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Development of Higher-Level Building Block Testing Standards

Standardizing Element-Level Testing Preliminary Design

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Wichita State University

ATLAS Advanced Technologies Lab for Aerospace Systems

Development of Higher-Level Building Block Testing Standards

Research Team

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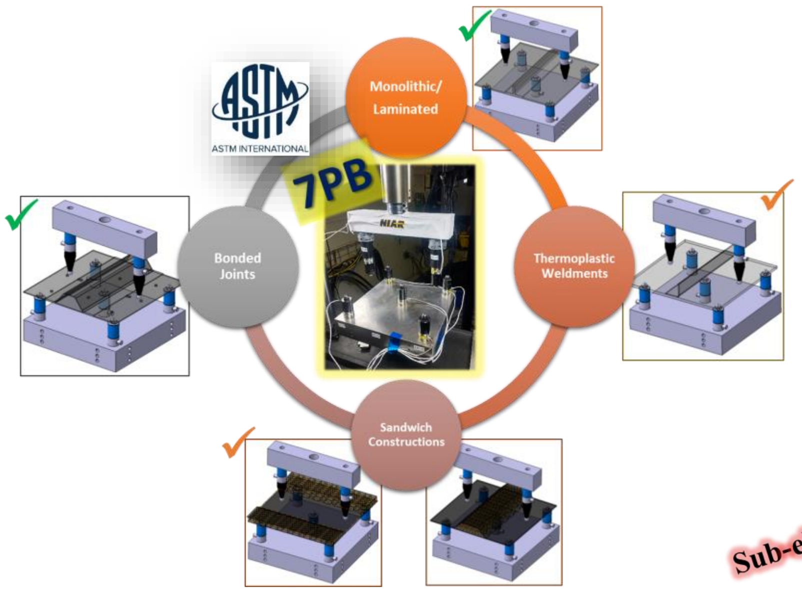
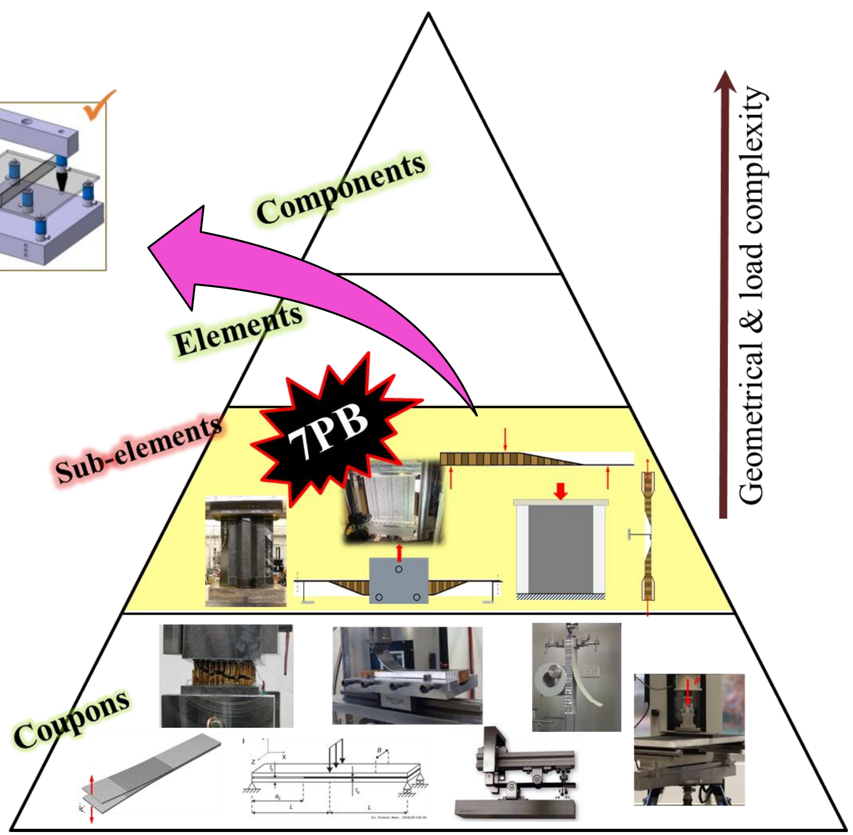
A Higher-Level Building Block Test Standard for Sub-Element level Features



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.

Project Goals

✓ **Design & Development of sub-element based test methodology for *Monolithic Structures***

✓ **Design & Development of sub-element based test methodology for *Bonded Structures***

Key Observations & Test Findings

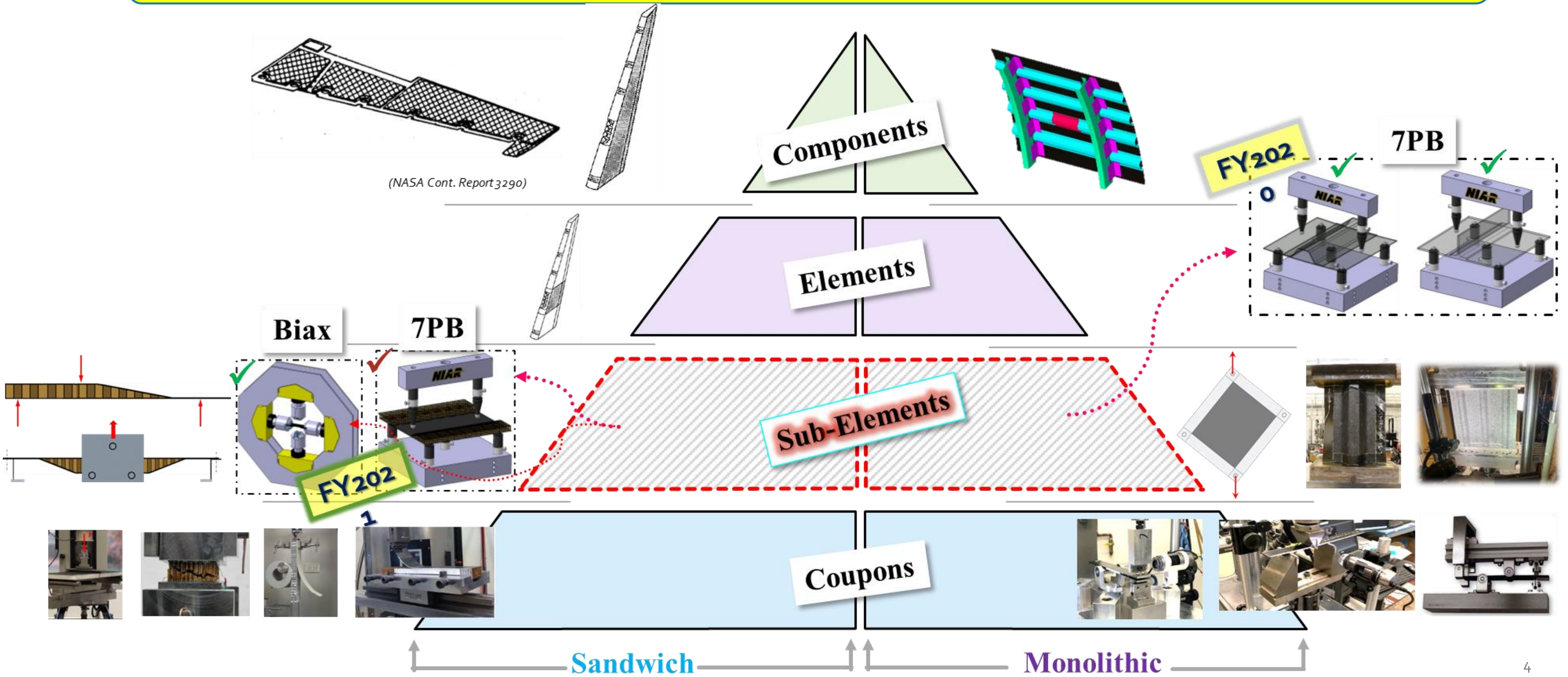
- **Seven Point Bend (7PB) is clearly a mixed-mode test**
- ***Sub-element-level* test methodology suited for Laminated, Monolithic, Bonded, Sandwich & Thermoplastic Weldments**
- **Demonstrated to perform Skin-stringer Interface Characterization across co-bonded (CB) & secondary-bonded (SB) coupons (Hat- & T-stiffened)**
  - **Pristine, Pre-cracked and Impacted coupons considered.**
- **Easy to install & operate; yet robust enough to introduce complex loading *(long. & transv. bending components)***
- **Presence of inherent flaw governs the damage migration load-level into first-ply & beyond.**
  - **A flaw such as an insert/impact damage causes the crack to lie in skin-stringer interface before kinking away and into skin/stiffener plies.**
- **Damage always initiates at the center of coupon; peak strain in the specimen mid-span.**

Analysis Takeaways

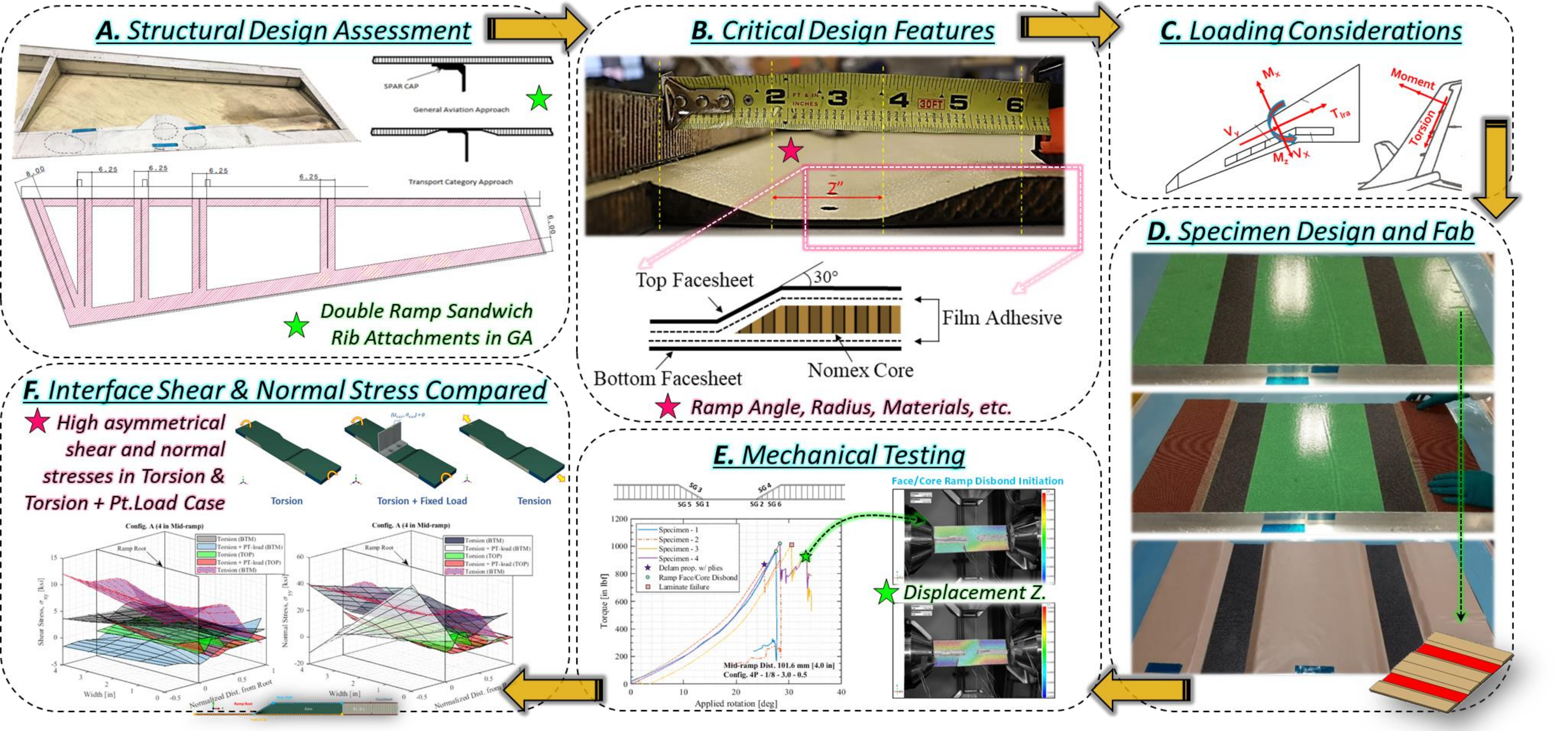
- **Developed *Cohesive Zone* based model is able to capture general specimen kinematics & damage growth.**
- **Self-similar crack progression at skin-stringer interface w/ Zero thickness cohesive layer is *robust*.**
- **Damage progression away from interface not captured & peak load; however, *Damage initiation is predicted.***
- **Failure load dependent on input cohesive properties *(Gc, τ)***

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

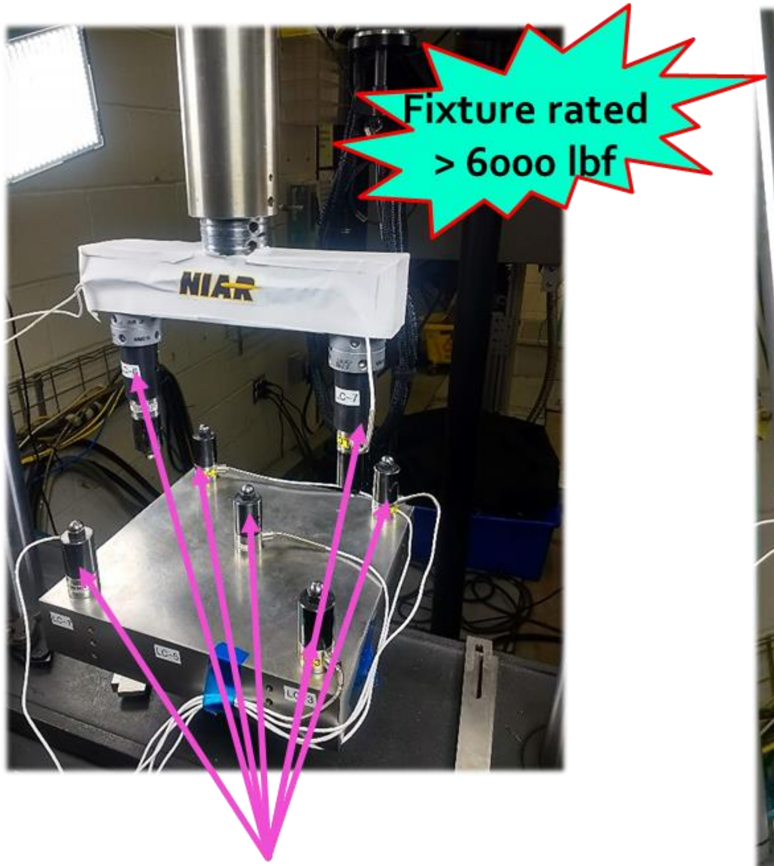
GOAL: *Identify **Weak Design** w/t Aid of selected Test Methodology which introduces **Complex Loading** Scenario (representative of an actual control surface).*

