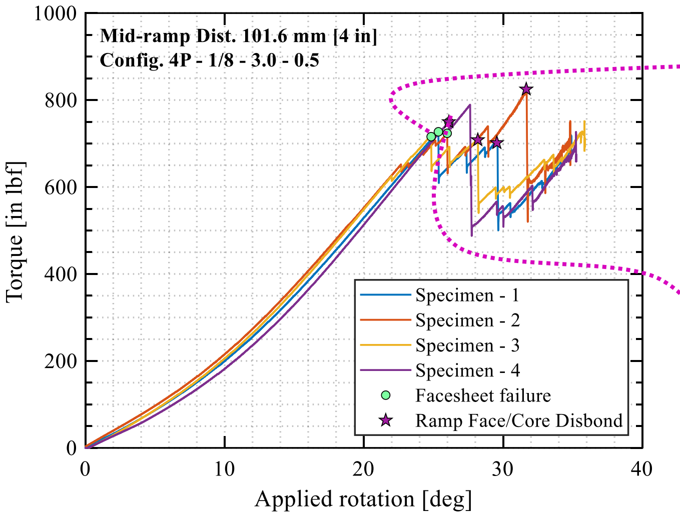


- Rotation control at 8 deg/min
- Lower actuator held at constant BC
- Horizontal actuators rotated 90 deg

Results & Discussion: Debonding, Peak Load & Strain Gage Correlation

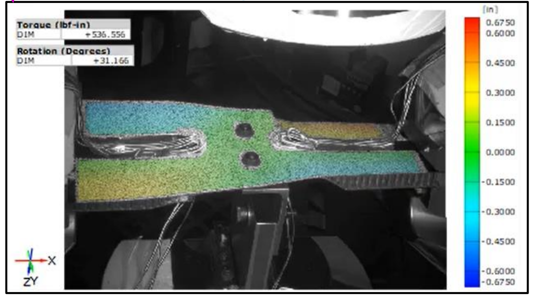
LOAD CASE:
Torsion + Pt-Load (fixed)

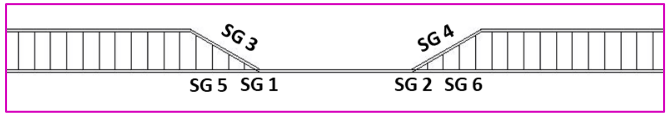
Configuration A (mid-ramp dist. = 4.0 in)

