STRENGTH AND LIFE ENHANCEMENT OF VERTICALLY-ALIGNED CARBON NANOTUBE (VACNT)-REINFORCED COMPOSITE AEROSTRUCTURES

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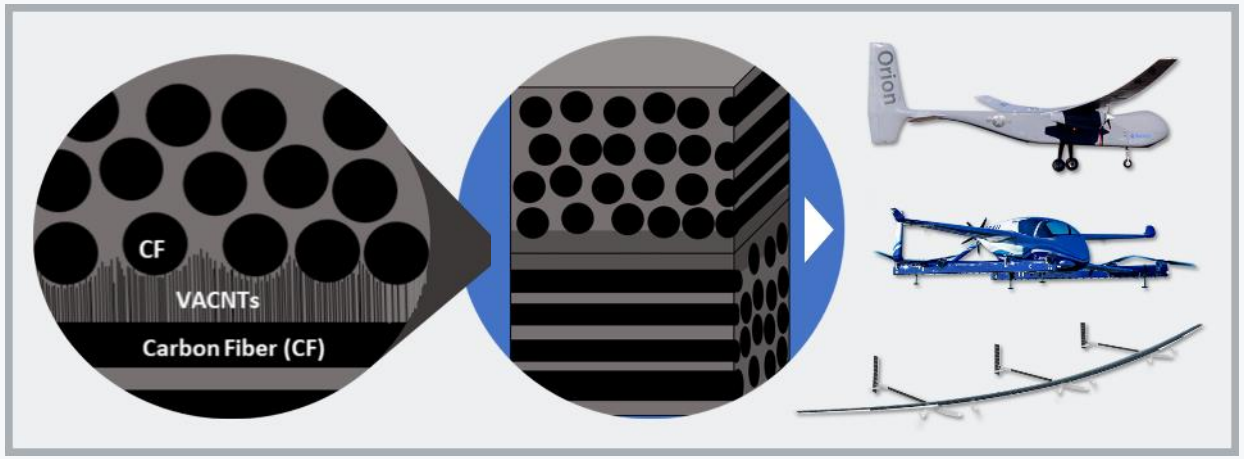
A Boeing Company

Approved, DCN# 543-718-23

BACKGROUND

- Composites are used in most modern U.S. Navy airframes.
- Laminated composites have weak out-of-plane properties and micro-scale reinforcement options degrade in-plane performance.
- VACNTs are a new market-ready interlaminar reinforcement technology shown on the coupon level to enhance the through-thickness properties of aerospace composites **without negatively impacting mechanical properties and current production processes.** This technology is **available on a production scale** amenable to prepreg/film transfer.



Data Source	Property	Improvement via NanoStitch® Inclusion
NAWA (N12) and MIT ▪E. J. Garcia et al. (2008), *Compos. Part Appl. Sci. Manuf.* ▪Guzman et al. (2012) *AIAA SDM Conf.* ▪NAWA America, Inc. (2021), *NAWAStitch® Performance Data Sheet.*	Mode I Interlaminar Fracture Toughness	+50%
	Mode II Interlaminar Fracture Toughness	+200%
	Bearing Offset Strength	+30%
	Impact Damage Area	44% Reduction
	Compression After Impact	+12%
	Failure Strength at Ply Drops	+6%
	Combined Loading Compression	+10%
	Open Hole Fatigue Life	+140%

Property improvements via VACNT inclusion

OBJECTIVES

- Maturate the application of Vertically-Aligned Carbon Nanotube (VACNT) reinforcement of composite aerostructures from TRL3 to 4/5.

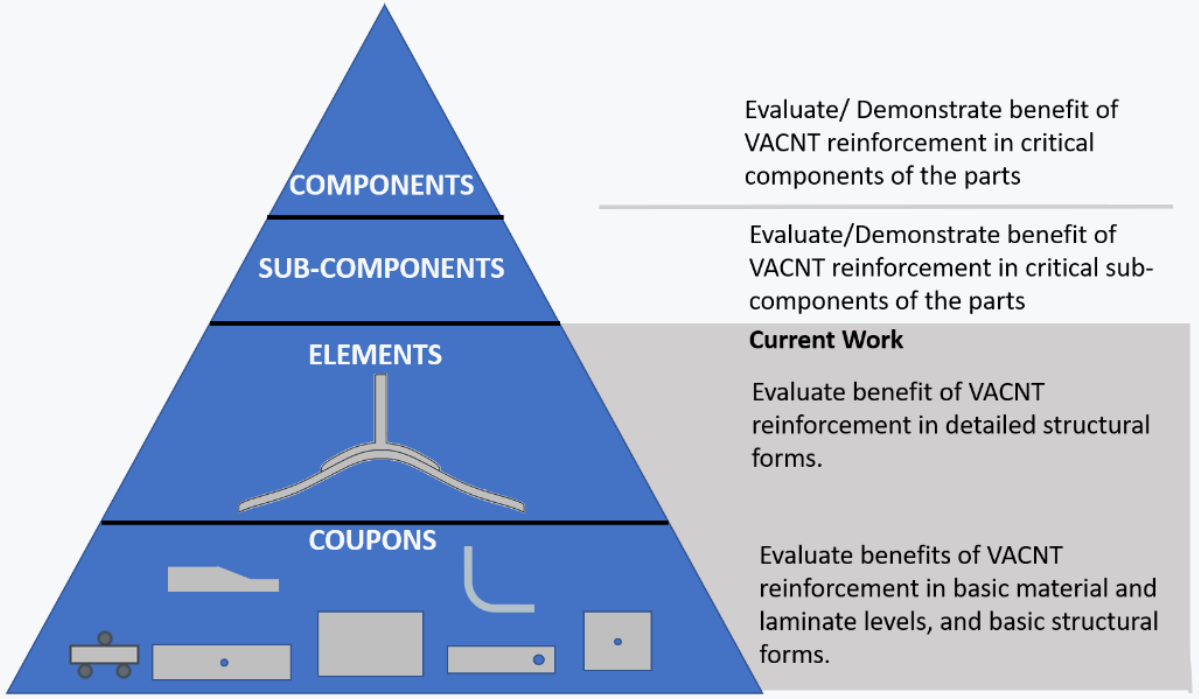
- Evaluate efficacy of VACNTs in reducing weight and extending service life of composite aerostructures via a building block approach.

VACNT-reinforced composite structure offers weight savings and improved durability

Higher fuel efficiency, longer missions, larger payloads and longer service life of the U.S. Navy fleet