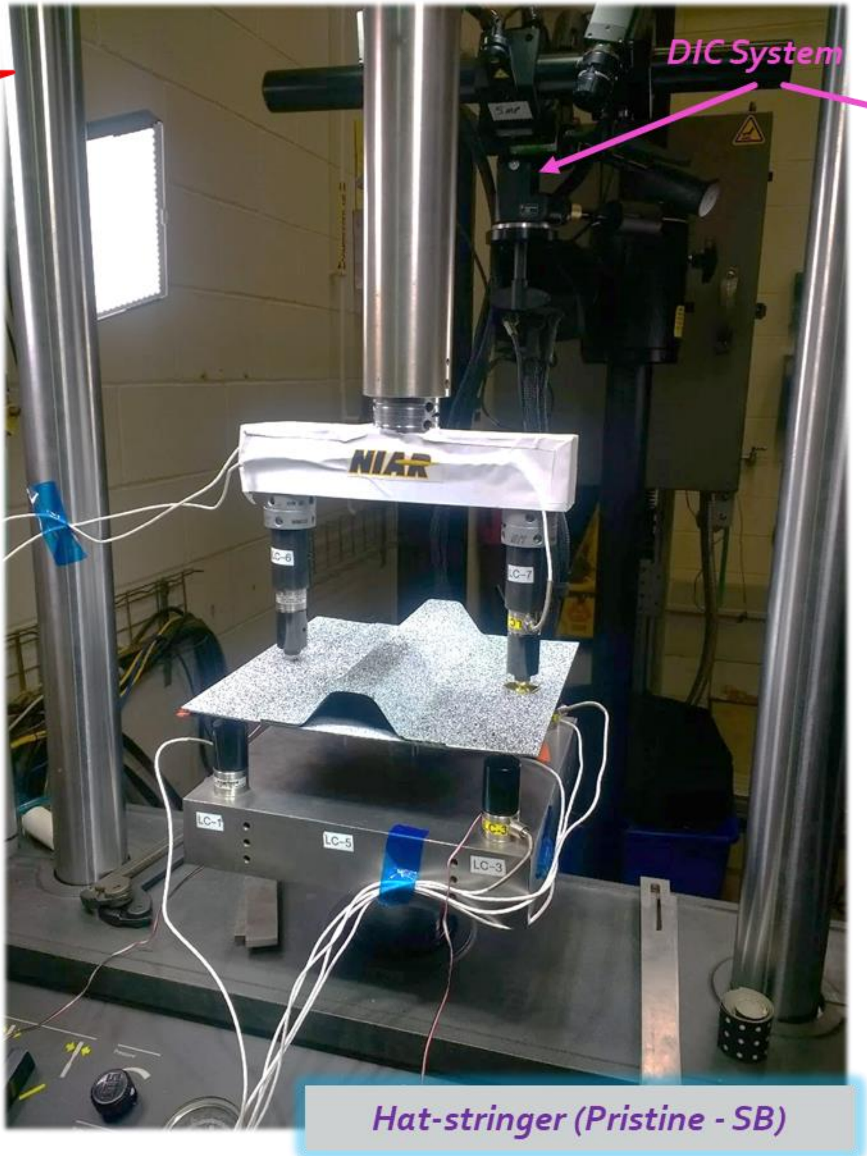


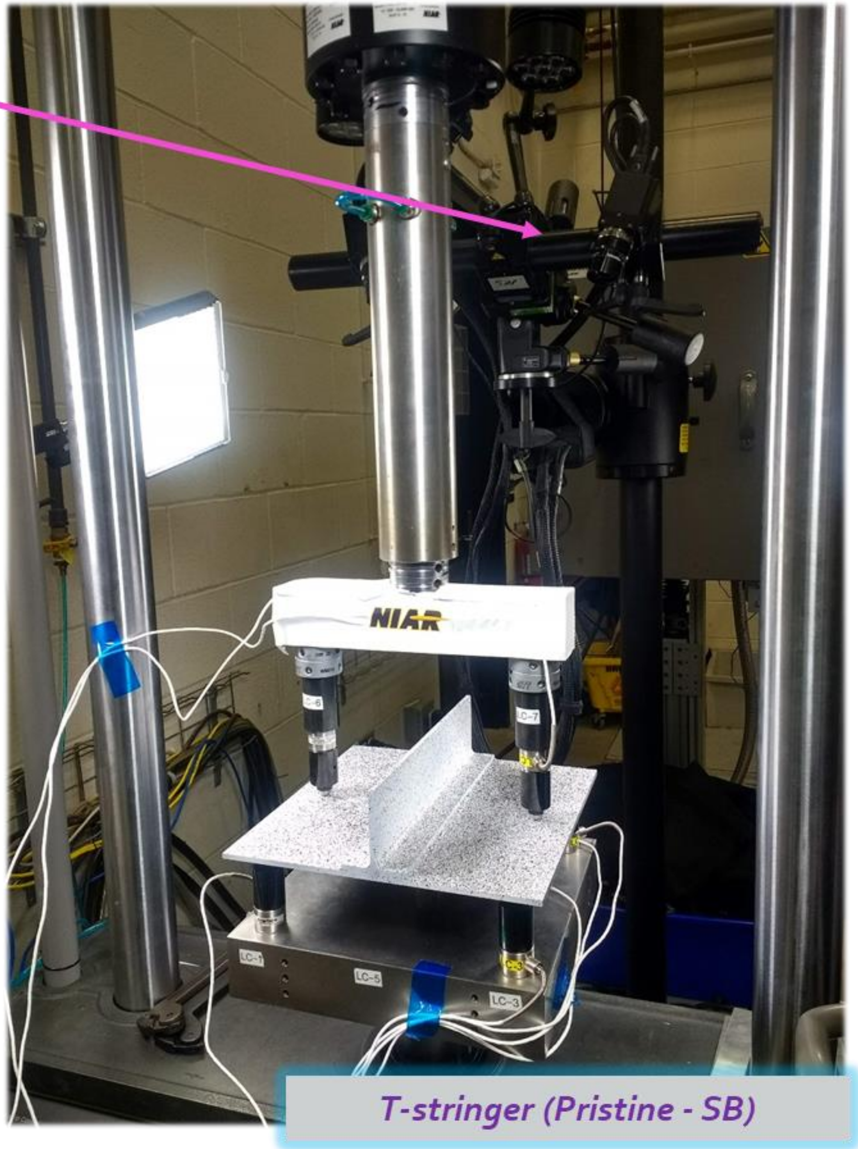
Analysis for Design Considerations in Sandwich Constructions



NIAR 7PB Test Setup: T & Hat – Stringers



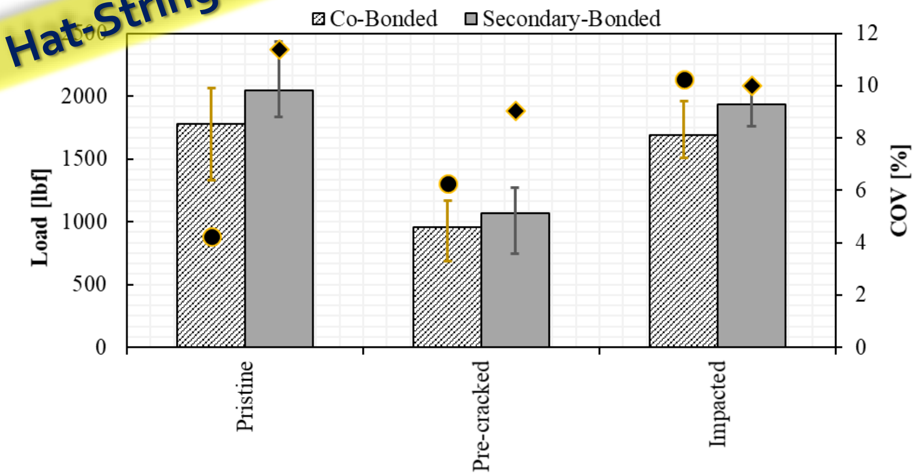




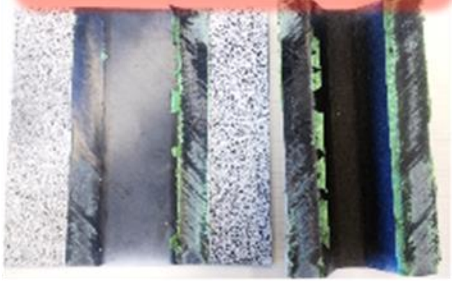
- **DIC Systems –** 2 employed (front & back)
- **Images** are stitched post-test
- **Each** load cell capacity **2050 lbf**
- **Test frame** rating **11 kip**

7PB Quasi-Static Tests: Brief Summary

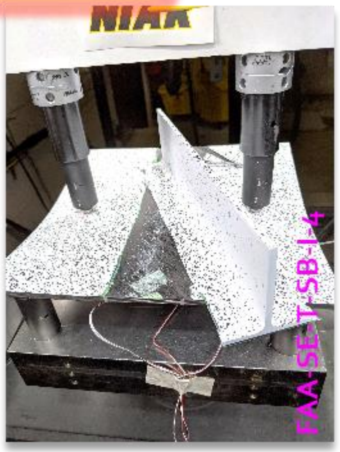
Hat-Stringer



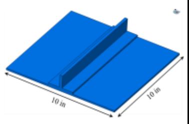
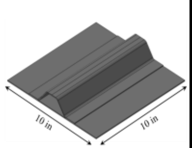
Skin/flange separation (cohesive failure w/ damage progression into first ply)

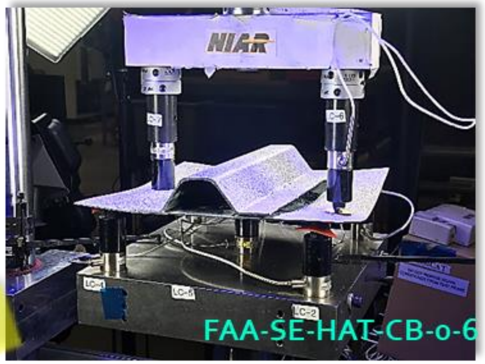


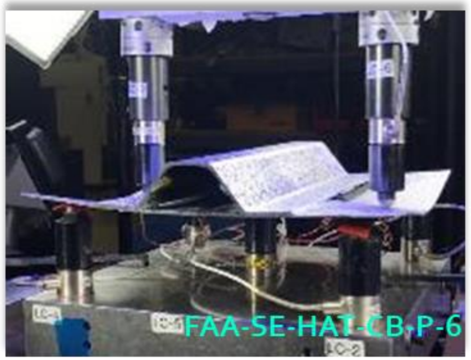
Cohesive failure w/ damage progression into first ply

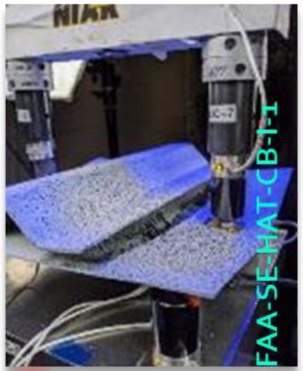


- Fairly Low COV: Highest 11% & lowest of 4%
- Predominantly Cohesive failure observed
- Inter-ply failure by crack migration into fist ply and beyond

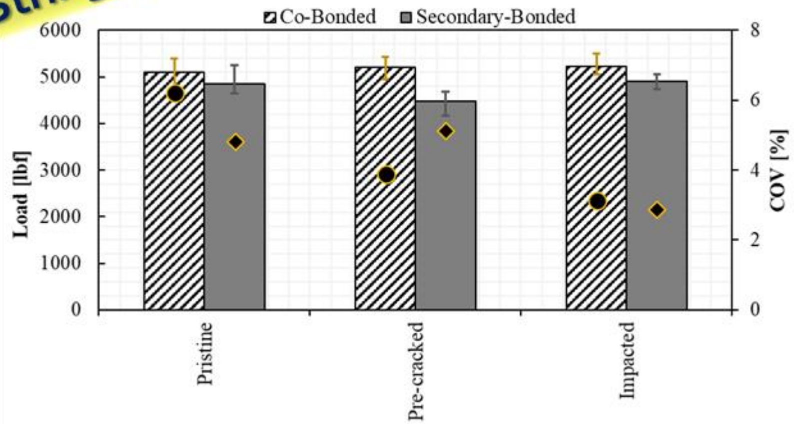
Specimen Type	Fab. Process	Specimen Config.	Avg. Failure Load [lbf]	COV [%]
T-Stringer 	Co-bonded	Pristine (Baseline)	5096.4	6.2
		Pre-cracked	5211.1	3.9
		Impacted	5231.2	3.1
	Secondary bonded	Pristine (Baseline)	4856.2	4.8
		Pre-cracked	4478.7	5.1
		Impacted	4910.1	2.9
Hat-Stringer 	Co-bonded	Pristine (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



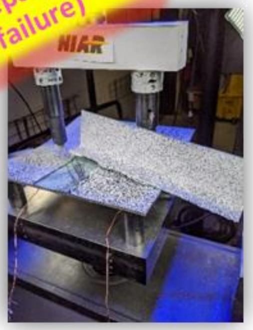




T-Stringer

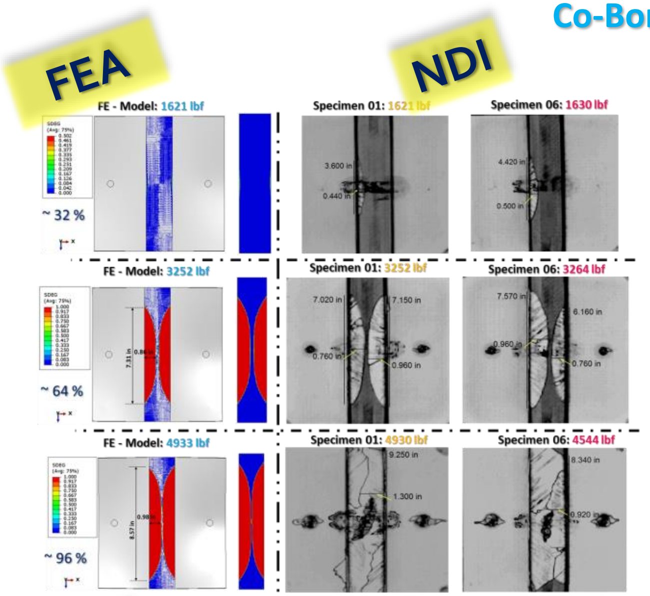


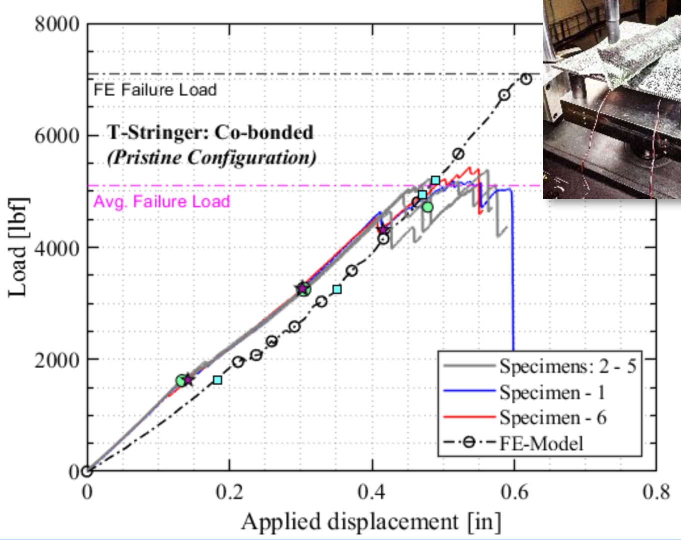
Skin/flange separation (cohesive failure)