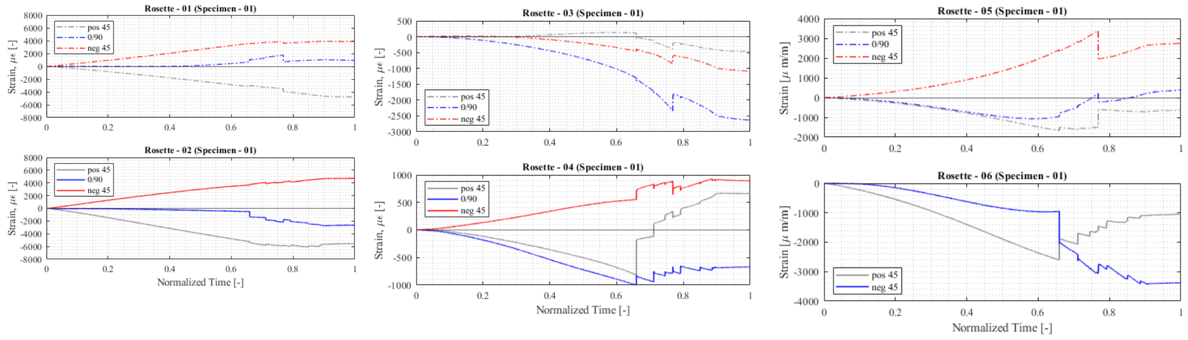


Facesheet Failure Initiation

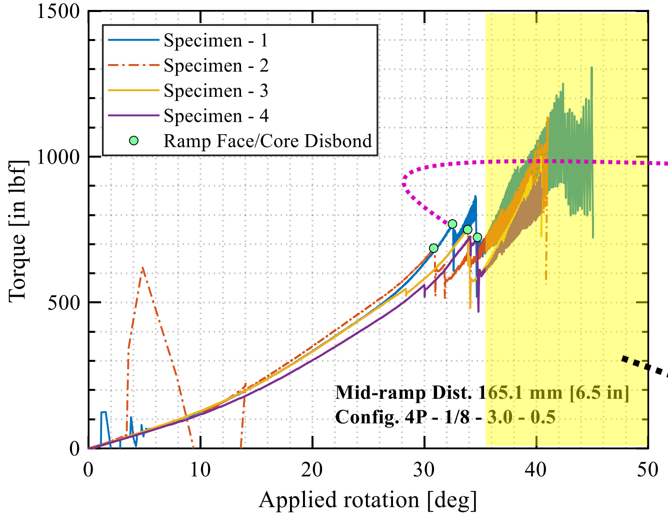
Face/Core Ramp Disbond Initiation



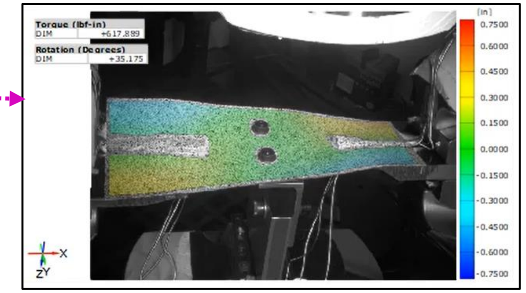




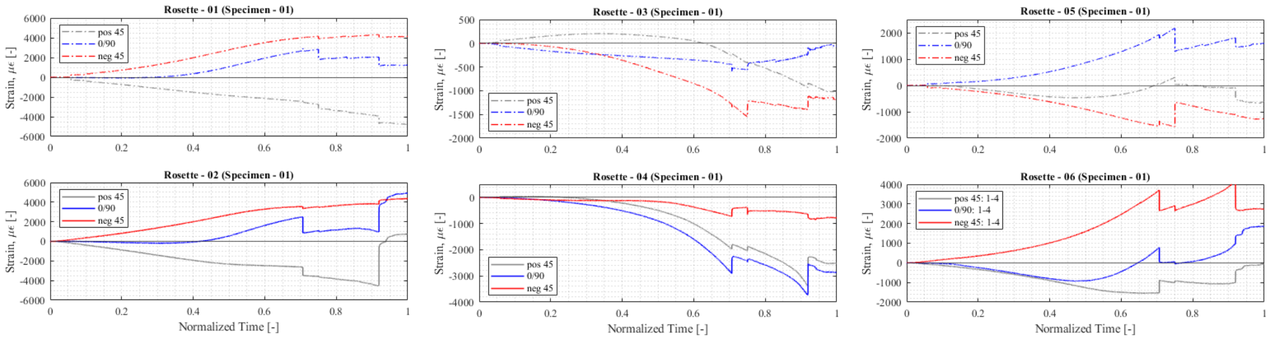
Configuration B (mid-ramp dist. = 6.5 in)



Face/Core Ramp Disbond Initiation



(Beyond First Disbond Event)

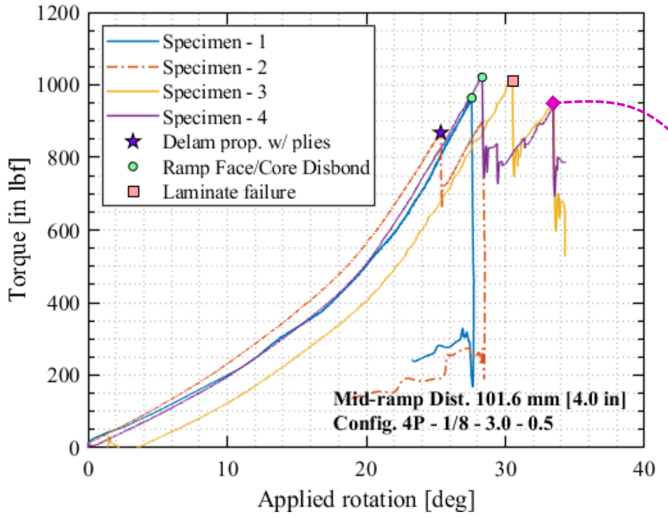


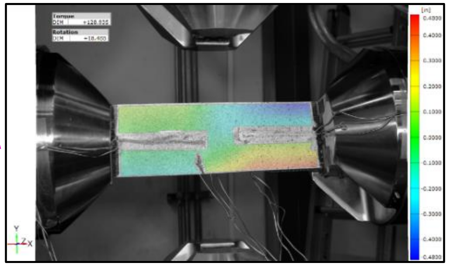
- Disbond initiation picked up by SG1 & SG2
- Config A. Both facesheet failure & debonding occurred simultaneously
- Config B. Only debonding observed

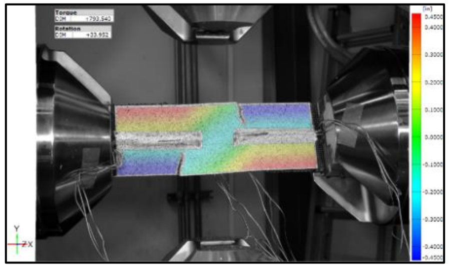
Results & Discussion: Debonding, Peak Load & Failure

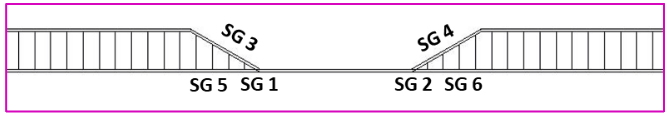
*** LOAD CASE: Torsion only ***

Configuration A (mid-ramp dist. = 4.0 in)

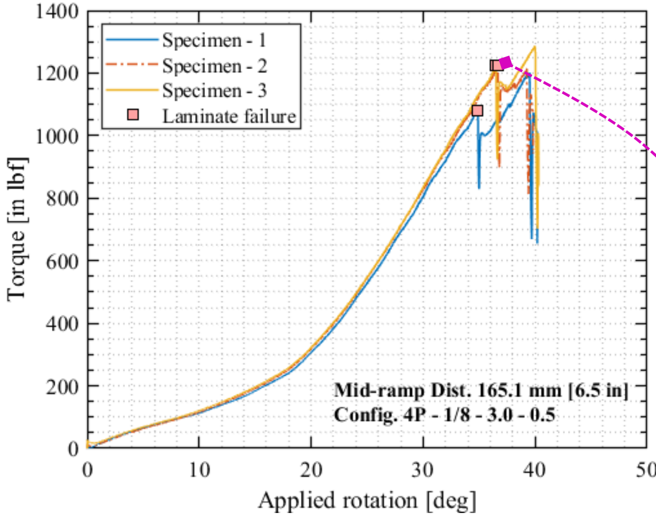




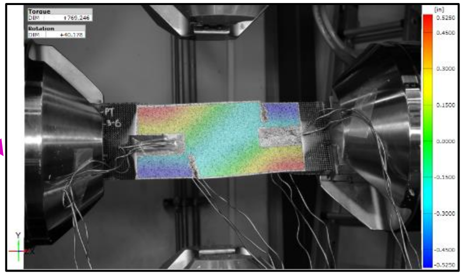




Configuration B (mid-ramp dist. = 6.5 in)