TECHNICAL APPROACH

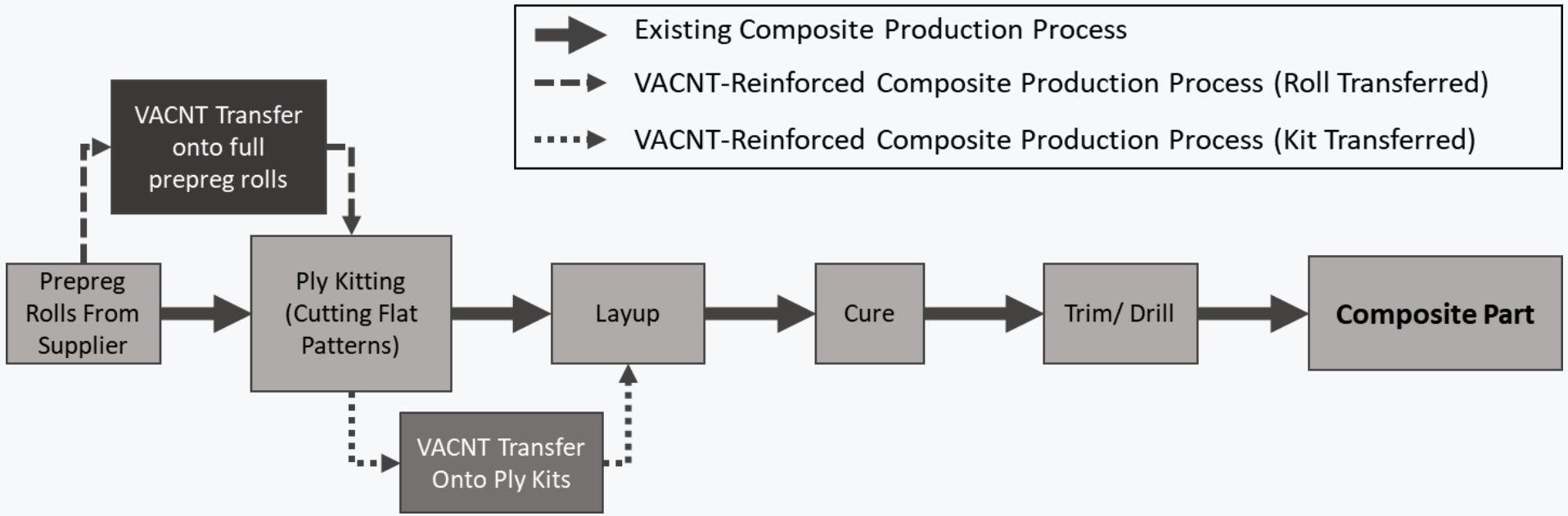
- Representative aerospace thermoset / intermediate modulus fiber of material systems used by DoD and commercial platforms.
- A **building block approach** [1] is followed to mature the technology via the evaluation and demonstration from coupon through sub-component level tests.



[1] Composite Materials Handbook: Polymer Matrix Composites: Materials Usage, Design, and Analysis.

KEY MANUFACTURING INTEGRATION LEARNINGS

VACNT TRANSFER OPTIONS

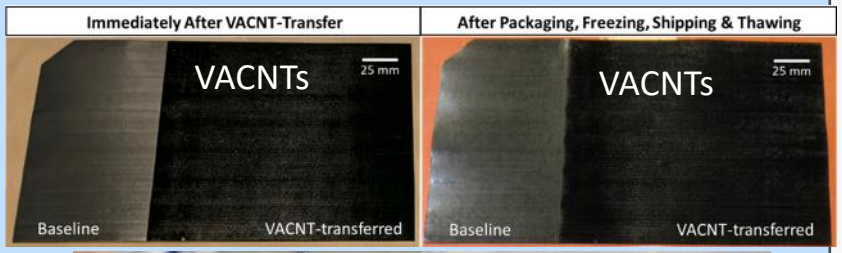


- Current program uses ply kit transfer method
- Minimal impact to the part fabrication process.

VACNTS INTEGRATE INTO EXISTING PRODUCTION

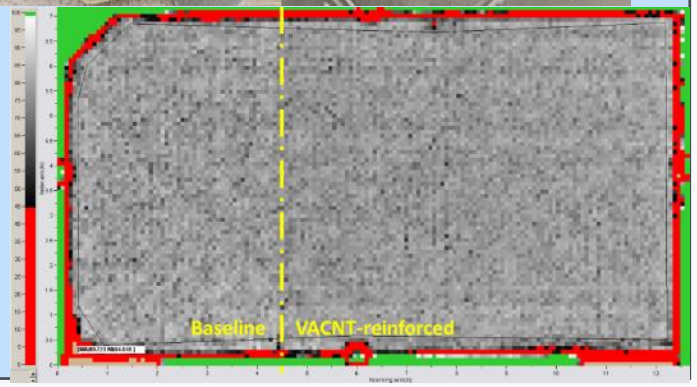
Process Compatibility

Shipping /Layup Handling



Dimensional Stability - No thickness changes

NDI – No differences in TTU C-Scans

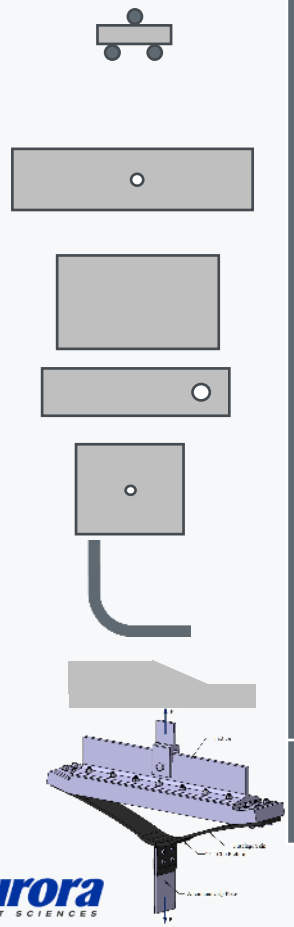


MECHANICAL PERFORMANCE COUPON STUDY

AUTOCLAVE CURED AEROSPACE THERMOSET / INTERMEDIATE MODULUS FIBER MATERIAL SYSTEM

TEST ARTICLES

All articles are fabricated using standard aerospace thermoset / intermediate modulus fiber material system



BBA Level	Article	Standard	Load	Evaluation Goals	Applicability to Airframe
Coupon	Short-Beam Shear	ASTM D2344	Static, Fatigue	SBS Strength, Fatigue Life	Skin, Frames, etc.
	Open Hole Compression	ASTM D6484, ASTM D7615	Static, Fatigue	OHC Strength, Fatigue Life	Skin
	Compression After Impact	ASTM D7137	Static	CAI Strength	Skin
	Bearing	ASTM D5961	Static	Bearing Strength	Fastened Joints
	Pull-Through	ASTM D7332	Static	Pull-Through Strength	Fastened Joints
	Curved Beam	ASTM D6415	Static, Fatigue	Interlaminar Tensile Strength, Fatigue Life	Frames, Brackets, Features, etc.
	Ply-Drop	3-Point Bend	Fatigue	Fatigue Life	Spar, Skin, Frames, etc.
Element	"Y"-Joint	Pull test	Static, Fatigue	Joint Strength and Fatigue Life	Y/Pi- Clip and Skin Joints