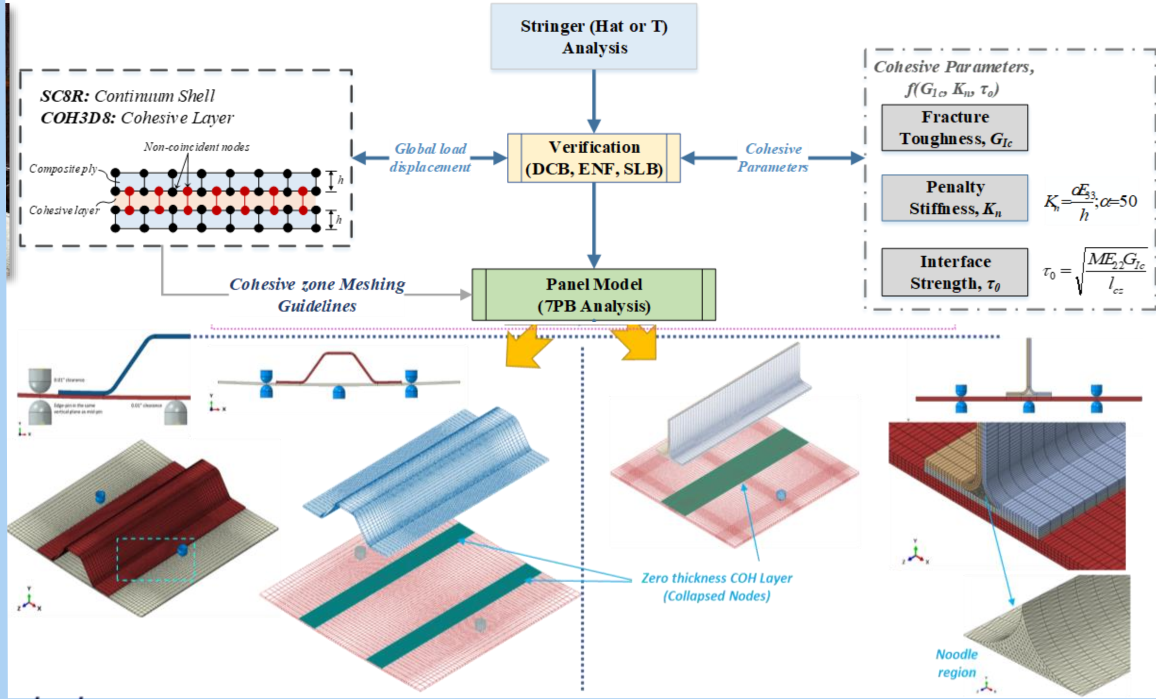


Prediction of Damage Initiation & Evolution in Co-bonded T & Hat-Stringers

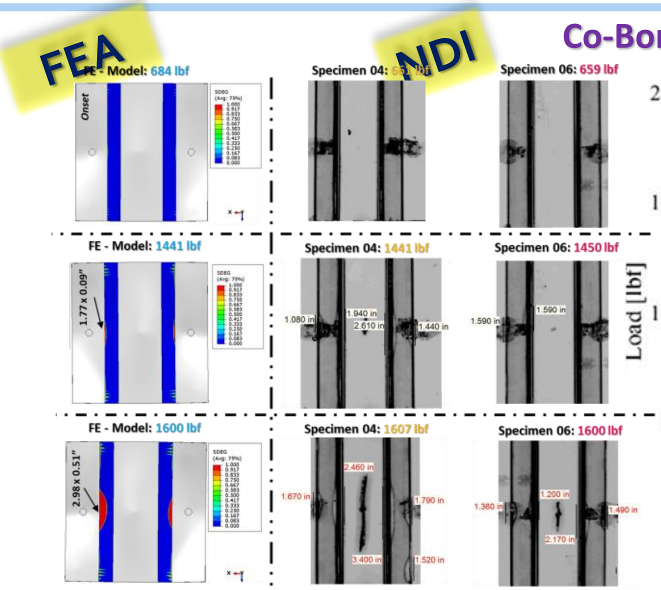
Co-Bonded T-Stringer (Pristine)

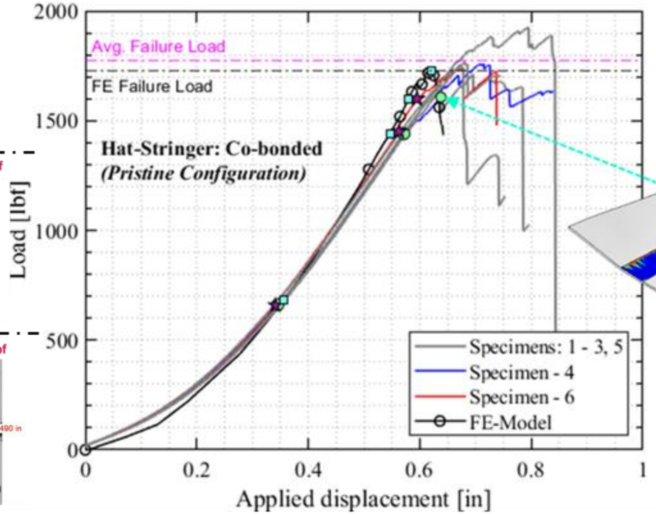




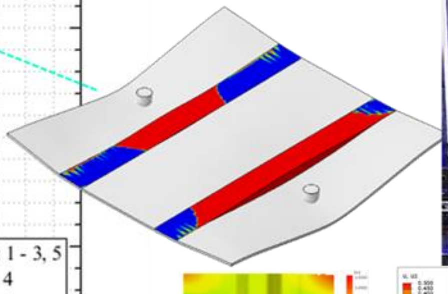


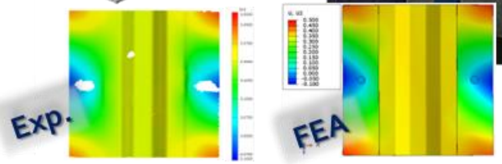
Co-Bonded HAT-Stringer (Pristine)

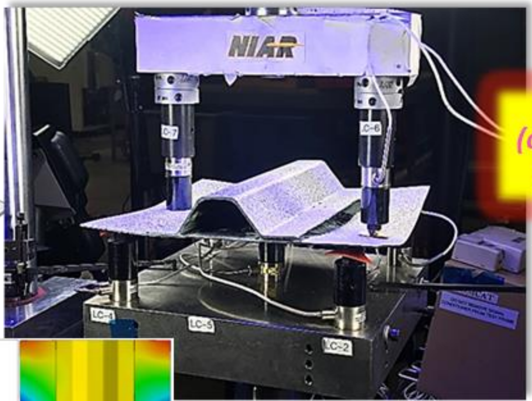


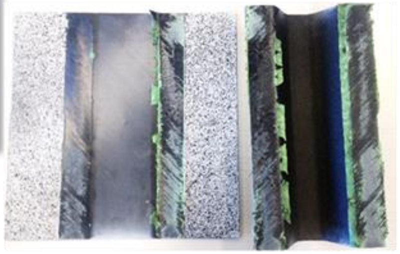


- *Failure load predicted within 3%*

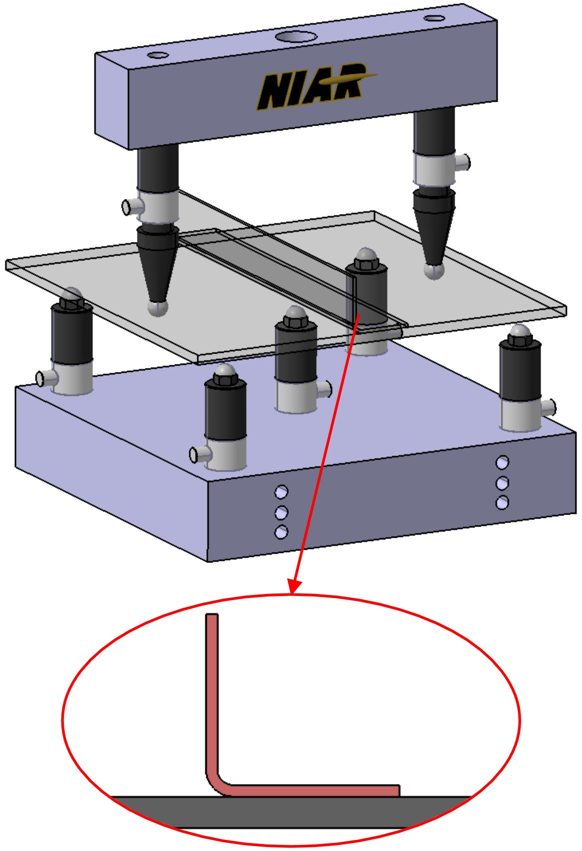




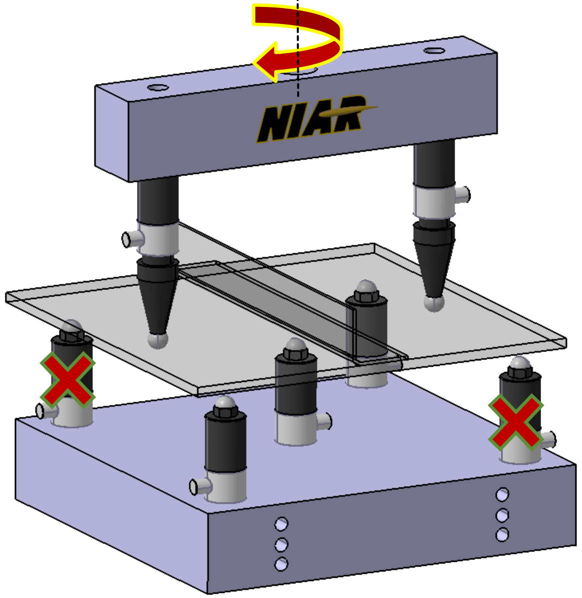


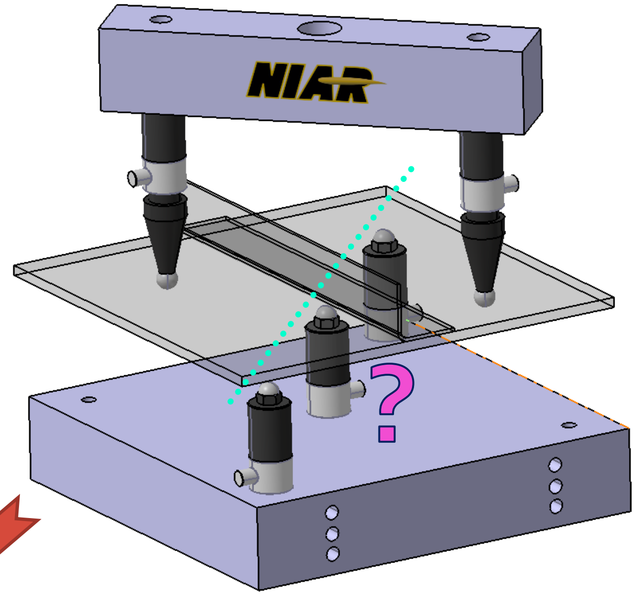


7PB Test Methodology extended to ECT

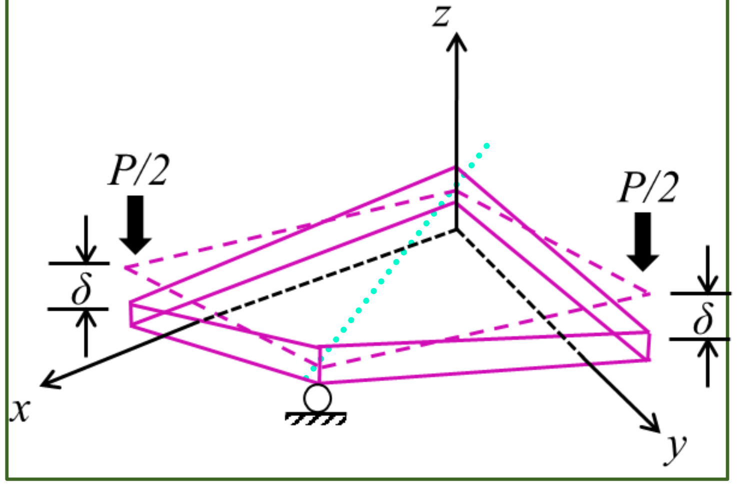


Remove two End supports & Twist the load-arm



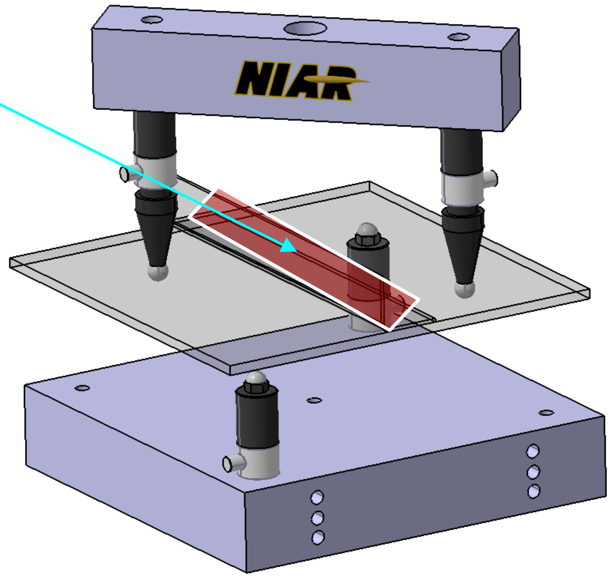


*Akin to a **Plate Twist** scenario*



TP Weldment Qualification

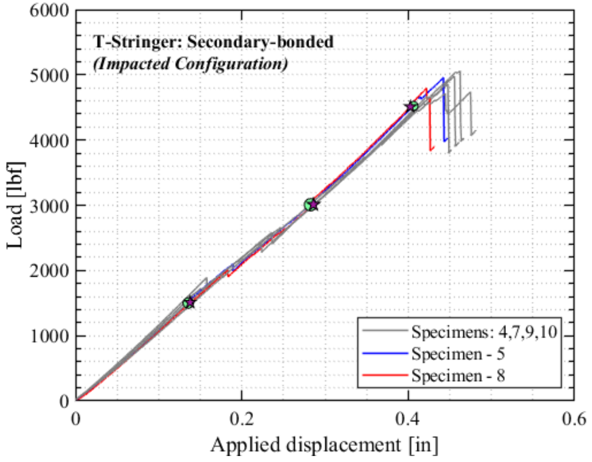
Twisting induced skin/stringer delamination