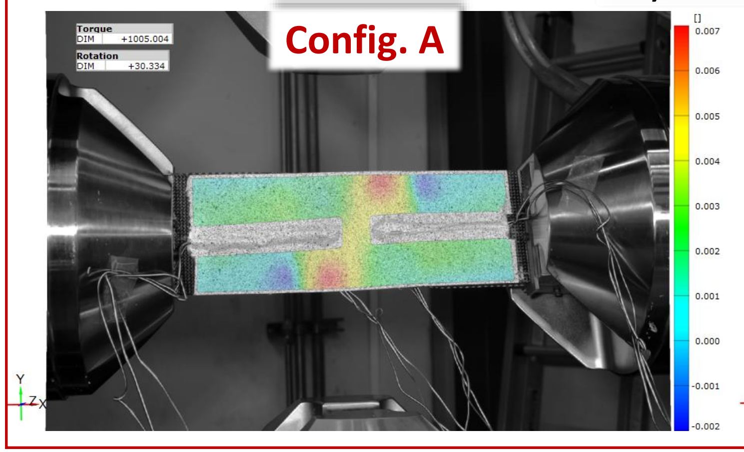


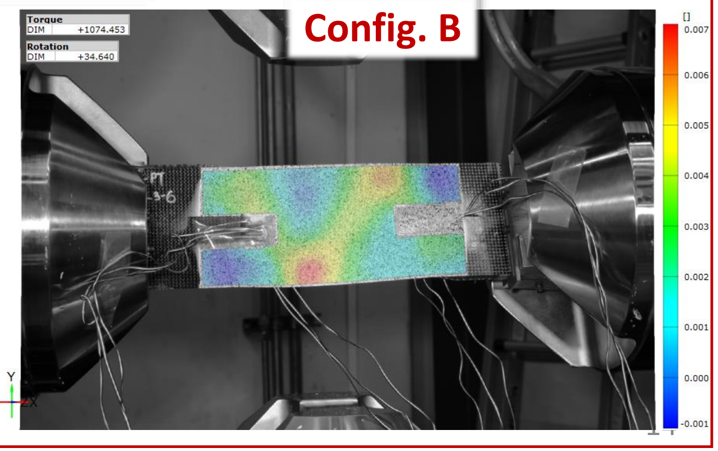
Face/Core Ramp Disbond Initiation



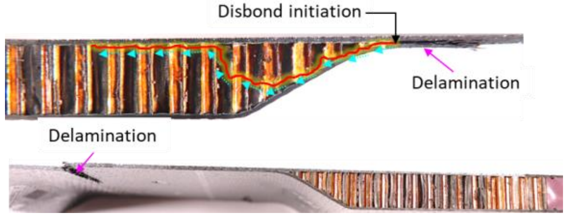
- Disbond initiated @ SW Ramp Root for both 4 .0 (Config. A) and 6.5 in (Config. B)
- Subsequent Mid-ramp laminate failure observed post debonding
  - Laminate failure closely follows debonding
  - Load path: Debonding weaken interfaces, hence load path alters leading to laminate failure
- Debonding absent on diagonal opposite end due to facesheet out-of-plane tear
- Disbond occurred at bottom face/core interface