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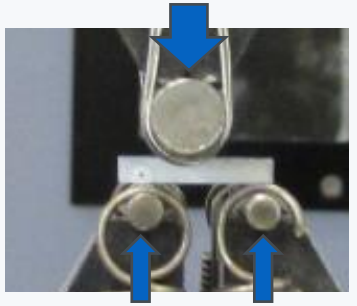
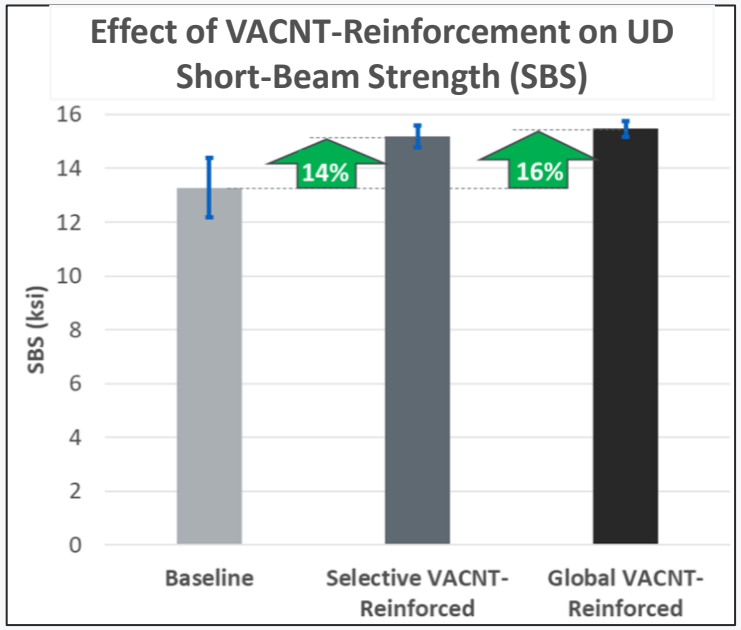
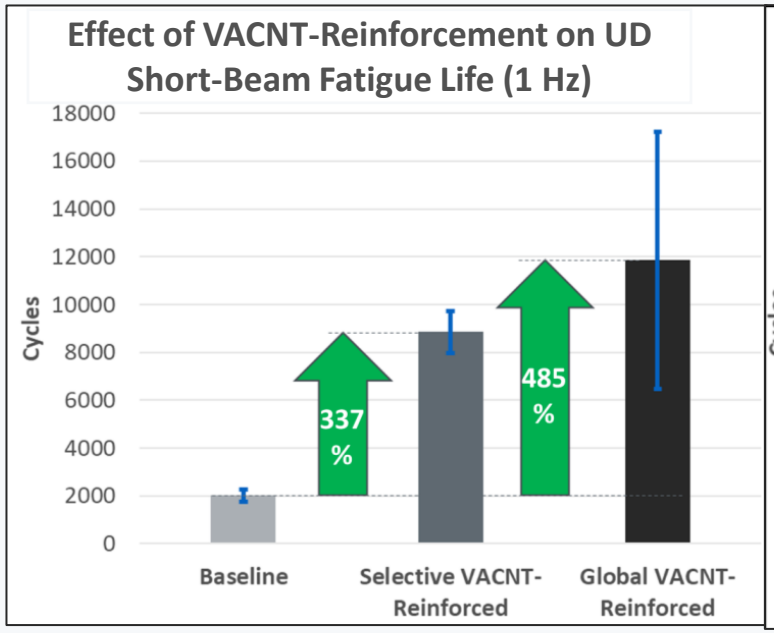
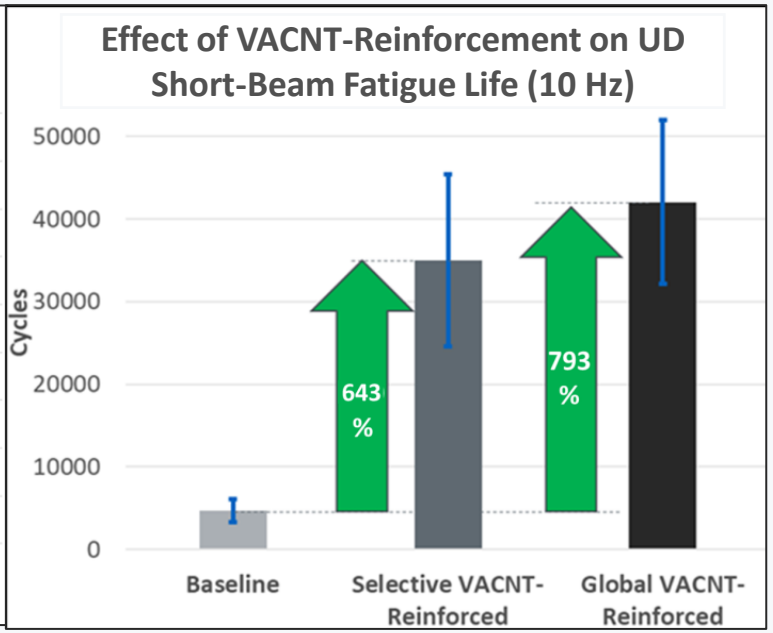
SBS COUPON



UD based QI Laminate



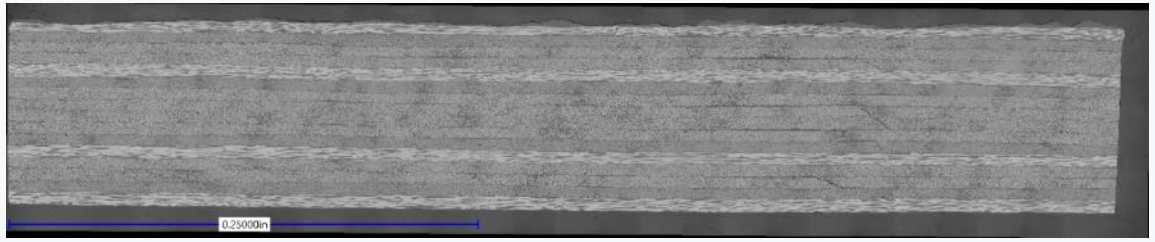




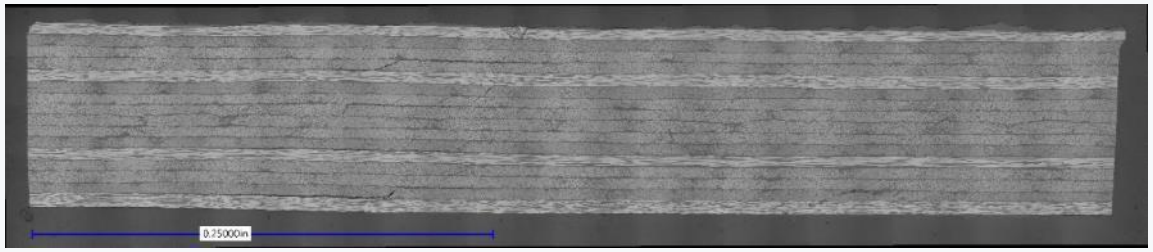
- Improvement in static strength and fatigue life with VACNT reinforcement.
- Fatigue life benefit observed in both 1Hz and 10 Hz frequencies.