- ***ECT** can be **easily** implemented in the existing **7PB*** rig
- Akin to a *CLPT - plate twisting problem* or *ASTM D3044* standard

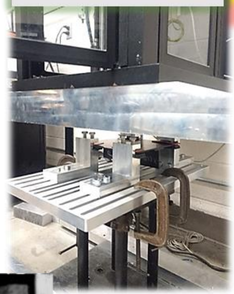
Impact Study w/ 7PB:

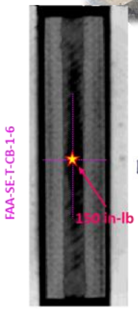
Secondary-Bonded T-Stringer (Impacted)

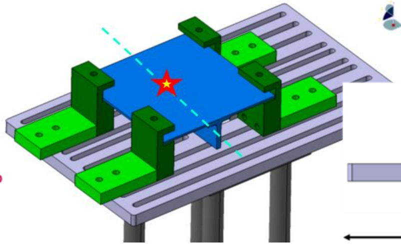


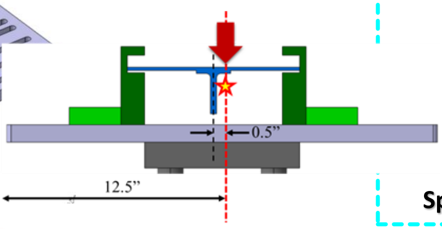
Avg. failure load = 4910.1 lbf

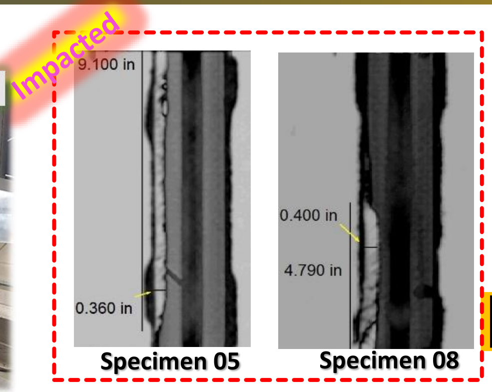
FAA-SE-7PB-T-SB-1-2

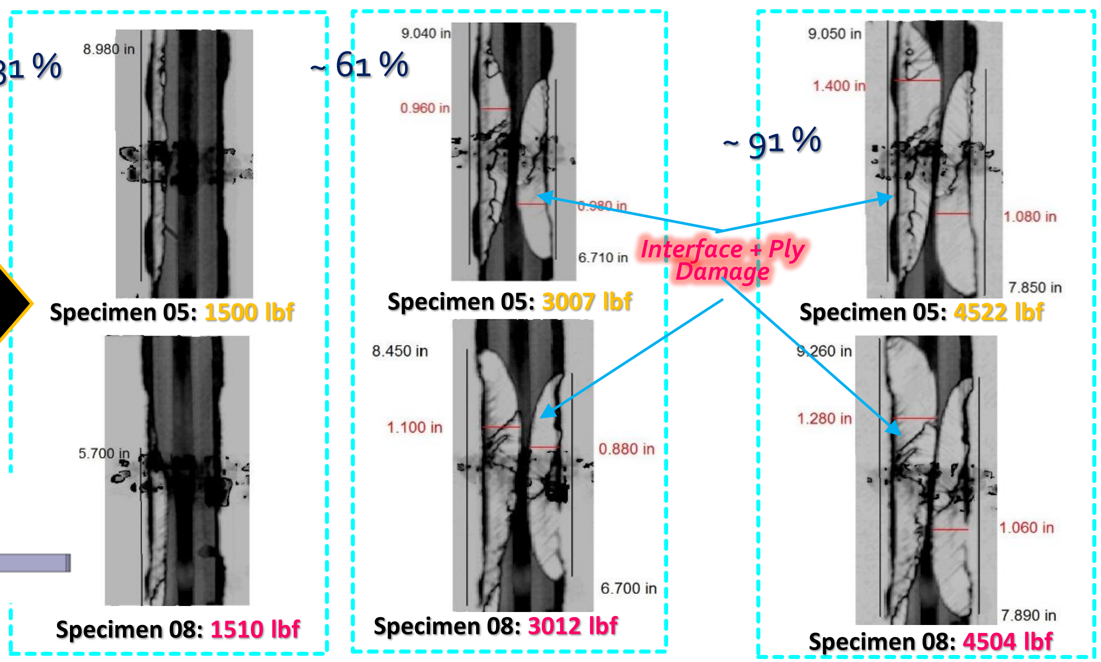




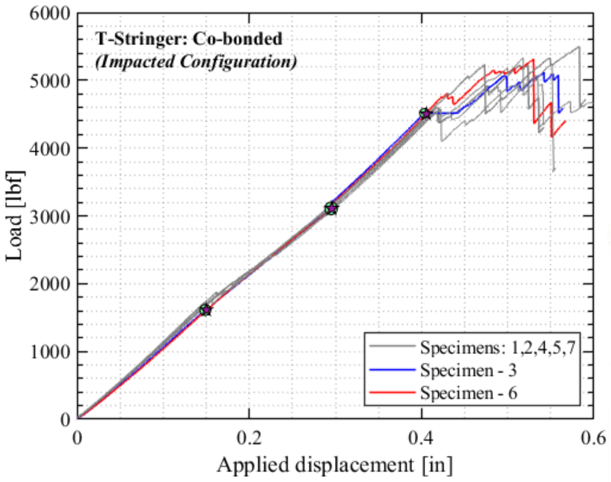




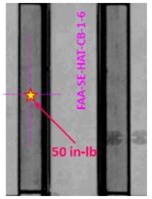


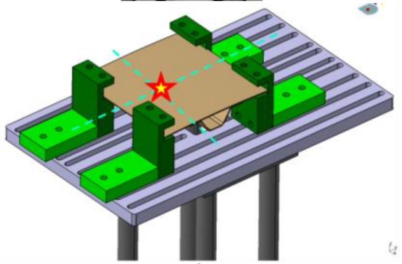


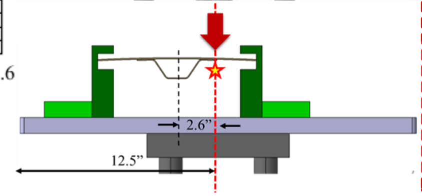
Co-Bonded HAT-Stringer (Impacted)

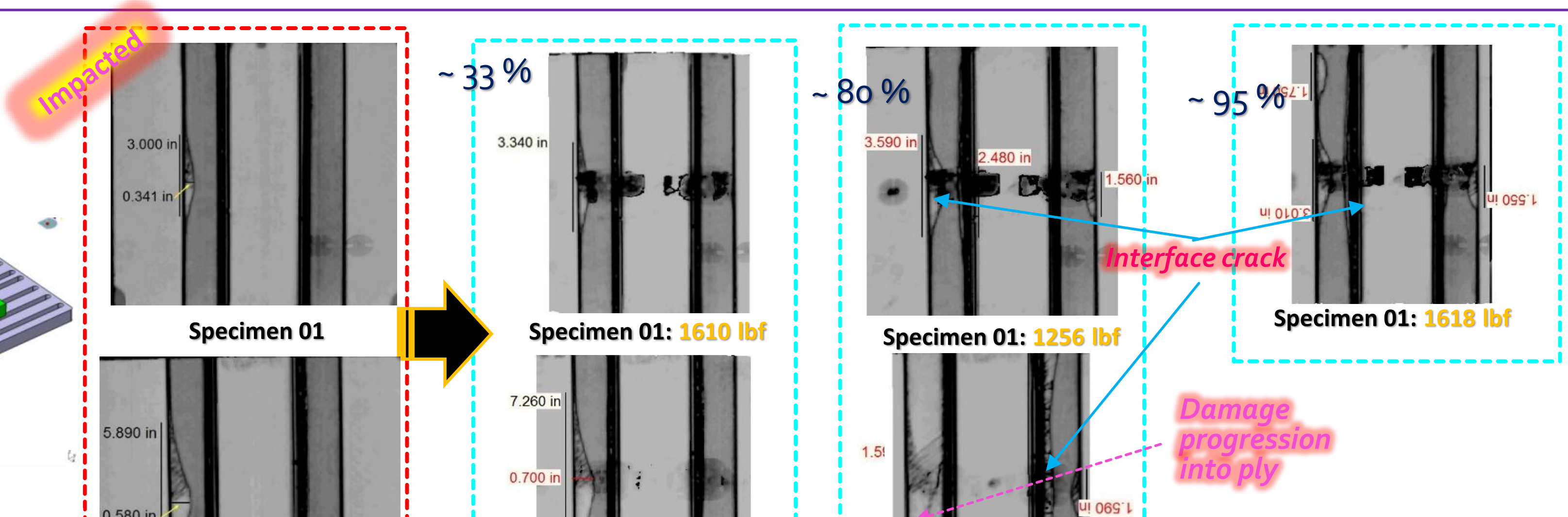


Avg. failure load = 1691.2 lbf





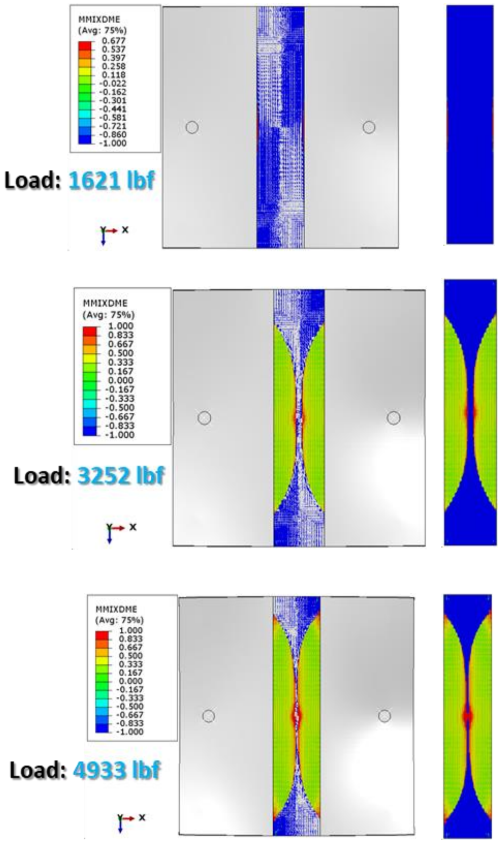


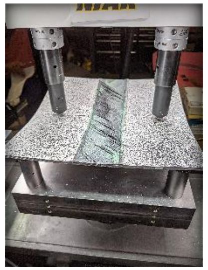


Study conducted on both ***Secondary-bonded (SB) & Co-bonded (CB)*** *configurations*

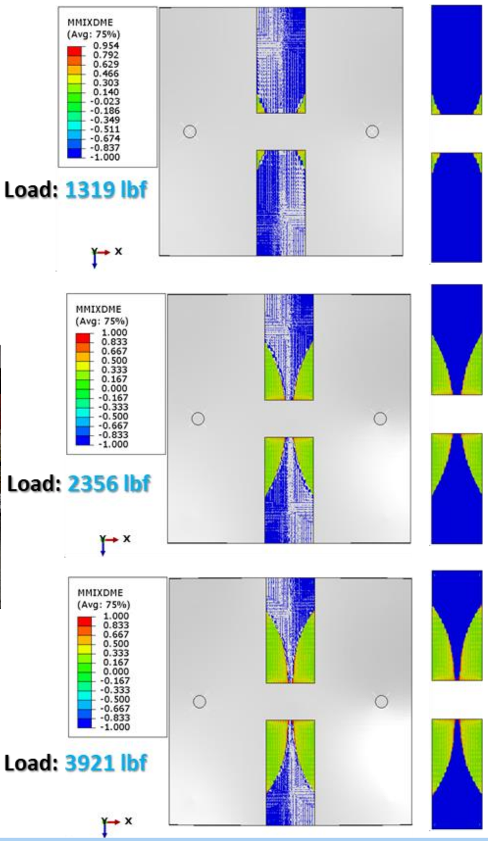
Mode-Mixity Evolution in Co-bonded T- & Hat-Stringers: 7PB Quasi-Static Tests

Co-Bonded T-Stringer (Pristine)

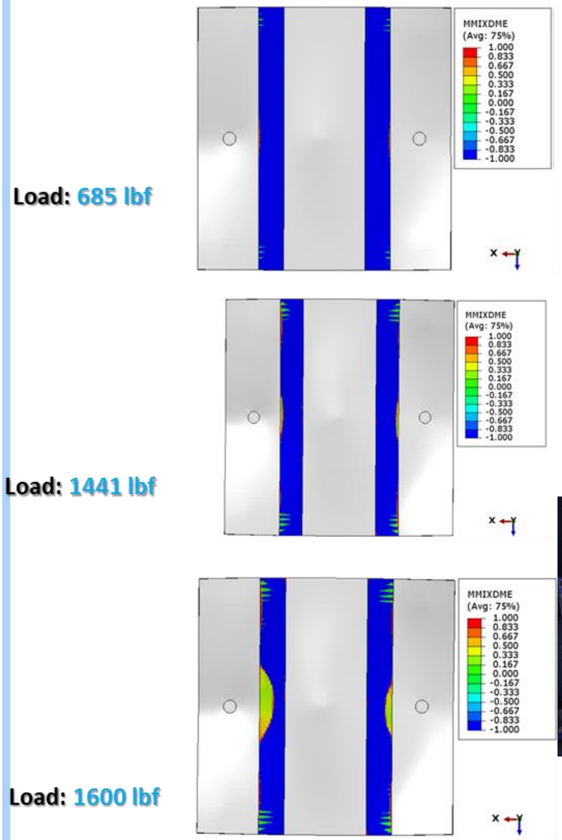


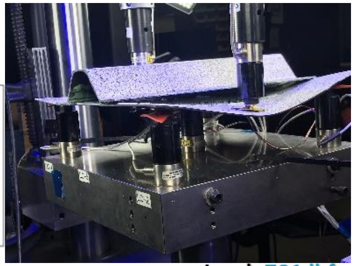


Co-Bonded T-Stringer (Pre-Cracked)