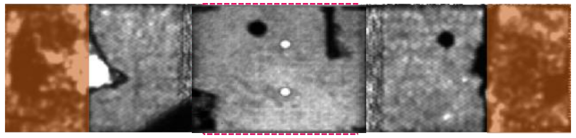
ε_{xy} Component

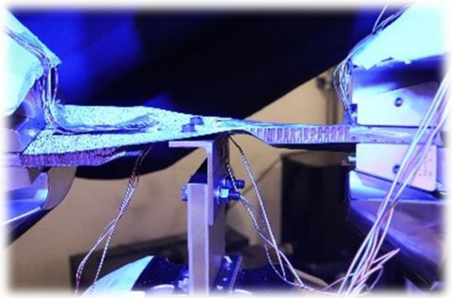


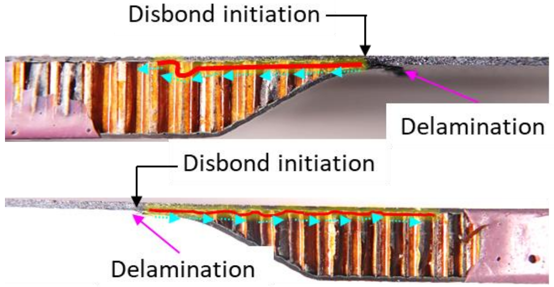


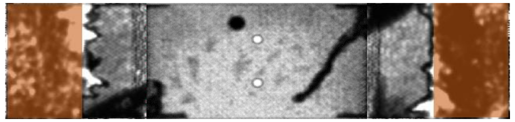
Summary: Failure Load & Mechanisms

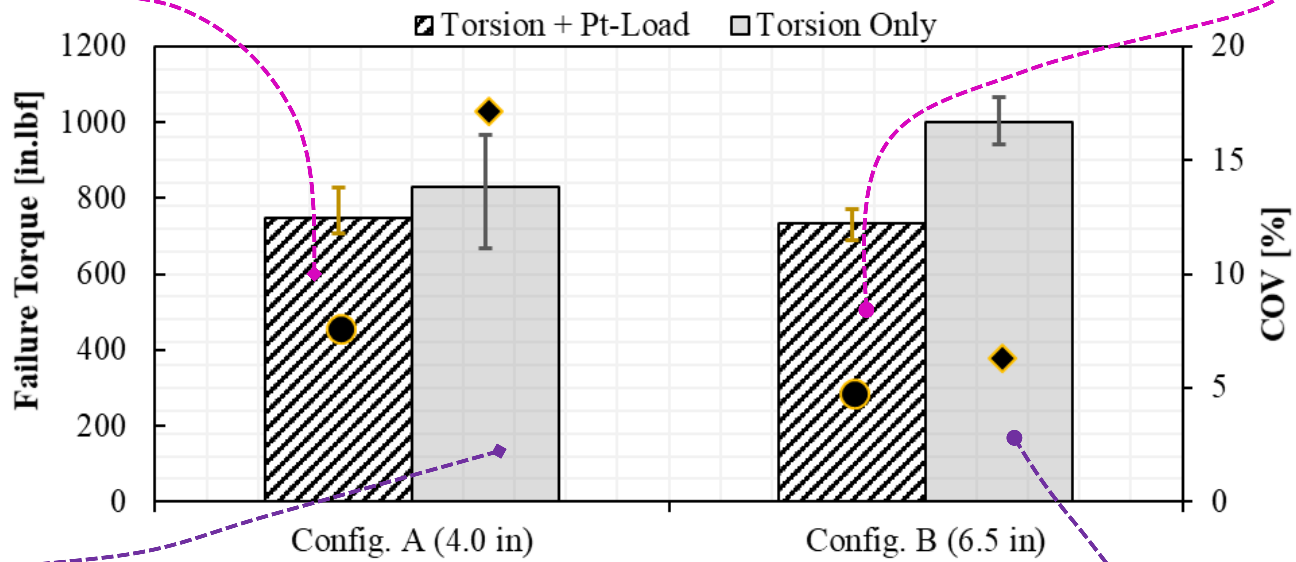


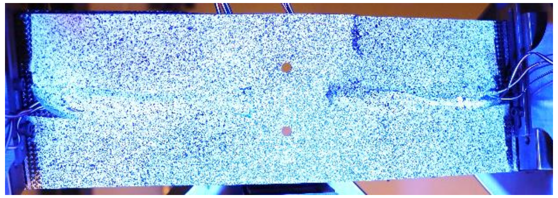


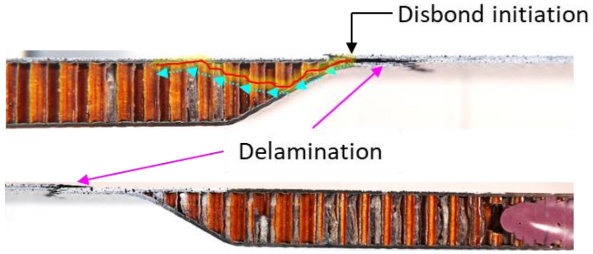


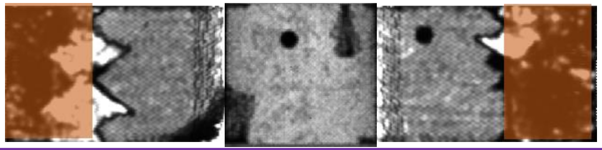


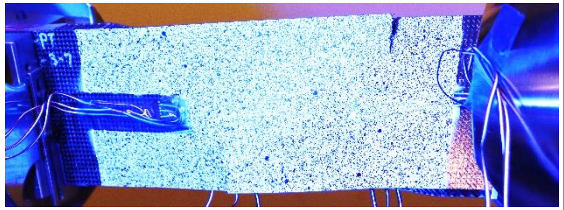


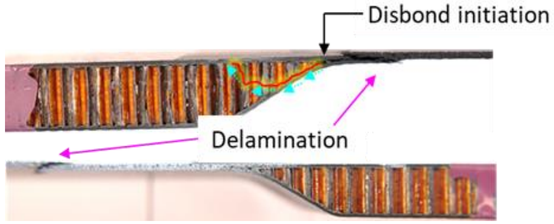