SBS COUPON- POST TEST STUDY

UD Static

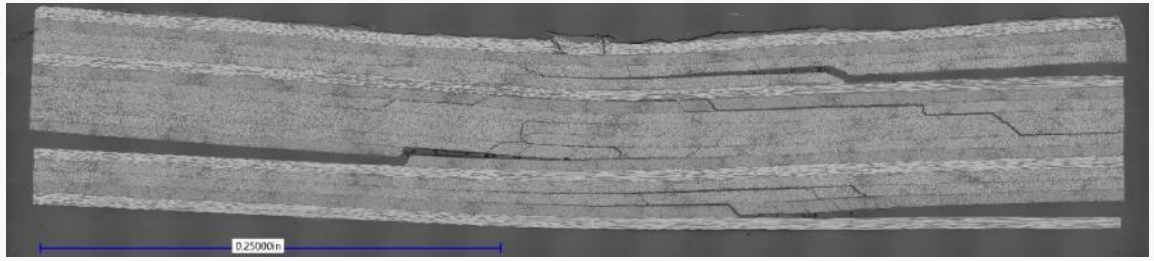


Baseline

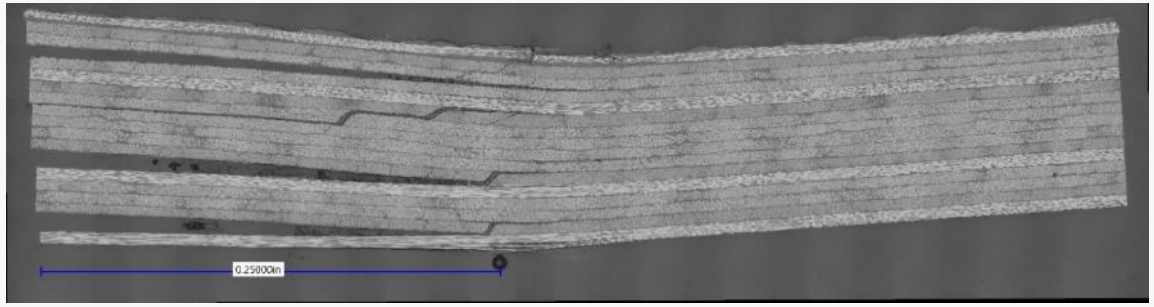


Global VACNT-reinforced

UD Fatigue



Baseline

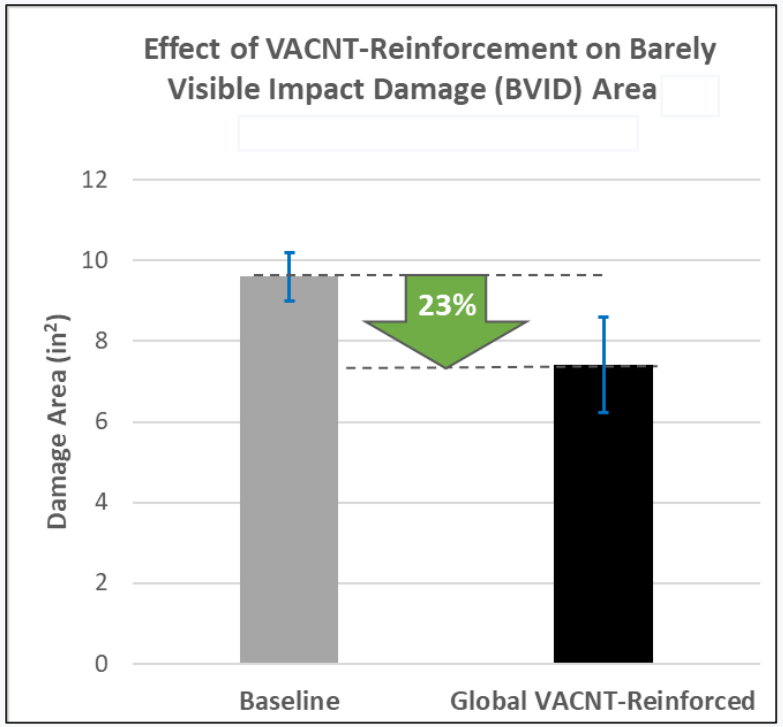


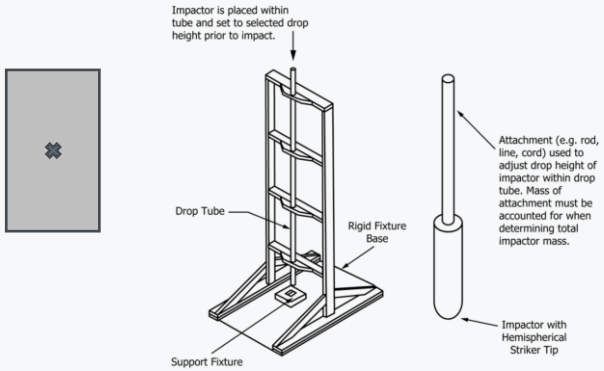
Global VACNT-reinforced

- VACNT-reinforcement specimens show damage closer to the surface of the specimen and away from mid-plies in static, fatigue failure isolated to half of the specimen in contrast to both halves for baseline.
- VACNTs may be slowing crack propagation in matrix.

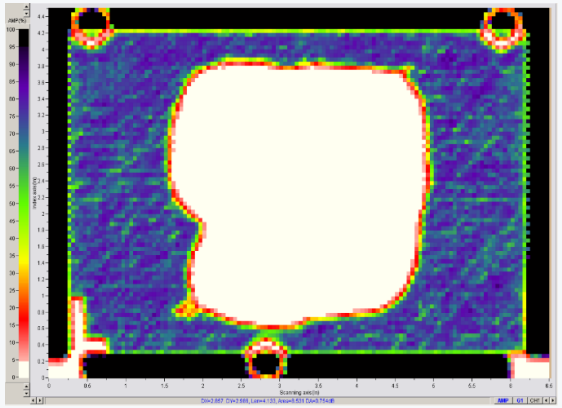
CAI COUPON

UD based QI Laminate

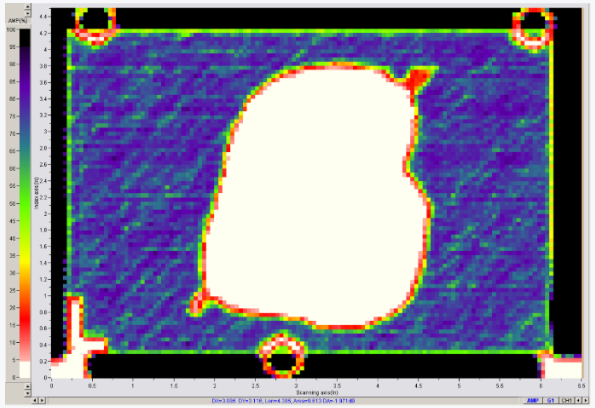




C-scan images of representative laminates after Barely Visible Impact under ~40 ft-lbs impact.