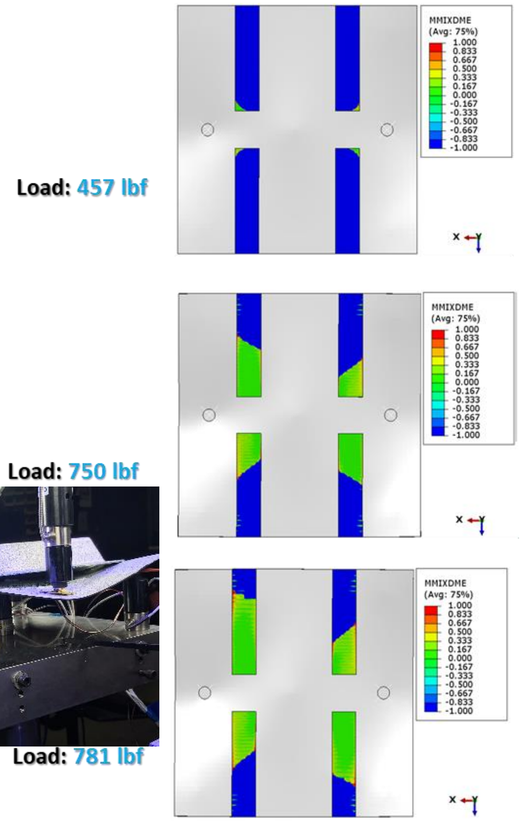


Co-Bonded HAT-Stringer (Pristine)





Co-Bonded HAT-Stringer (Pre-Cracked)



Key Analysis Findings

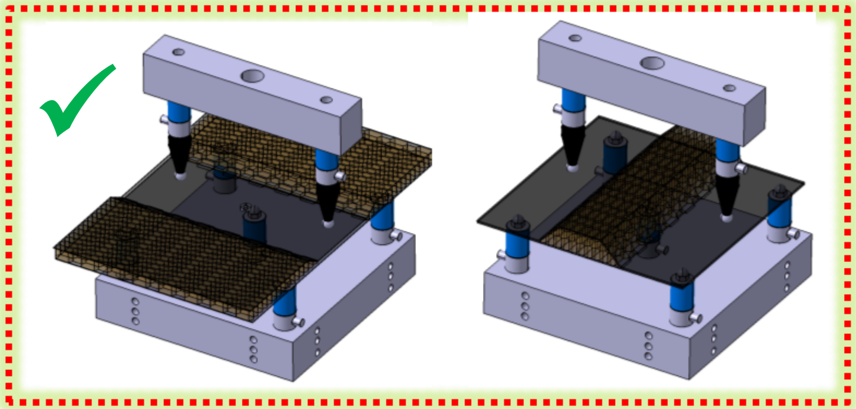
- ✓ Cohesive zone model employed to capture mode-mixity
- ✓ Boundary conditions influence mode-mixity
- ✓ Predominant Mode-I condition observed at coupon mid-span with mixed-mode conditions at damage front.

Current Work

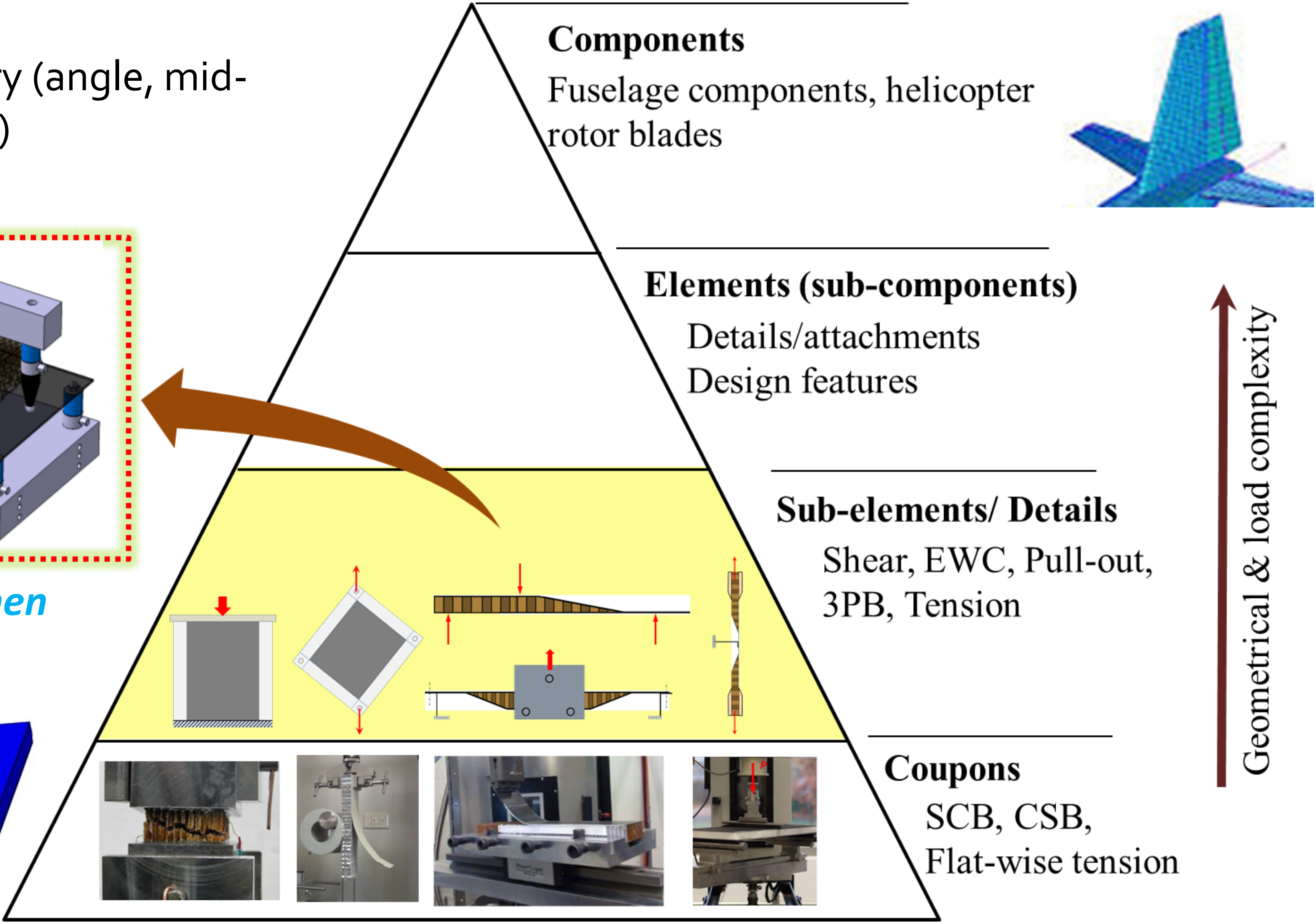
- Sizing study w.r.t damage metric (pre-crack/impact)
- Fracture qualification of co-bonded/secondary-bonded coupons
- Applying 7PB to other design feature e.g.: *thermoplastic weldments*

Seven-Point Bend (7PB) based Sandwich Ramped Coupon

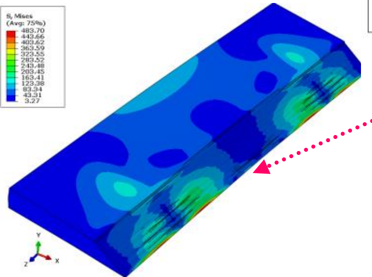
- **Critical area:** Ramp region
- **Design check:** material, ramp geometry (angle, mid-ramp distance, potty, noodle, adhesive)