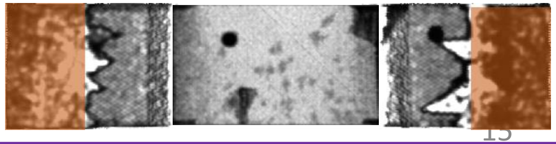








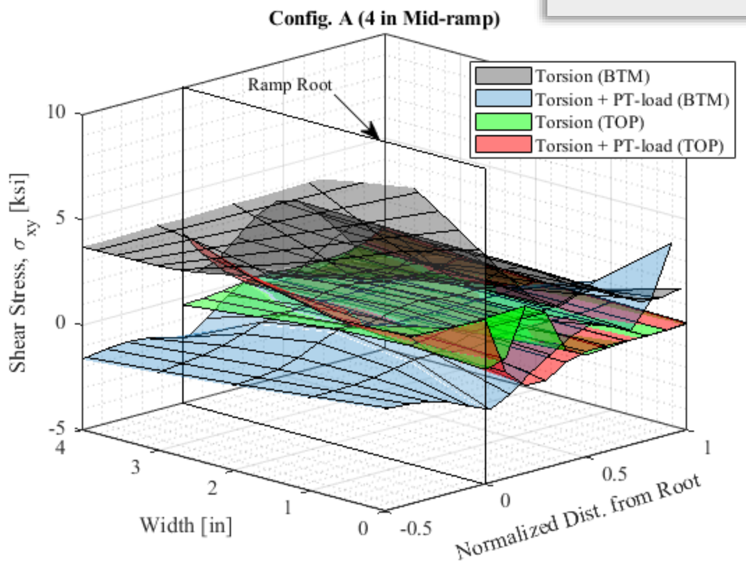


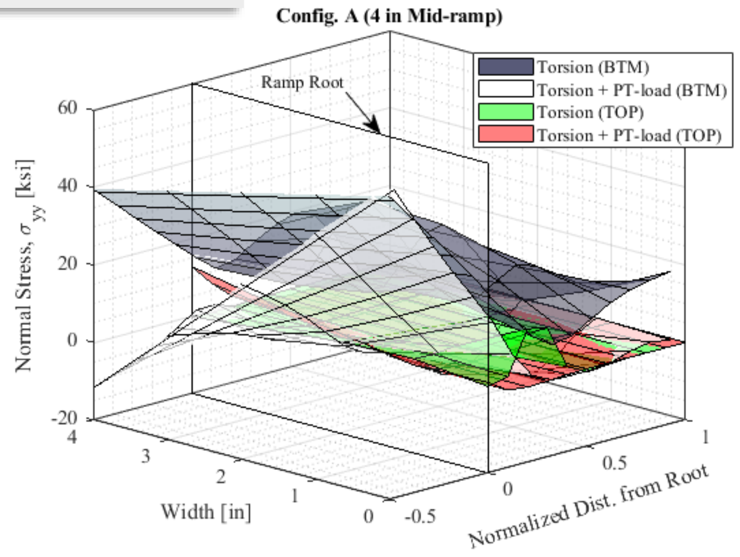


- Disbond *always* initiated from ramp root
- Largest Failure Load observed on Torsion only load cases
- Highest COV 17% Config A (Torsion only) and lowest 4.7% Config B (Torsion + PT-Load)
- High COV in shorter 4.0 in - Config.; attributed to laminate tear

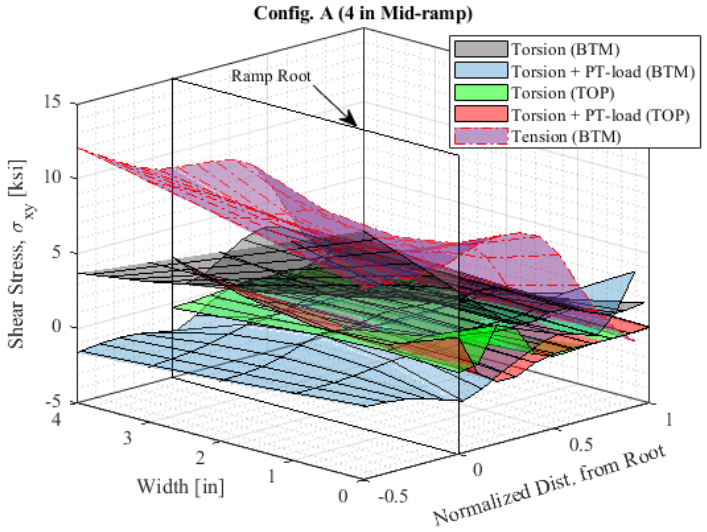
Interface Shear & Normal Stress Comparison