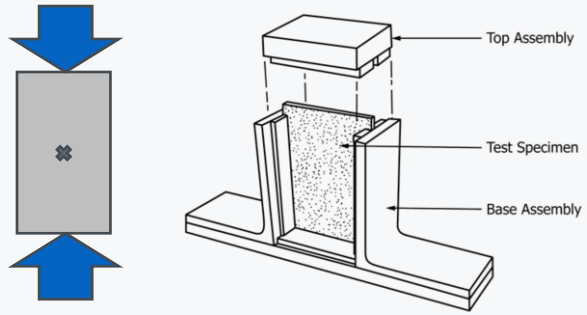
Baseline



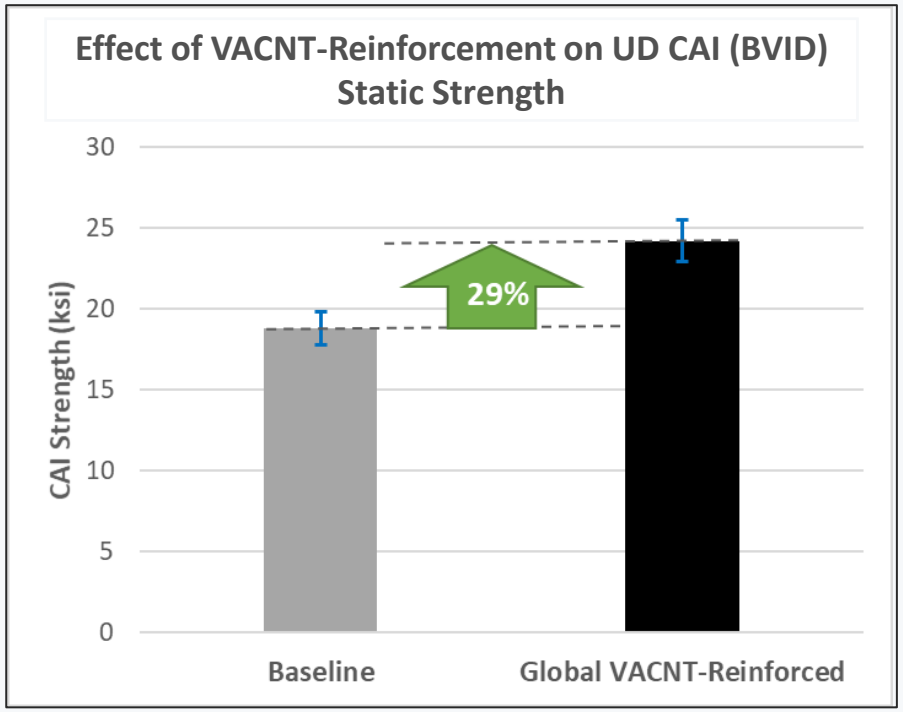
Global VACNT-reinforced

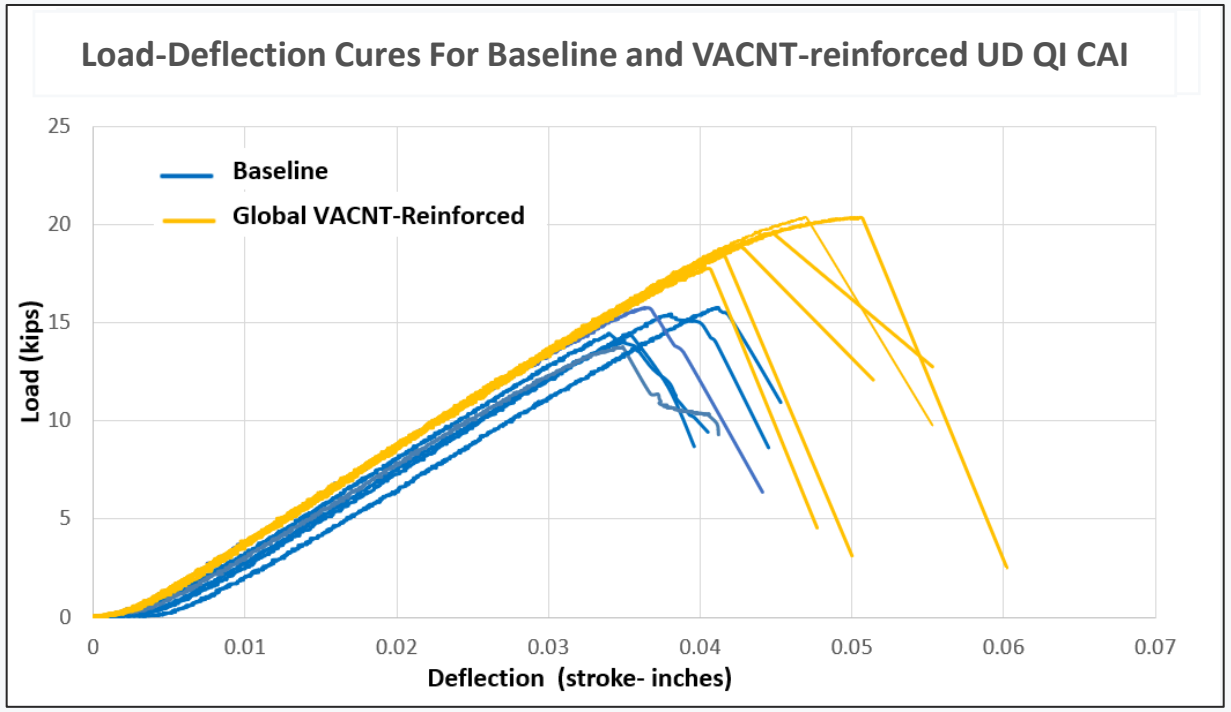
BVID damage size reduction (increased damage resistance) with VACNT reinforcement.

CAI COUPON



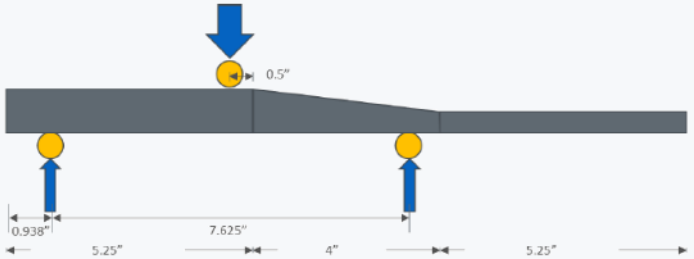
UD based QI Laminate



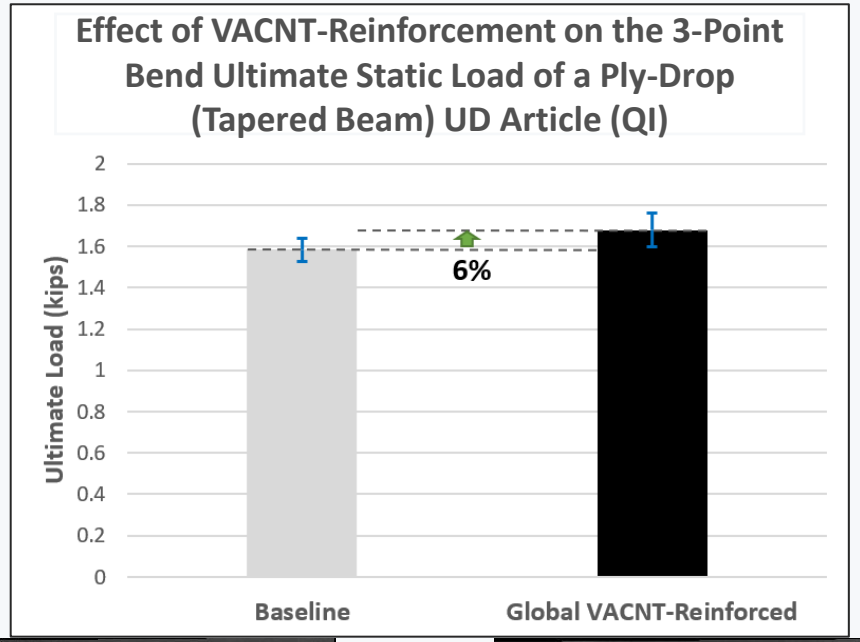


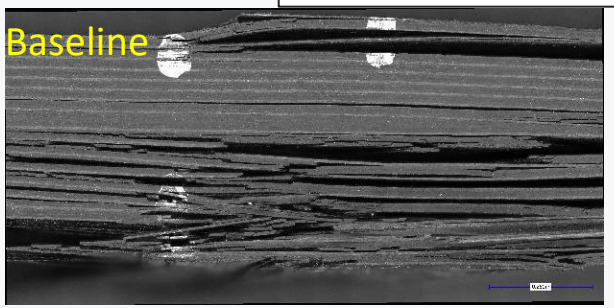
Increase in CAI strength (damage tolerance and residual strength) with VACNT reinforcement.