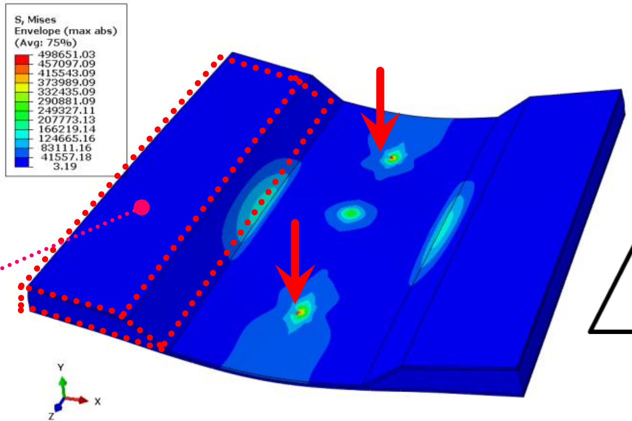


7-PB based Sandwich Ramp Specimen

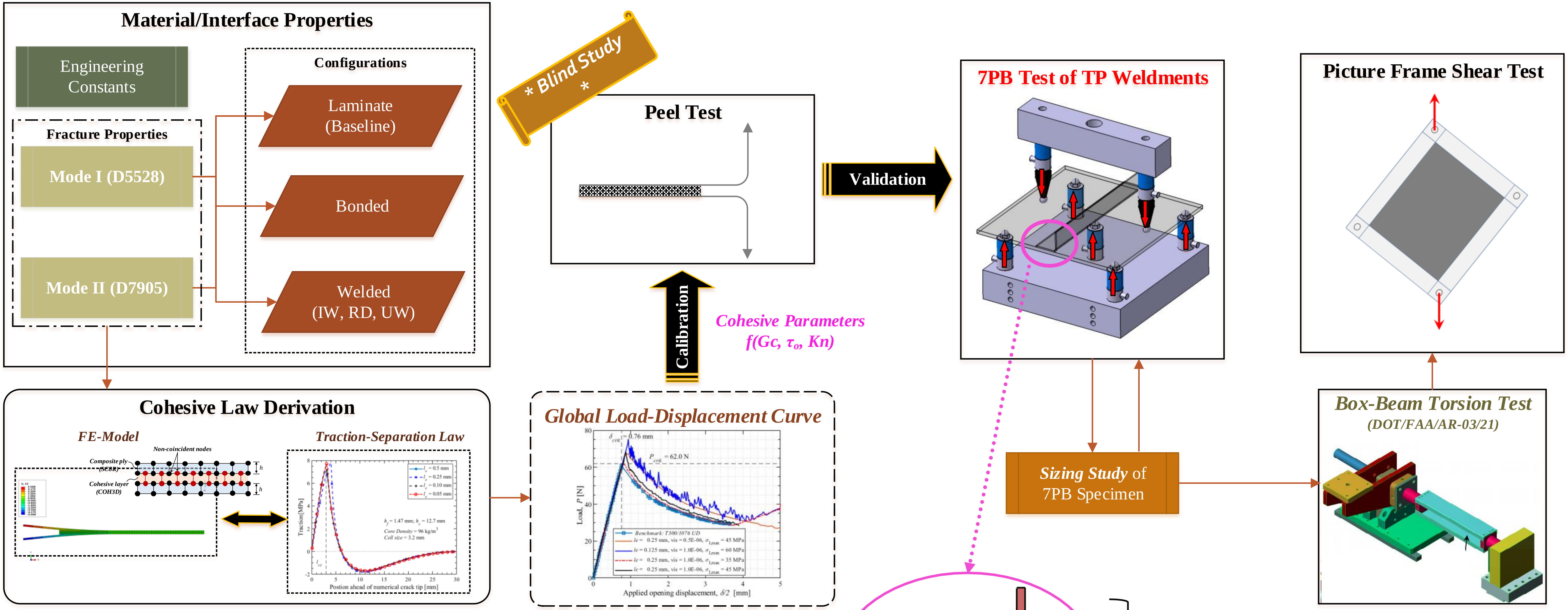


4P facesheet, 0.5"core

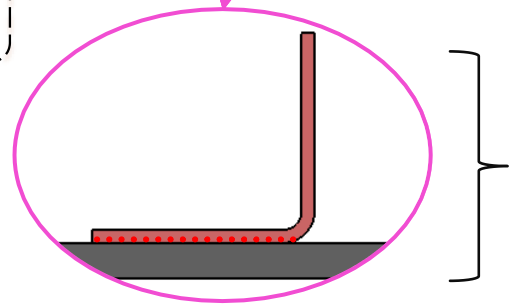




Qualification of Thermoplastic Weldments using 7PB Test Methodology

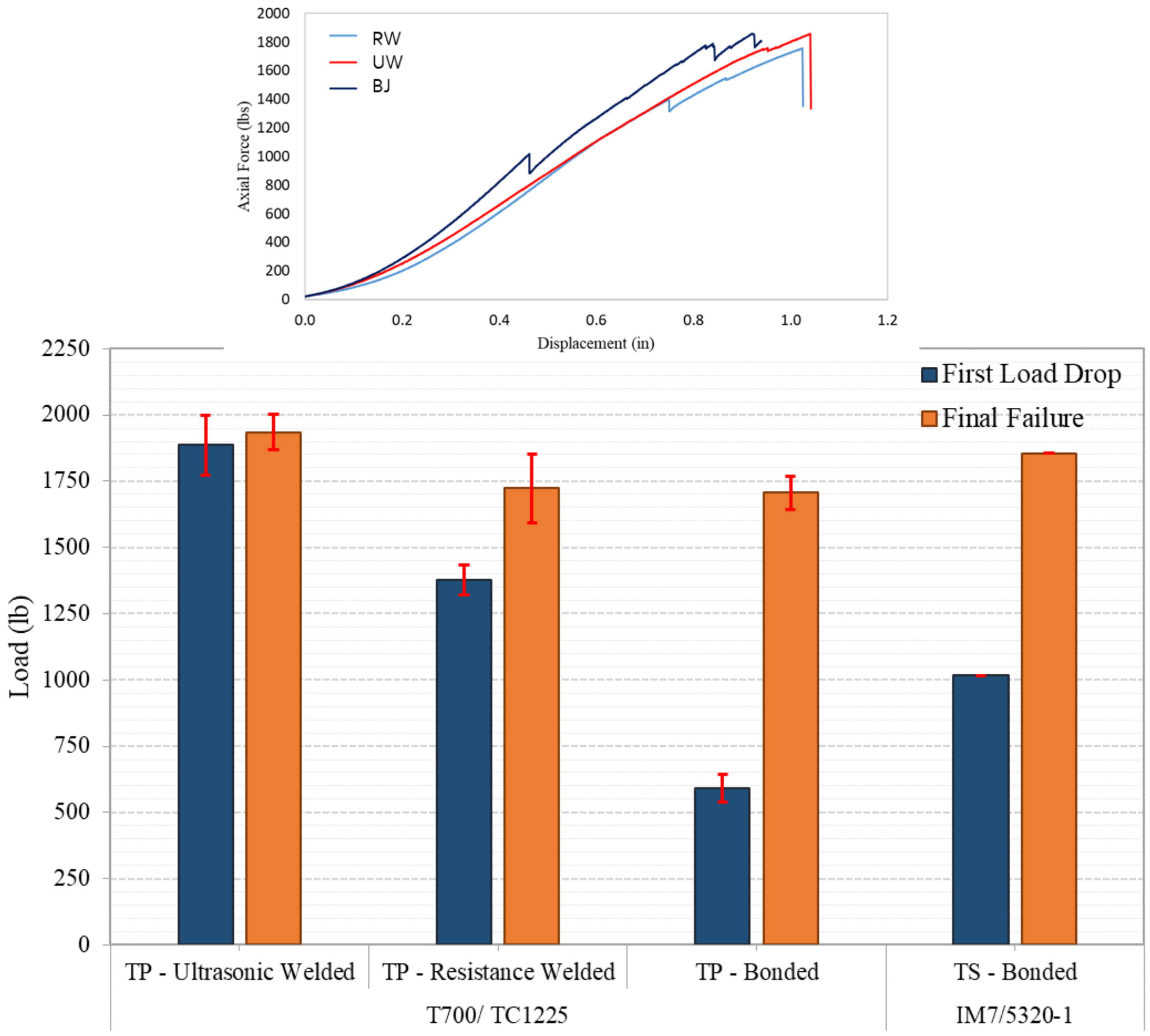


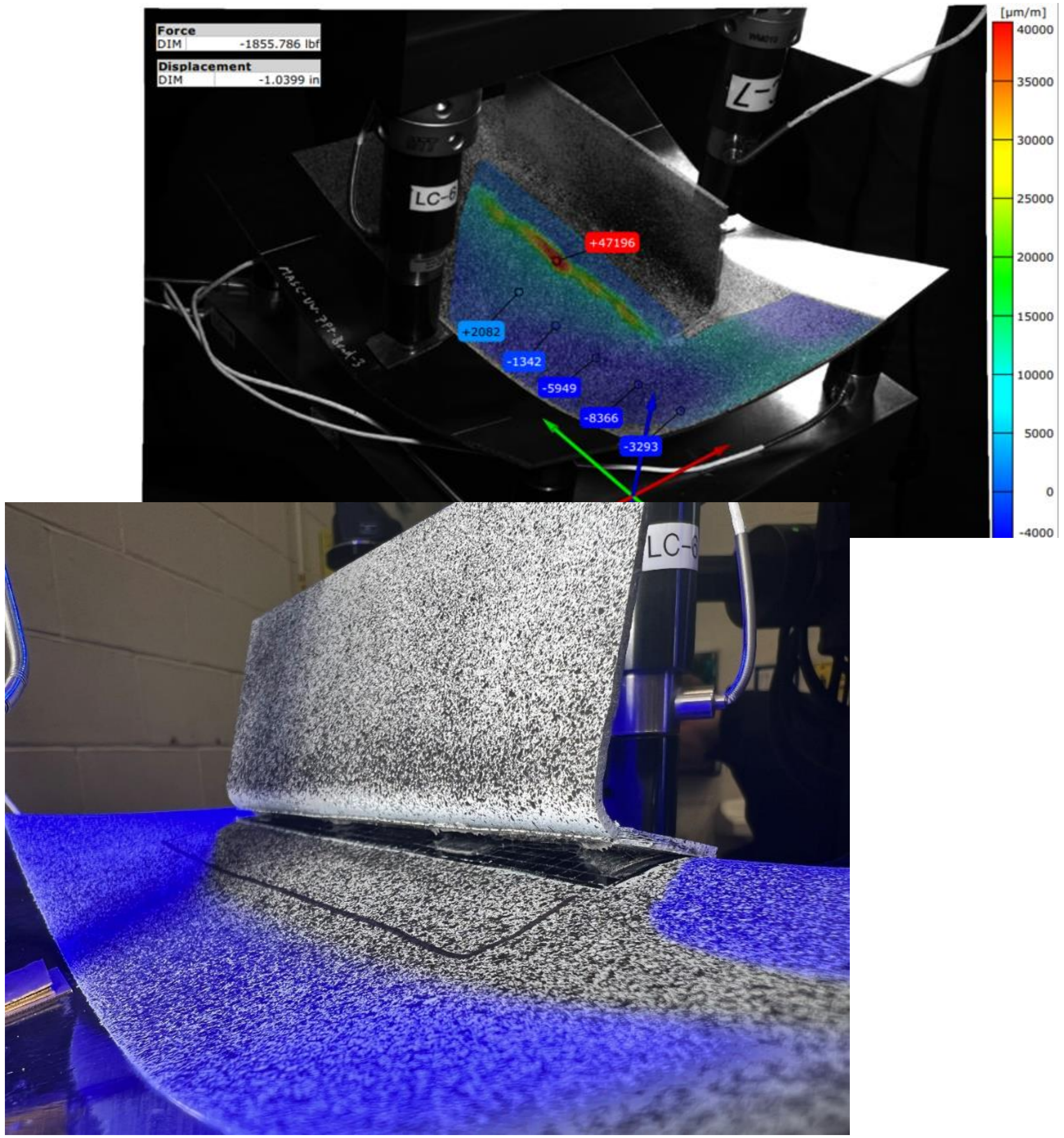
- ***TP Weldment qualification using 7PB*** test method
- Analytical benchmarking, calibration & validation exercises
- ***Sizing study*** *of 7PB test load application points & effect on* ***mode-mixity***



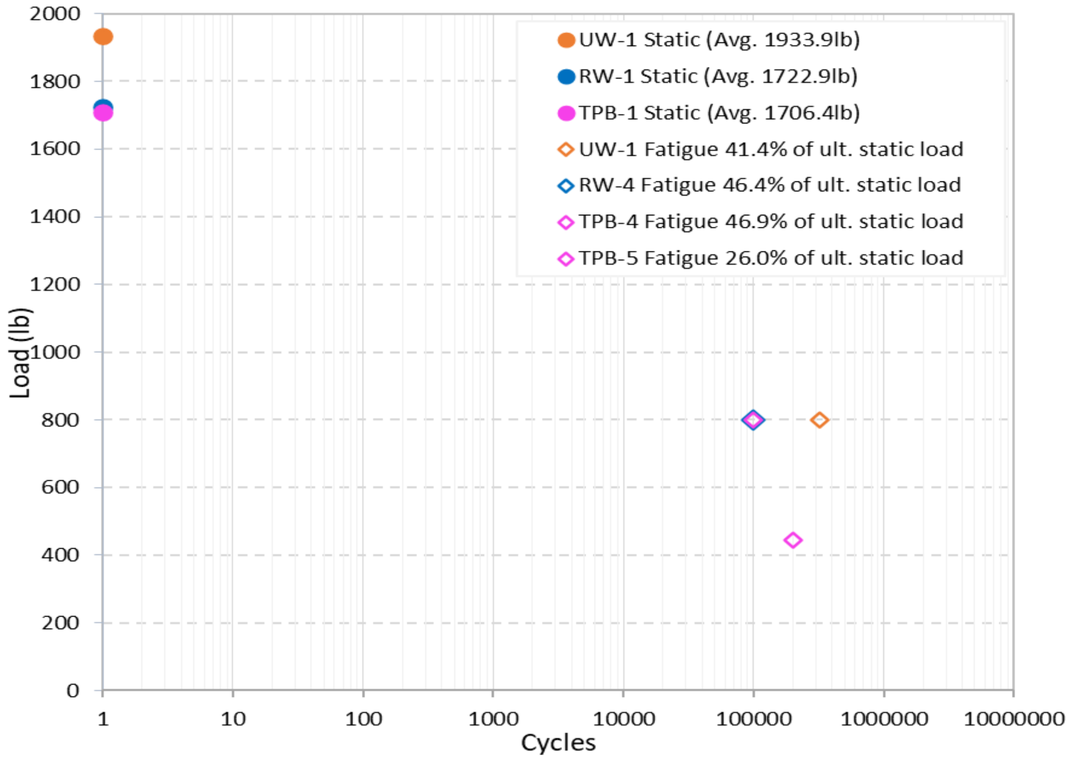
- *Induction Welding (**IW**)*
- *Resistance Welding (**RW**)*
- *Ultrasonic Welding (**UW**)*

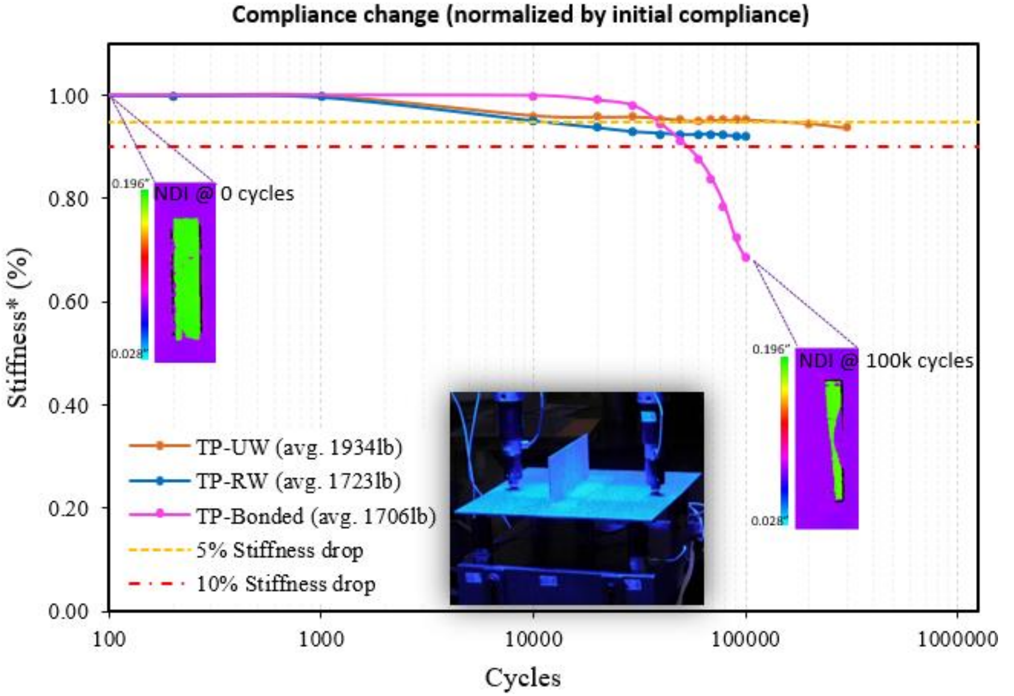
7-Point Bend Testing for Thermoplastic Joint Evaluation





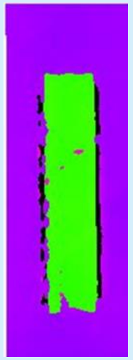
Thermoplastic Welded Element Level – 7pt Bend Test



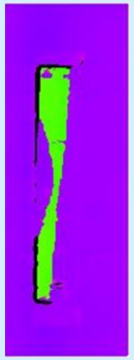


Progressive failure monitored during fatigue using video camera + intermittent NDI (UT-PE and XCT)

NDI pre- and post-fatigue on thermoplastic bonded specimen



Before fatigue
@ 0 cycles



After 100k cycles @ 444lb
fatigue max. load

After 100k cycles @ 800lb
fatigue max. load

A Review of Edge Crack Torsion Specimens

- **ECT** used for Mode III characterization in both *laminated & SW composites*.
- Originally proposed by *S. Tsai (1965)* to obtain orthogonal *engineering constants*
- Diagonal opposite support points; Easy to install on standard test machines
- *ECT can be achieved* using existing 7PB test rig

Old ECT Design

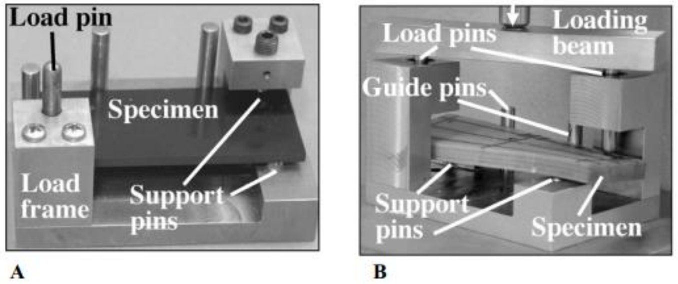
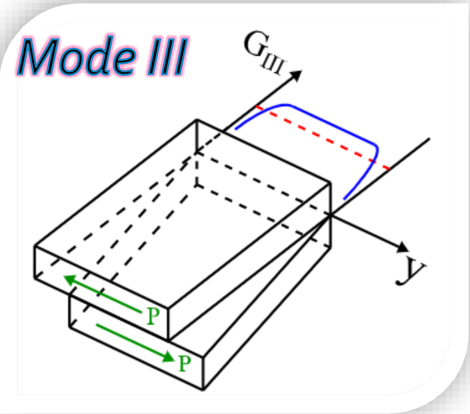


FIGURE 2. (a) Original ECT test fixture. (b) Current ECT test fixture (showing deformed specimen).