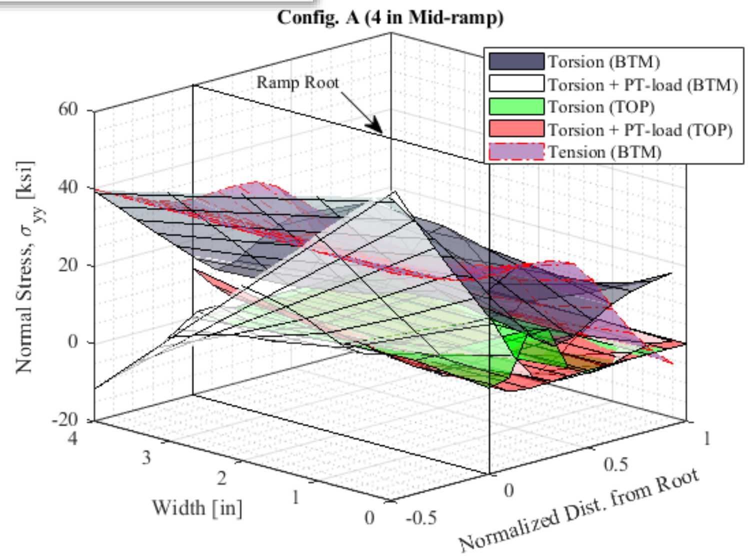
Torsion & Torsion + Fixed-load

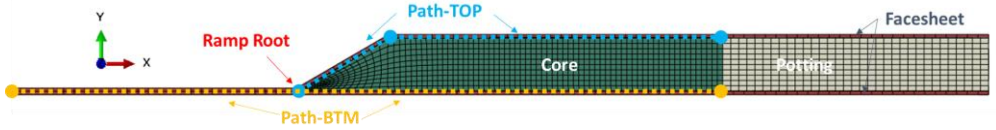


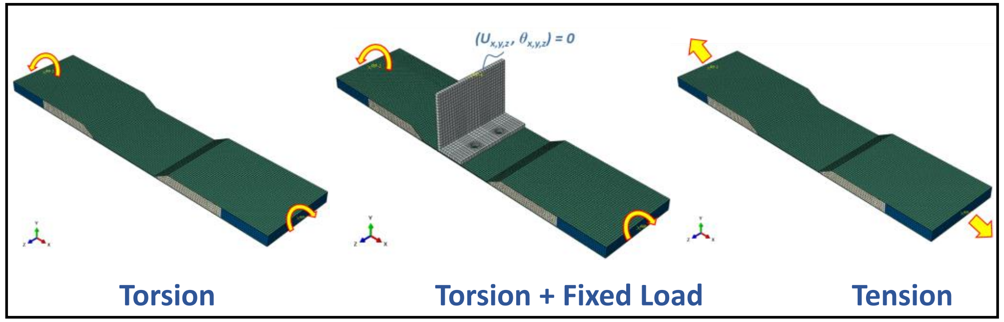


Torsion, Torsion + Fixed-load, and Tension

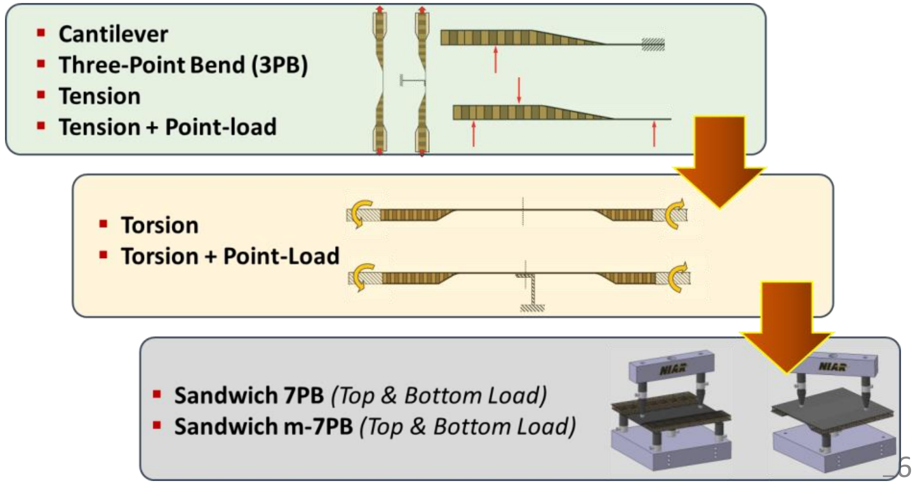






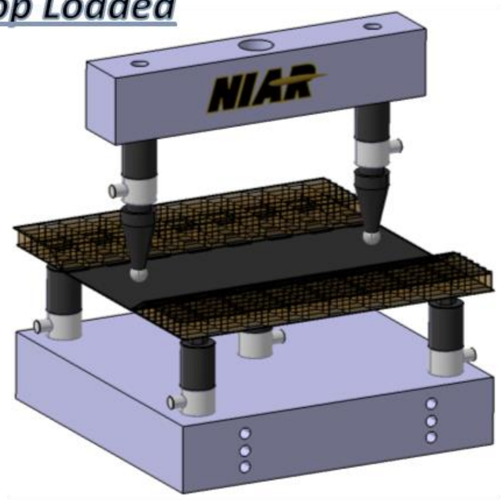


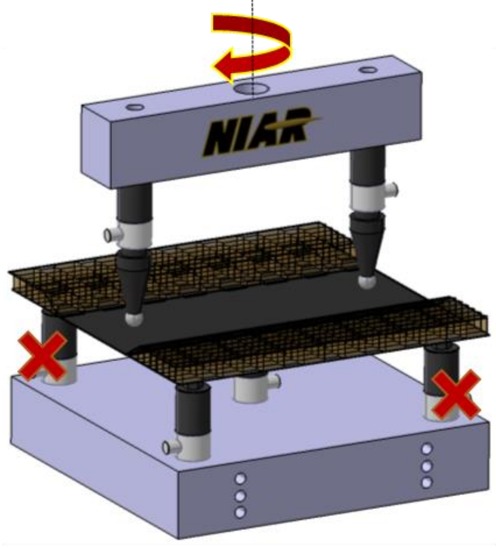
- **Load Configurations; Torsion, Torsion + Fixed-Load and Tension** investigated
  - *Interlaminar shear and normal stresses at ramp*
- ***High asymmetrical shear and normal stresses Torsion & Torsion + Pt-load case compared to Tension loaded coupon***