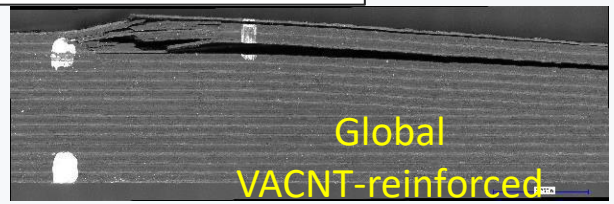
PLY-DROP COUPON - STATIC

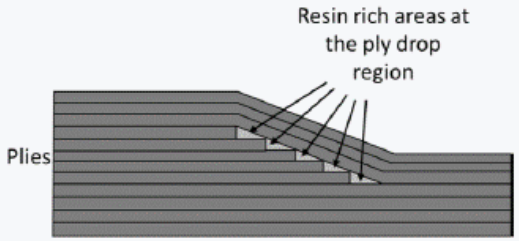


UD based QI Laminate





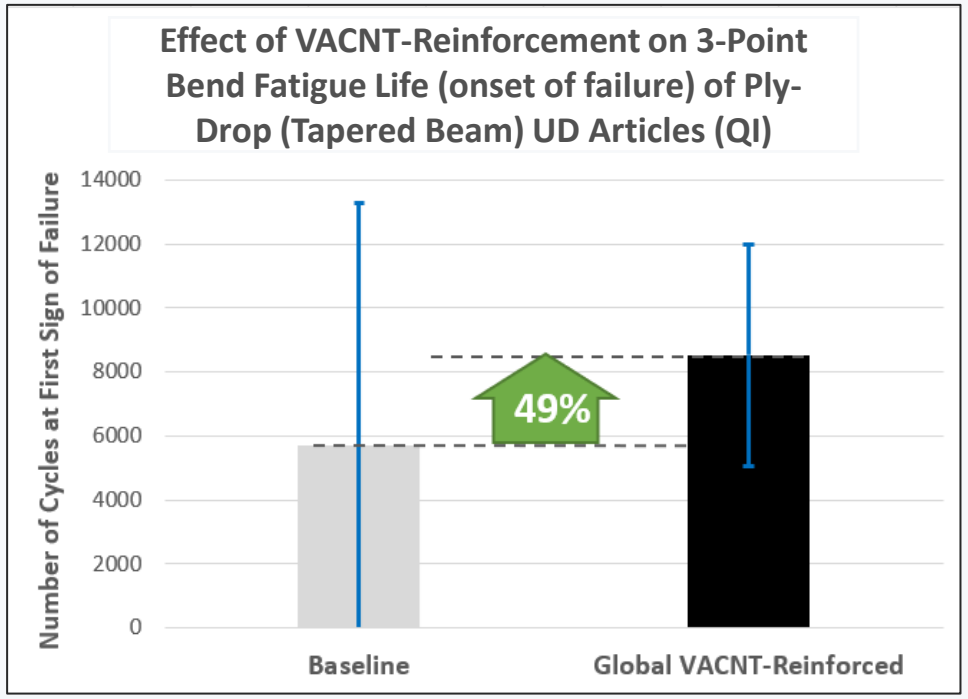


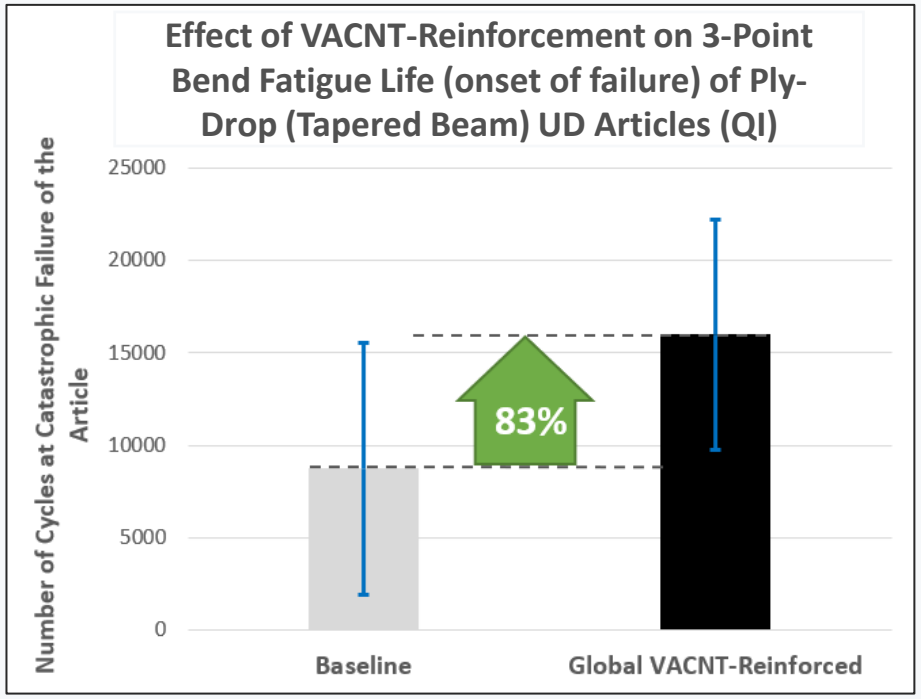


Increase in static ultimate load and reduced extent of damage with VACNT reinforcement.

PLY-DROP COUPON - FATIGUE

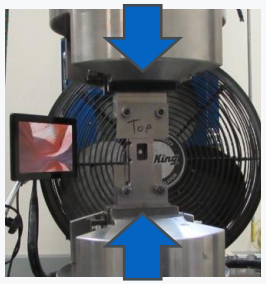
UD based QI Laminate



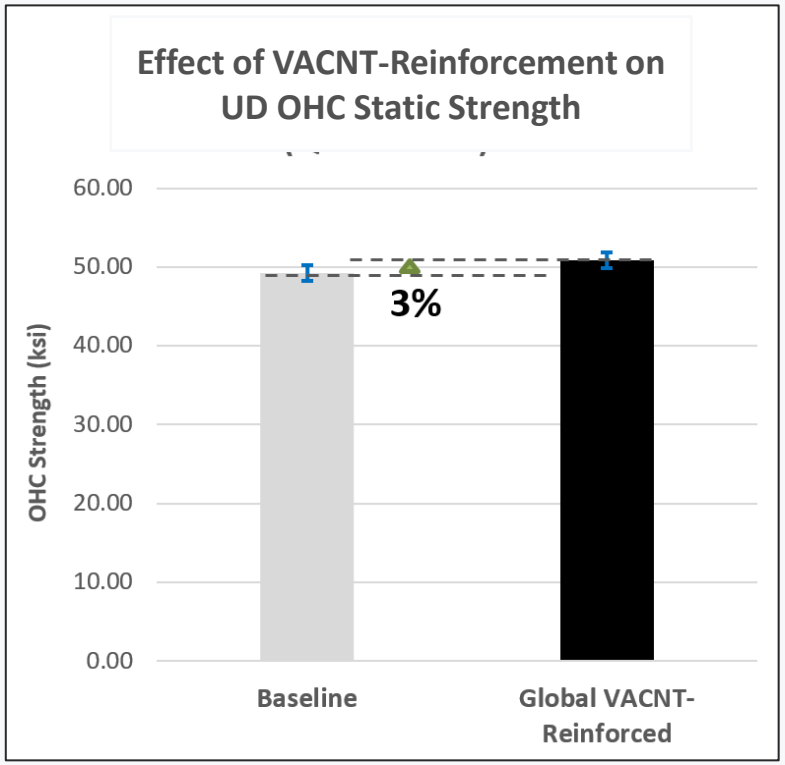


Delayed initiation of failure (crack) and increased fatigue life with VACNT reinforcement.

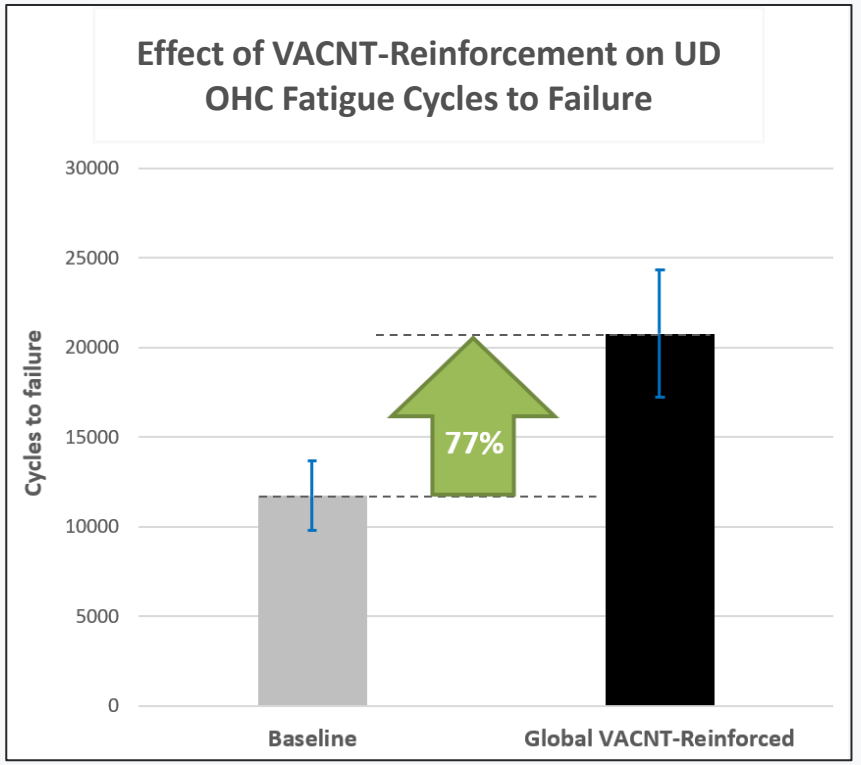
OHC COUPON



QI Laminate (static)