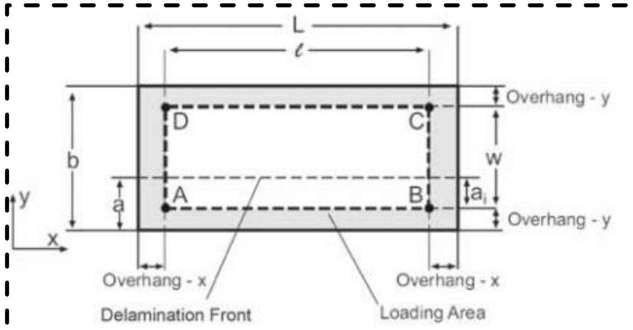
J. Ratcliffe (2004)

Out of plane shear component



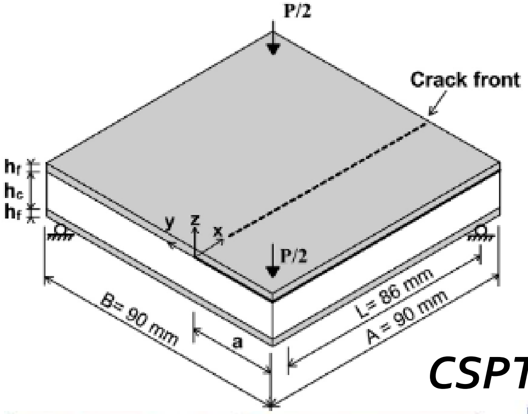
New ECT Designs

Laminate

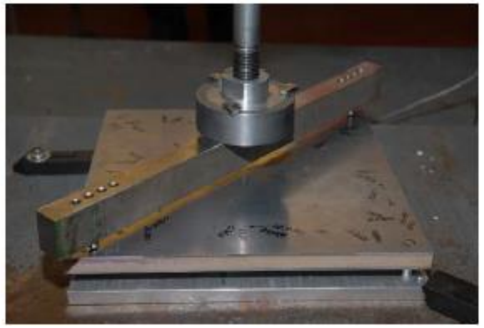


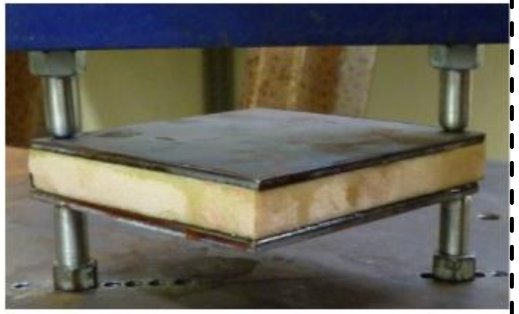
G. Browning et al. (2011)

Sandwich



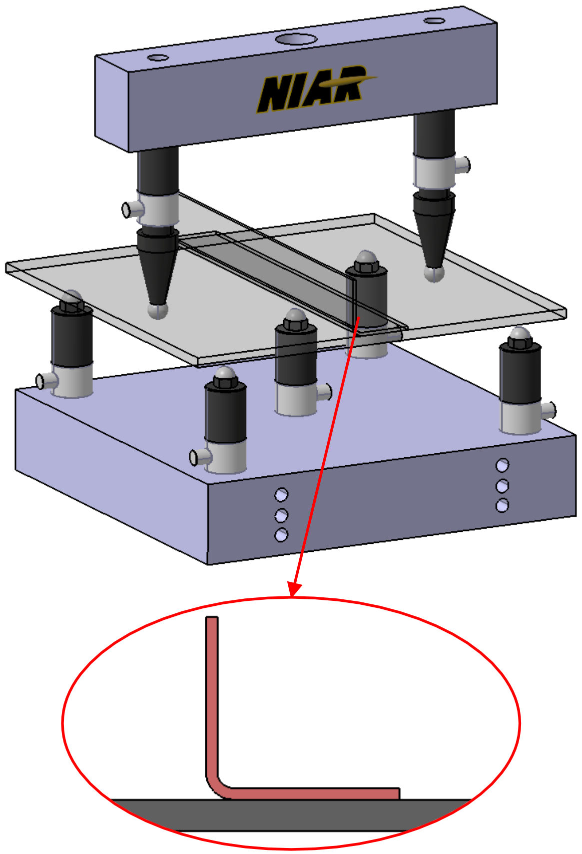
CSPT



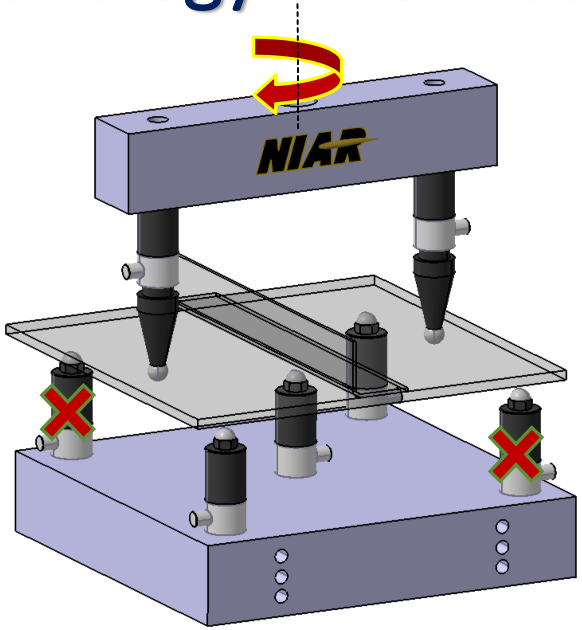


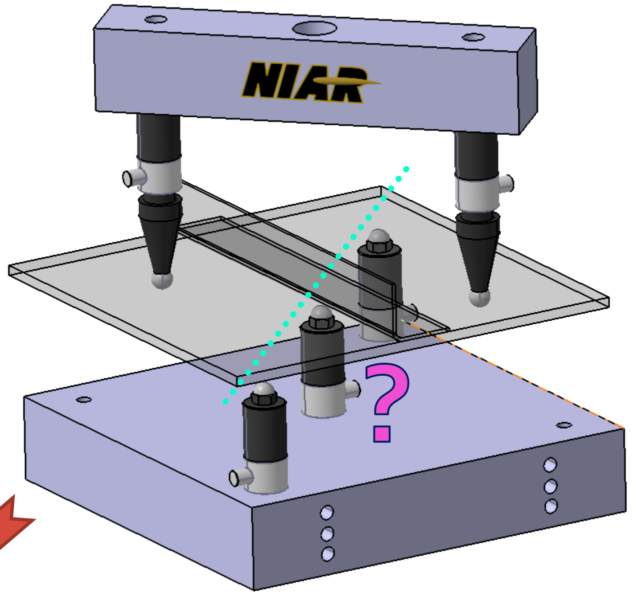
A. Hernández-Pérez et al. (2013)

7PB Test Methodology extended to ECT

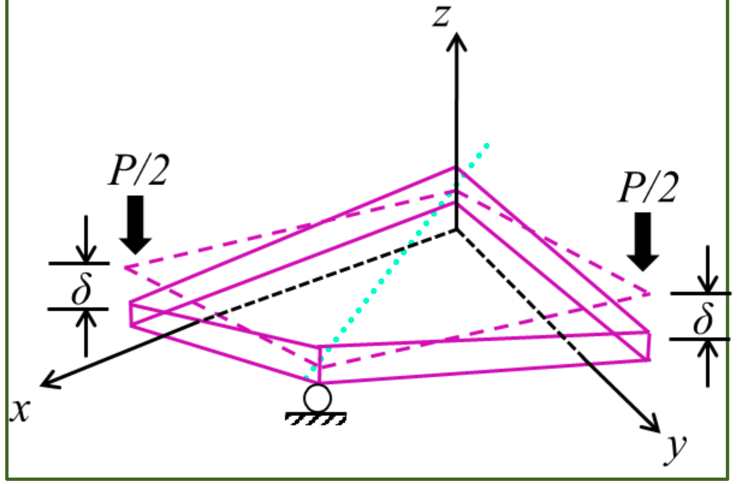


Remove two End supports & Twist the load-arm



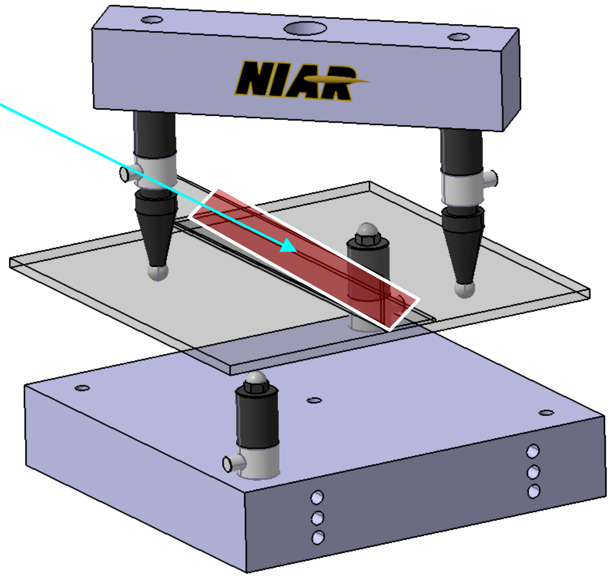


*Akin to a **Plate Twist** scenario*



<u>TP Weldment Qualification</u>

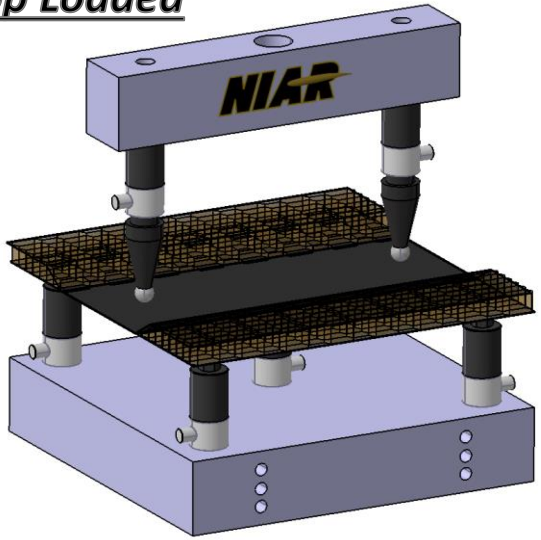
Twisting induced skin/stringer delamination

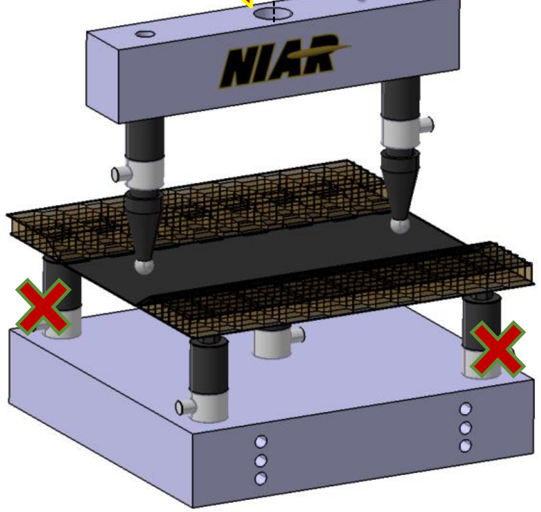


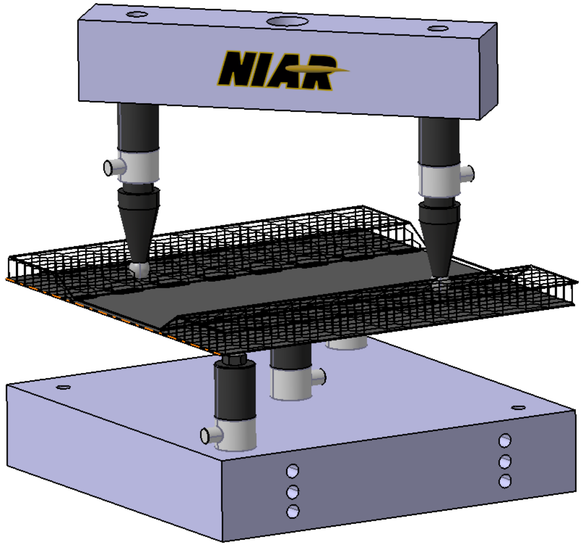
- ***ECT** can be **easily** implemented in the existing **7PB*** rig
- Akin to a *<u>CLPT - plate twisting problem</u>* or *<u>ASTM D3044</u>* standard

ECT w/ SW Ramped Coupons

Top Loaded

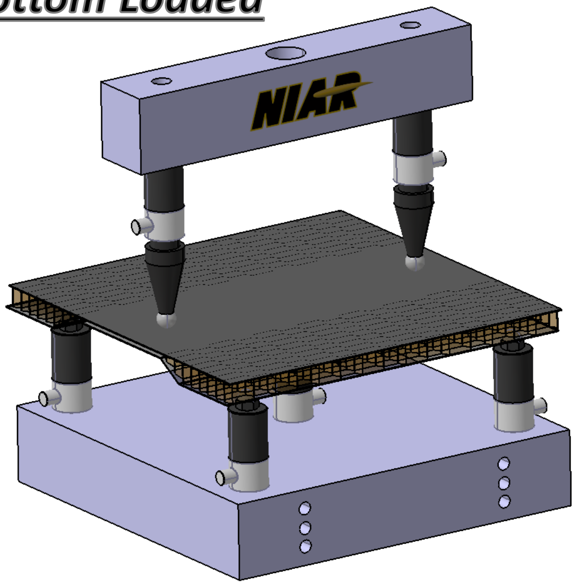


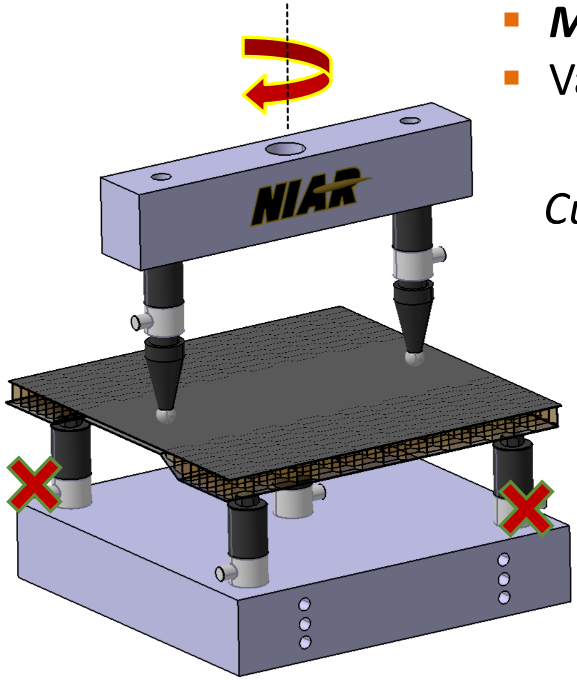




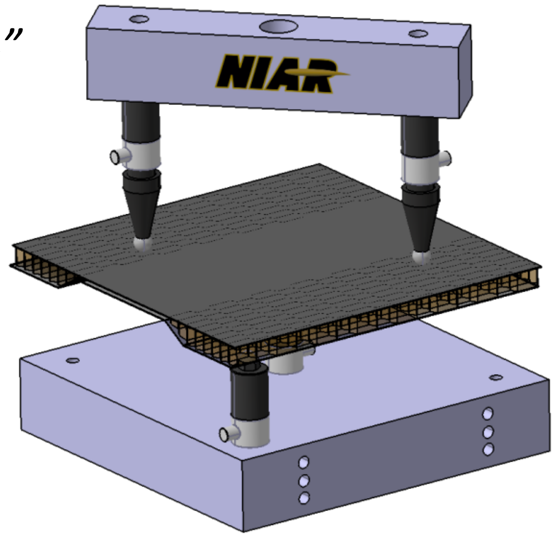
- ***Mid-Ramp distance*** dictates the *induced failure*
- Varies on ***Top OR Bottom*** Loading