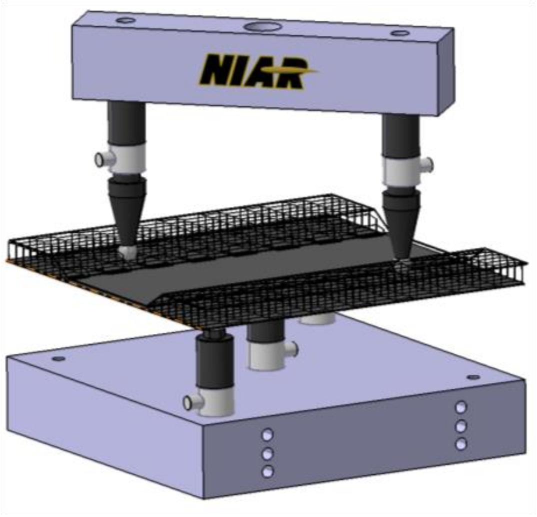


ECT based m-7PB w/t SW Ramped Coupons

Top Loaded



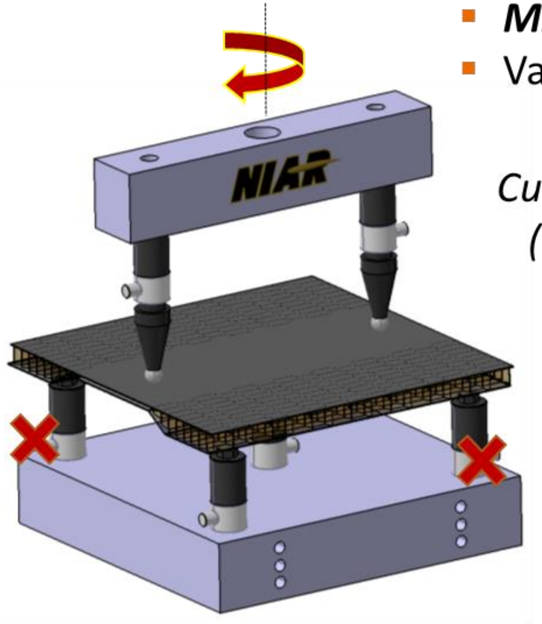


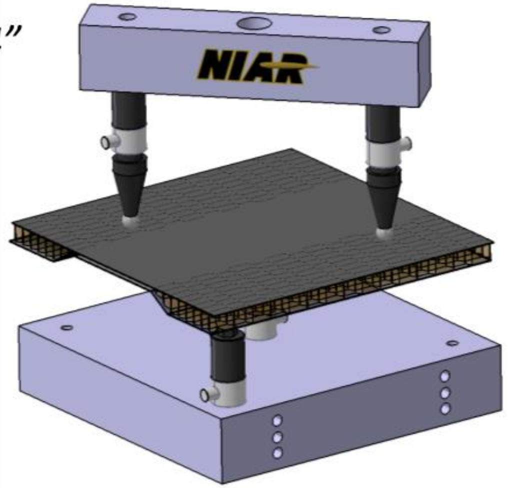


- ***Mid-Ramp distance*** dictates the *induced failure*
- Varies on ***Top OR Bottom*** Loading

Current mid-ramp dist. = 4"
(Typical Values = 2 – 6")