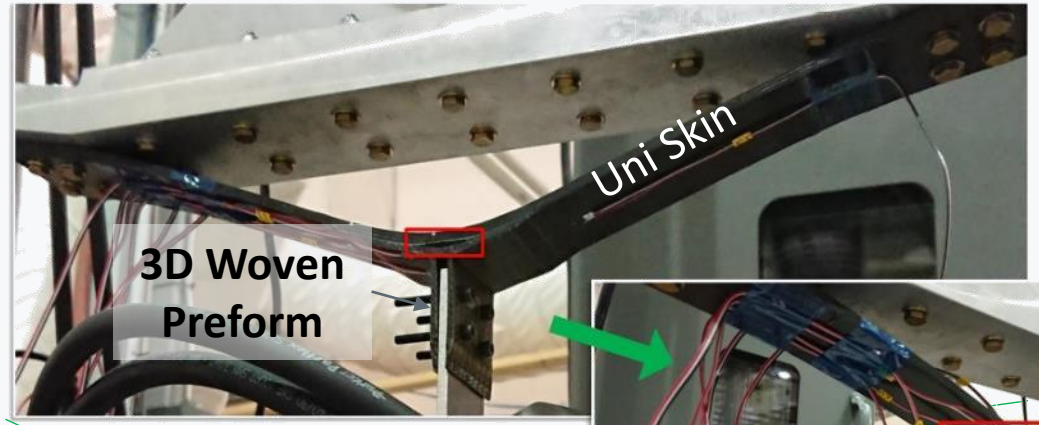
QI Laminate (fatigue)

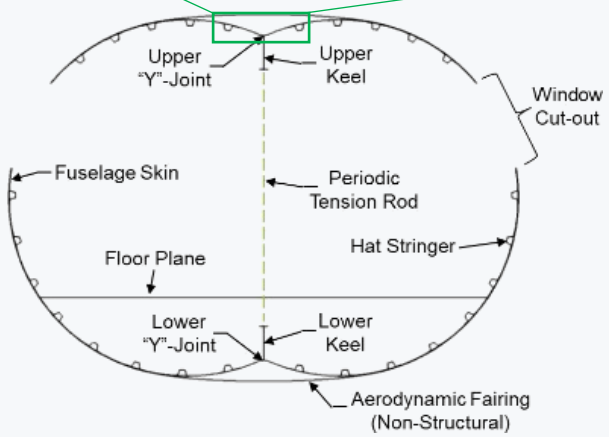


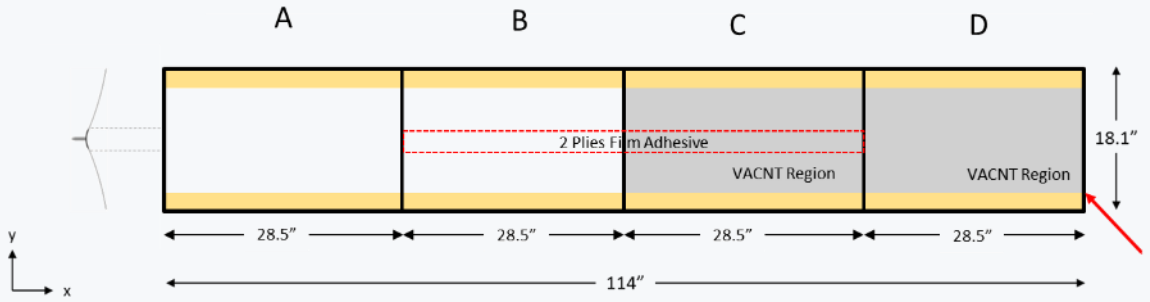
- No considerable improvement in static strength
- Improvement in fatigue life with VACNT reinforcement

Y-JOINT ELEMENT: TEST SETUP

- Zones:
  - A: Baseline cocured
  - B: Baseline + Film Adhesive
  - C: VACNT + Film Adhesive
  - D: VACNT cocured