Bottom Loaded



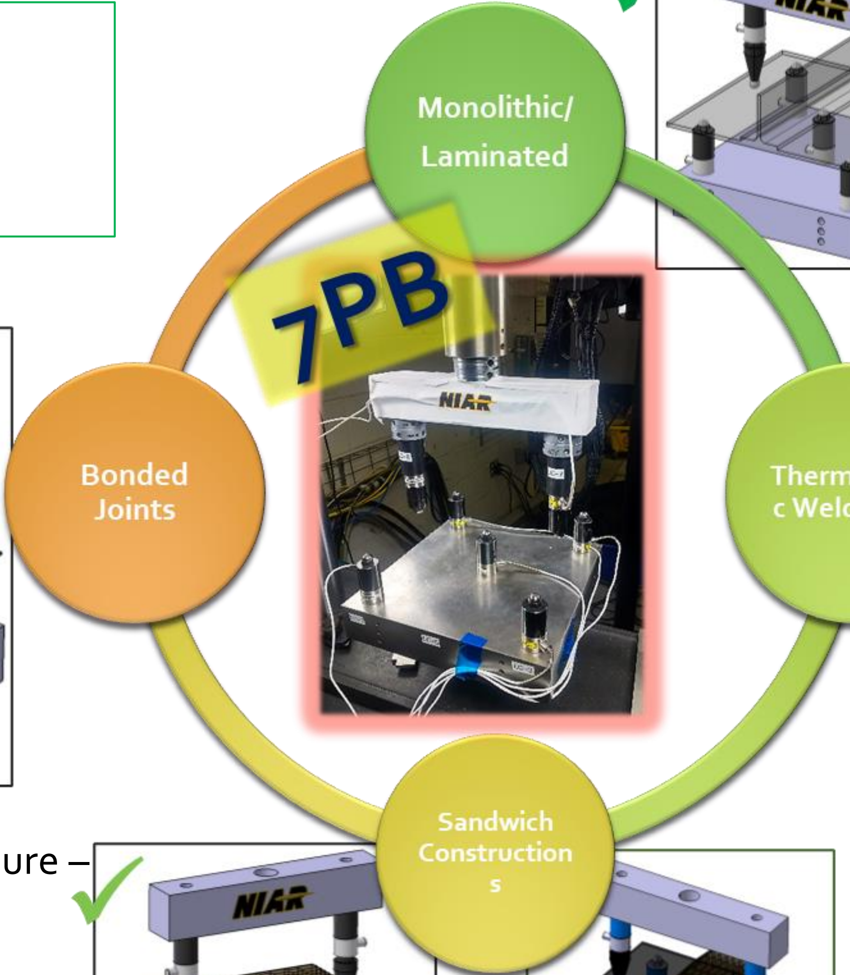


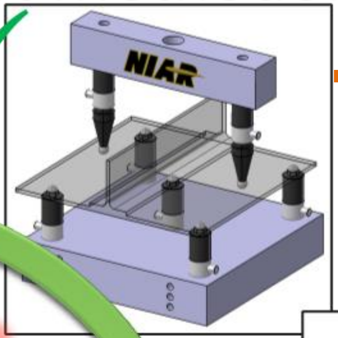
Current mid-ramp dist. = 4”
(Typical Values = 2 – 6”)

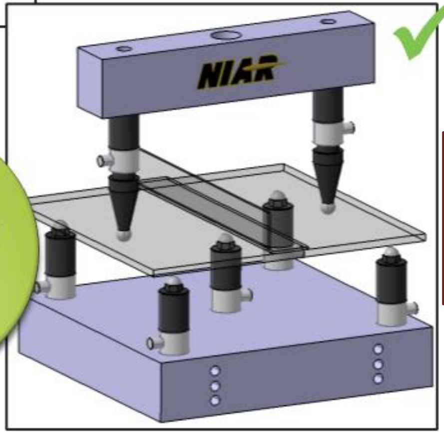


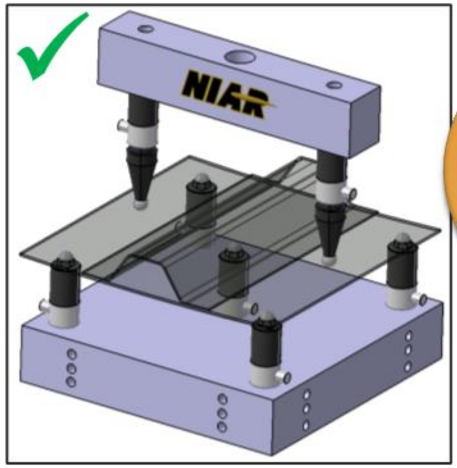
7PB Test Method – A Sub-Element Level Test Methodology for *Standardization*

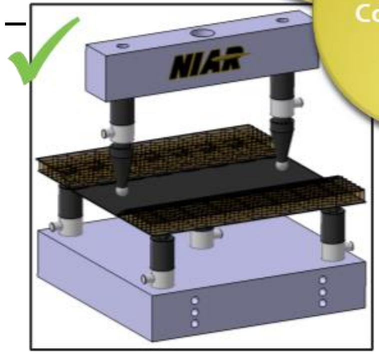
- ***Post-buckled*** induced separation
- Characteristic ***mixed-mode*** damage progression
- Suitable for ***Standardization***

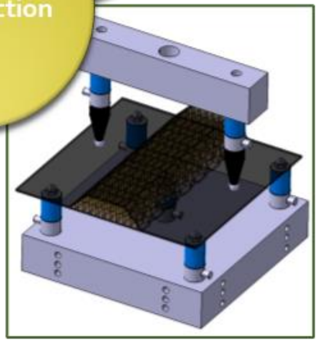






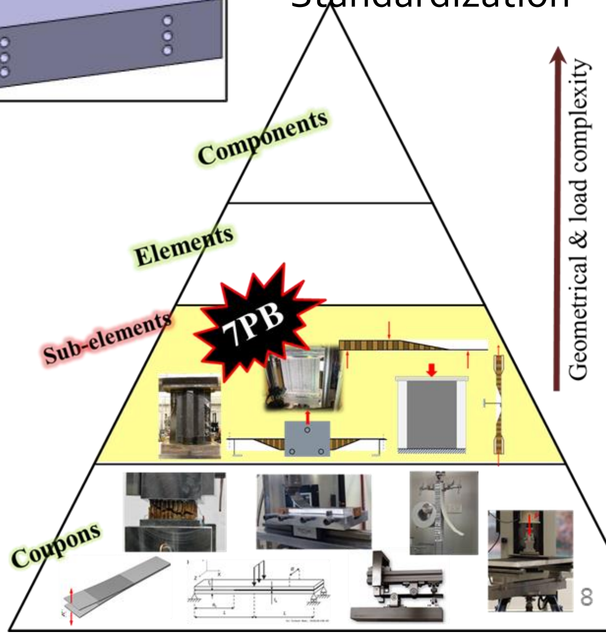






- ***Sub-Element-level test methodology*** *suited for* ***Laminated, Monolithic, Sandwich & Thermoplastic Weldments***

Round-robin w/ interested labs for **ASTM** Standardization



- ✓ ***Design*** evaluation (interlaminar ply failure – *joint-strength*)
- ✓ ***Material*** selection/evaluation
- ✓ ***Geometric*** config. evaluation
- ✓ ***Bondline*** qualification/selection
- ✓ ***Complex*** loading (*combined* bending about two axes)

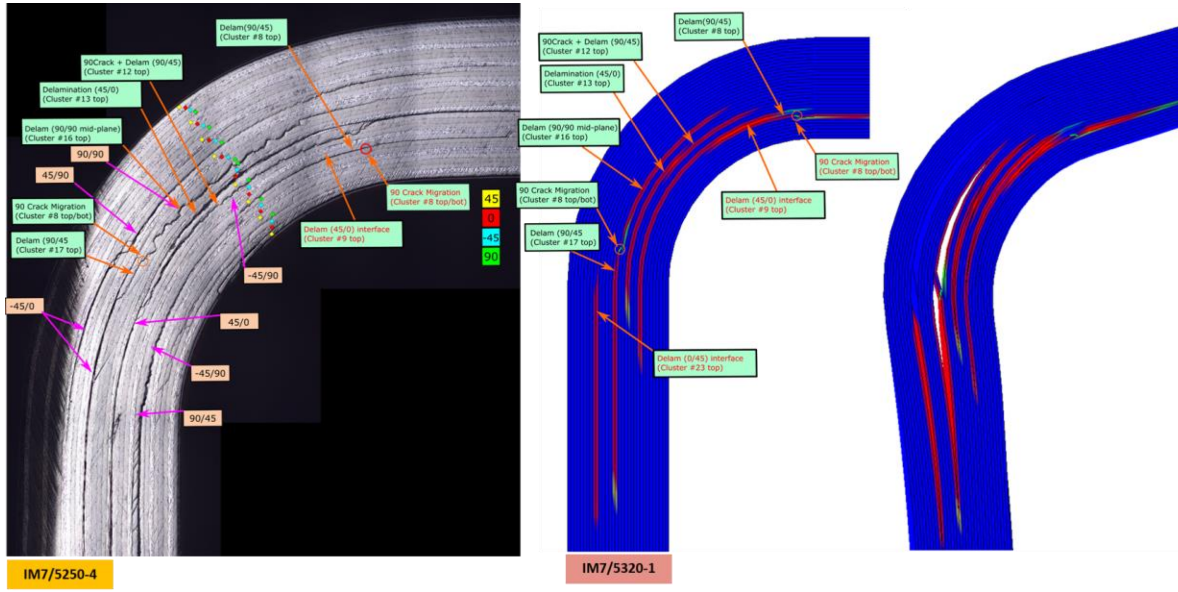
Summary

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

Analysis Validations

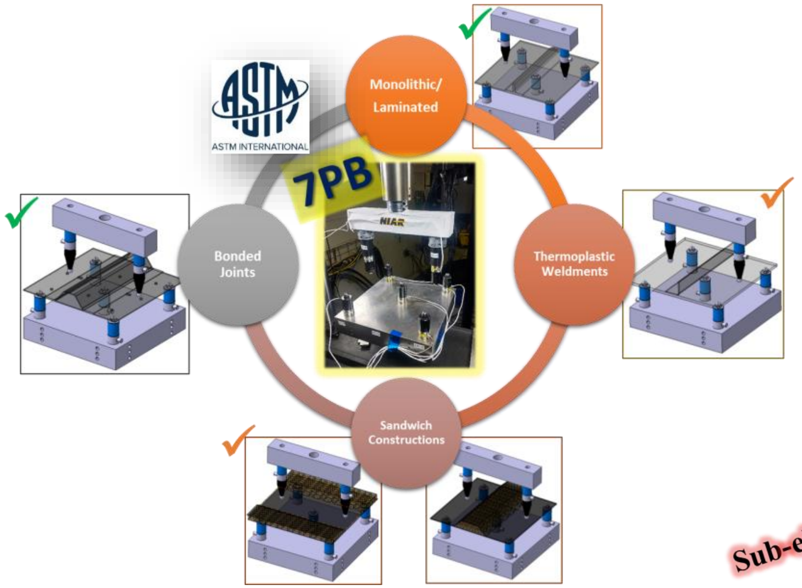
- Expand the continuum damage modeling and validations for **sandwich structural details** (secondary bonds, co-bonds, and co-cured hat- and T-stiffeners)
- Discrete damage modeling using regularized extended finite element analysis (ReFEM) for investigating competing failure modes and crack migration.



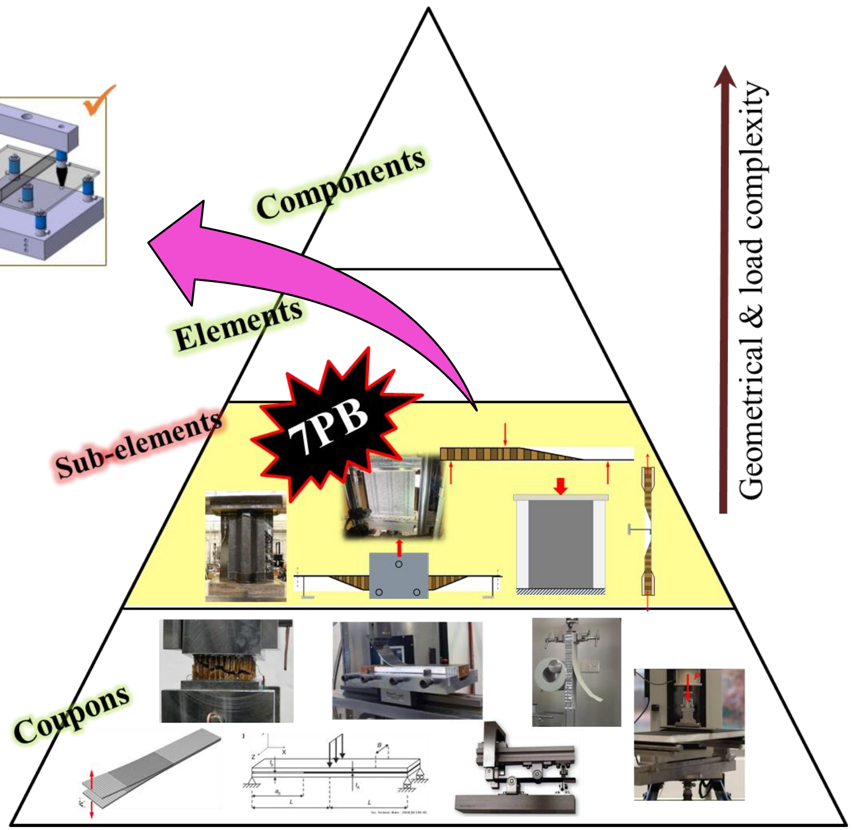
Looking Forward / Future Work

- 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
- Next Steps:
  - Complete 7-point bend testing of bonded and welded thermoplastic joints
  - Continued discussions with ASTM D30 about the possibility of standardizing 7-point bend testing

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.

Project Goals

- ✓ **Design & Development of sub-element based test methodology for *Monolithic Structures***
- ✓ **Design & Development of sub-element based test methodology for *Bonded Structures***

Key Observations & Test Findings

- **Seven Point Bend (7PB) is clearly a mixed-mode test**
- ***Sub-element-level* test methodology suited for Laminated, Monolithic, Bonded, Sandwich & Thermoplastic Weldments**
- **Demonstrated to perform Skin-stringer Interface Characterization across co-bonded (CB) & secondary-bonded (SB) coupons (Hat- & T-stiffened)**
  - Pristine, Pre-cracked and Impacted coupons considered.
- **Easy to install & operate; yet robust enough to introduce complex loading *(long. & transv. bending components)***
- **Presence of inherent flaw governs the damage migration load-level into first-ply & beyond.**
  - A flaw such as an insert/impact damage causes the crack to lie in skin-stringer interface before kinking away and into skin/stiffener plies.
- **Damage always initiates at the center of coupon; peak strain in the specimen mid-span.**

Analysis Takeaways

- **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*.**
- **Damage progression away from interface not captured & peak load; however, *Damage initiation is predicted.***
- **Failure load dependent on input cohesive properties *(Gc, τ)***