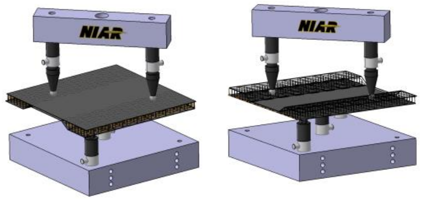
Bottom Loaded



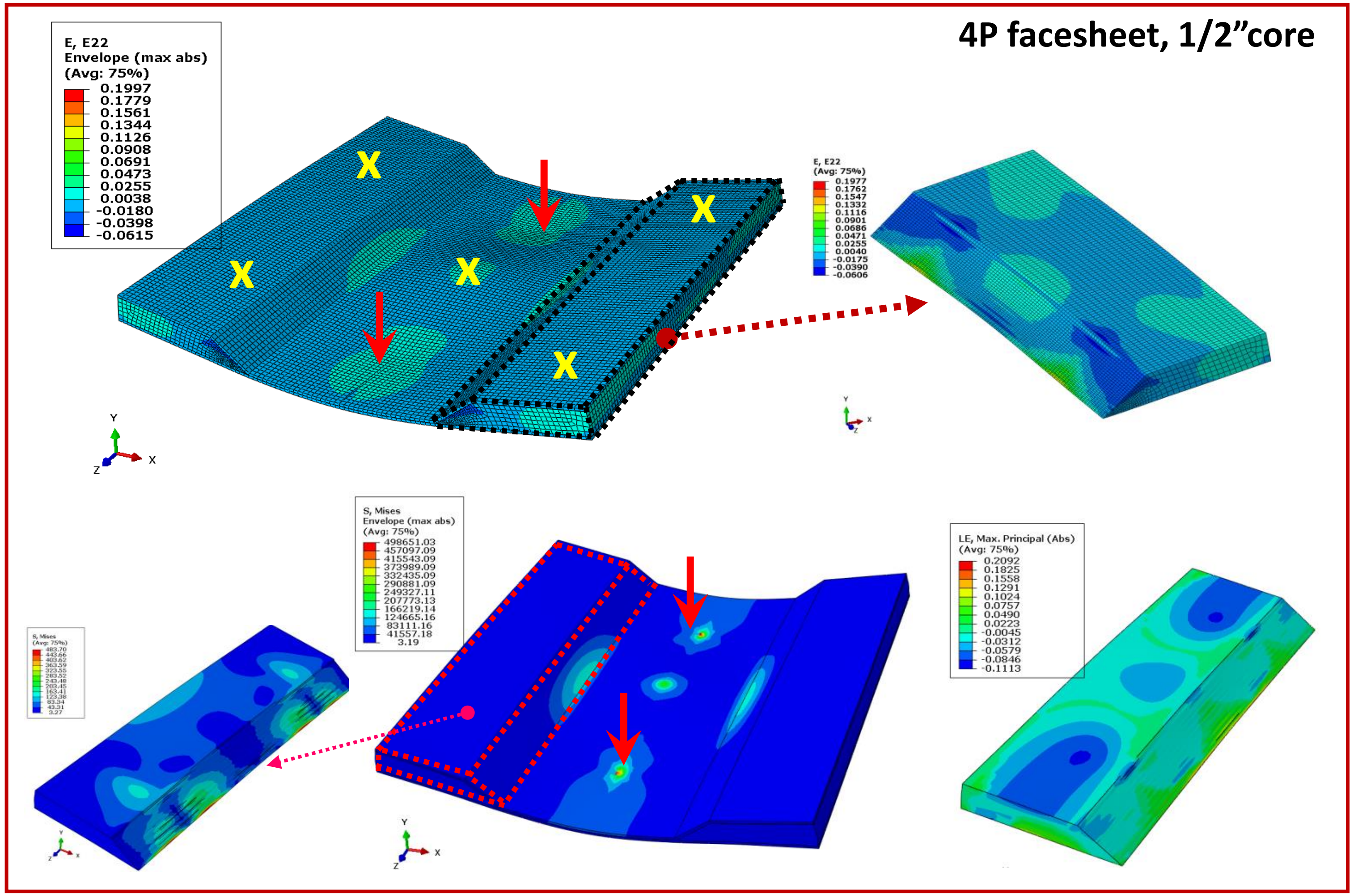


7PB & m-7PB Discussion

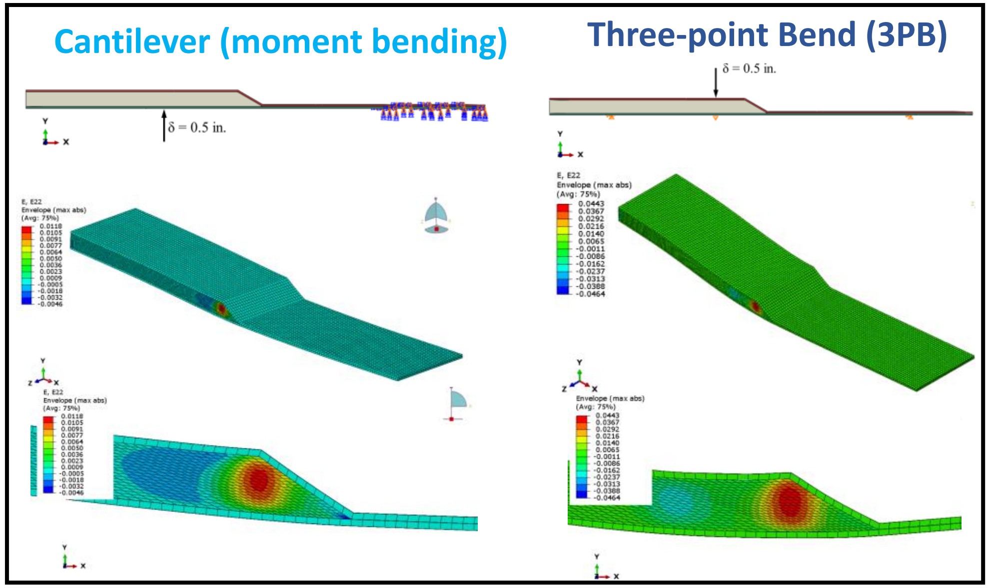
- Peak stresses at mid-span on top facesheet
  - Wrinkling observed on core
- Challenge to initiate disbond along ramp root before core crush
  - Potting at bottom load pin location to prevent core crushing
- Employability of 7PB-based test method to evaluate effects of defects



Test Method	N = 0 (Baseline) Pristine	N = 0 (Baseline) Microporosity	No. of Coupons
FWT			3 + 3
SCB			3 + 3
7PB			3 + 3
m-7PB			3 + 3
		Total No. Coupons	24



- Both 7PB & Cantilever configurations impose stress peaks at ramp
- 7PB is a case of moment bending in two axes
- Induced strain is higher compared to both Cantilever & 3PB



Summary

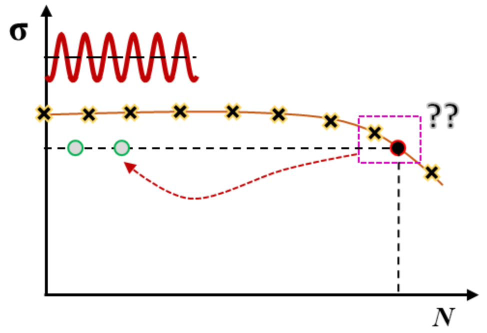
- Sandwich ramp failure assessed for Torsional and Torsion + Fixed-Loading conditions
  - Initial disbond always occurred at the root of taper followed by delamination in out-of-plane
  - Disbond Propagation dependent on mid-ramp distance for Combined Torsion + Fixed Loading
  - Torsional loading based tests demonstrated complex (asymmetrical) stress state as well as disbond growth
- Sandwich mid-ramp test article sized for a 7PB based test
  - A m-7PB test induce Torsion based test
  - 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)
- Test Matrix for evaluation of Effects of Defects established

Outlook & Future Work

- Benefit to Aviation:
  - Establish best practice to capture fabrication defects in the design phase
  - Quantitative knowledge on knock-down (relative damage growth) based on selected test methodology

Trial Test Matrix to introduce Microporsity				
Core Pre-Fab Condition	Co-Cured (CC)	Co-Bonded (CB)	Secondary-Bonded (SB)	Panel Size
Pristine				12 x 5 in
Untreated				
Proces/Treatment				

- Next Steps:
  - Complete Side Study to establish conditions to simulate microporosity at face/core interface
    - Document microporosity at interface for CB, CC & SB configurations
  - Evaluate 7PB & m-7PB Disbond Initiation scenarios (Trial Study)
  - Documentation in FAA Technical Report



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Facts and opinions are solely the personal statements of the authors and do not necessarily represent the views of the sponsoring agency.

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