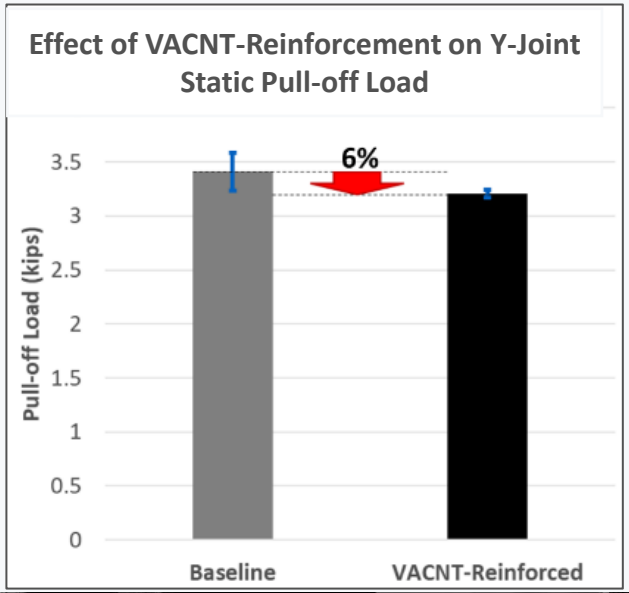


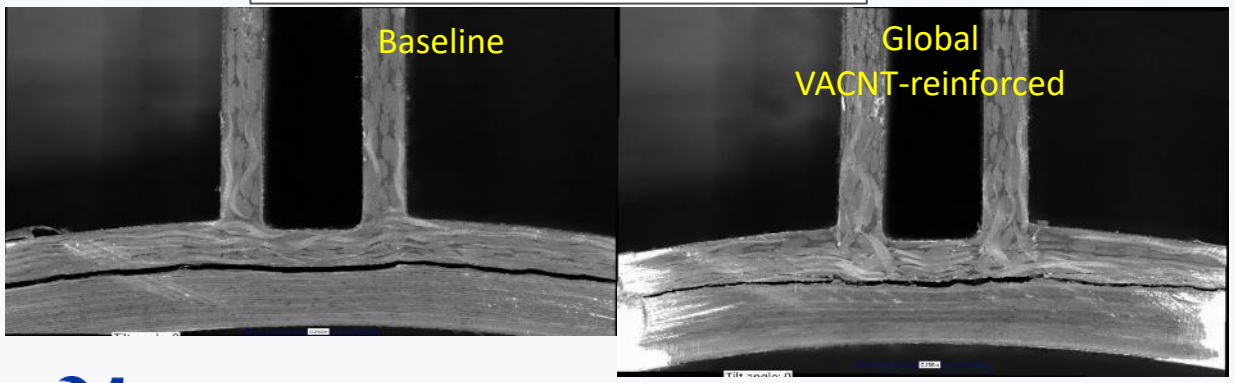




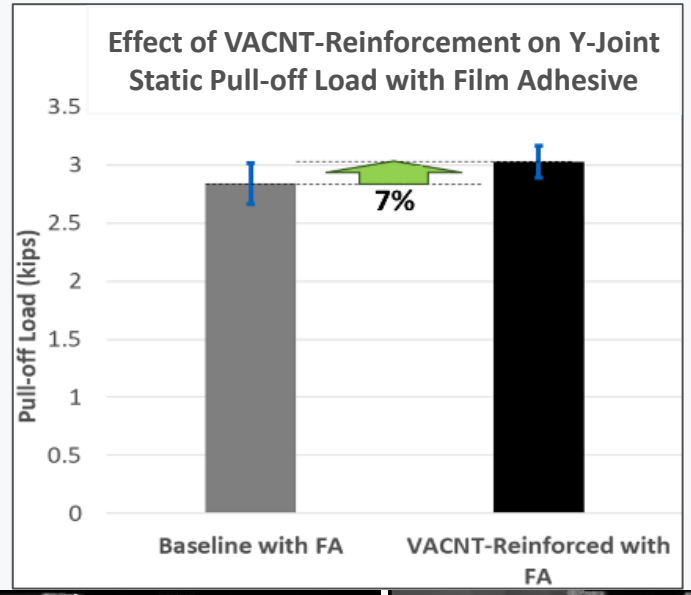
Y-JOINT ELEMENT – STATIC TESTS

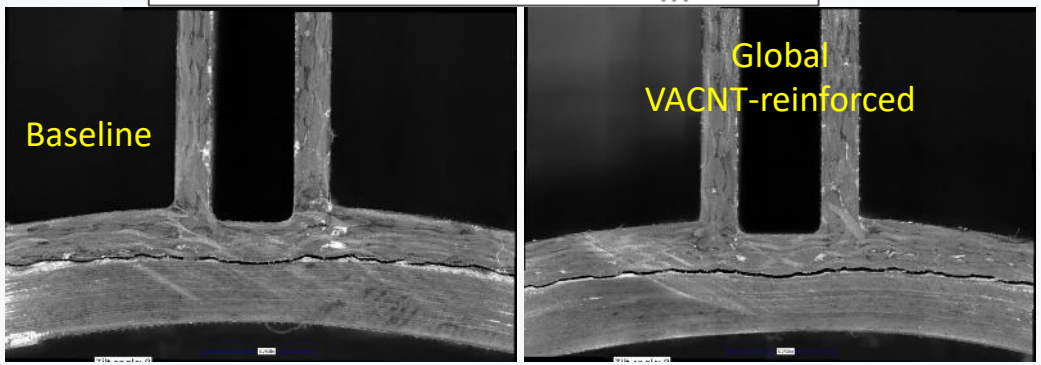
No Film Adhesive





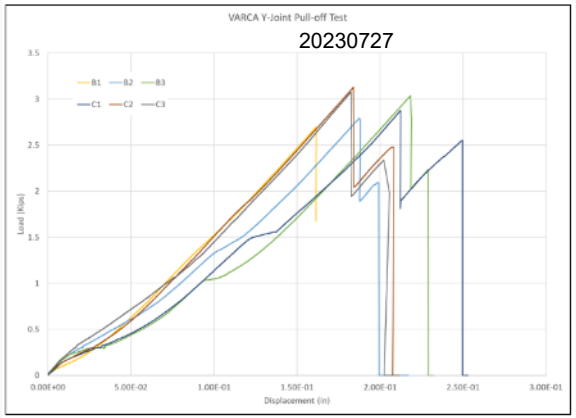
With Film Adhesive



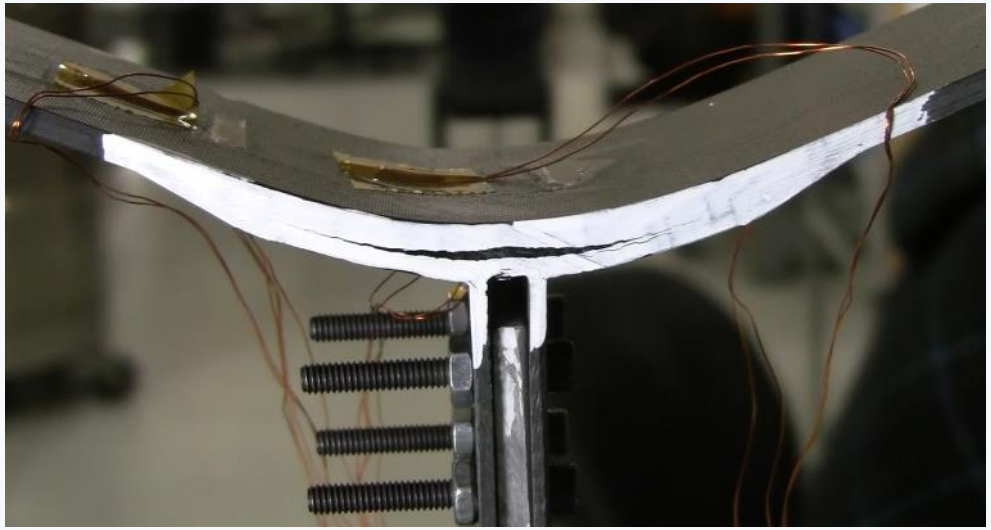


Y-JOINT ELEMENT

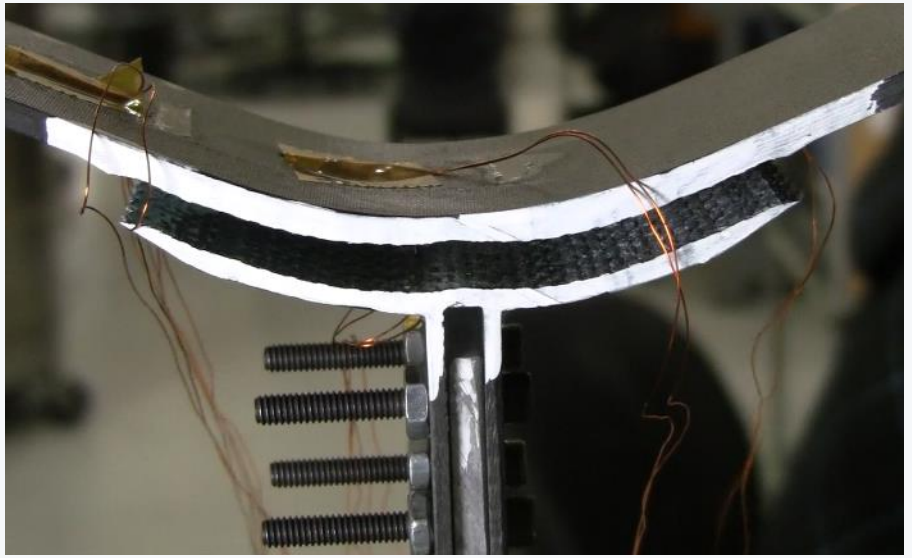
Co-cured skin and Y-preform with film adhesive (between skin and Y-preform) under static load



Crack Arrestment for VACNT-Reinforced+Film Adhesive Article After Initial Load Drop

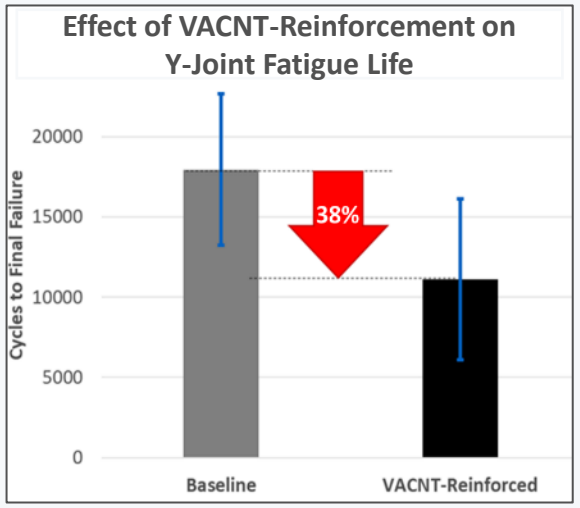


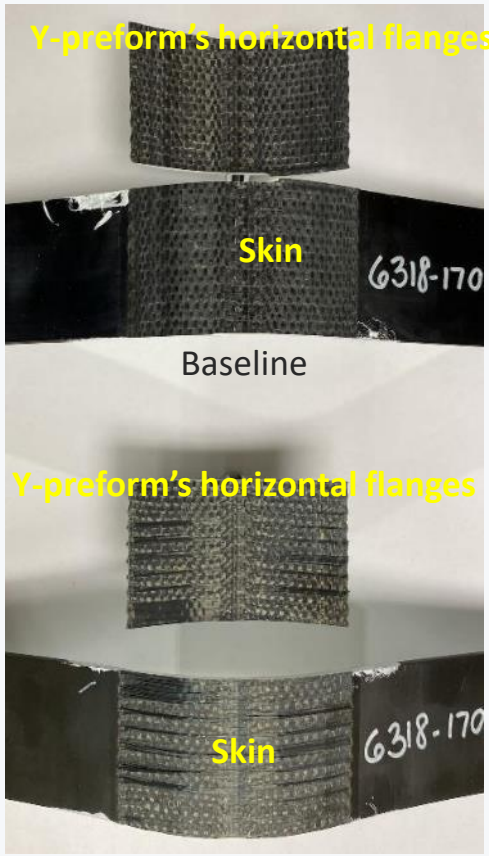
Final Failure for VACNT-Reinforced+Film Adhesive Article After Recovery



Y-JOINT ELEMENT – FATIGUE TESTS

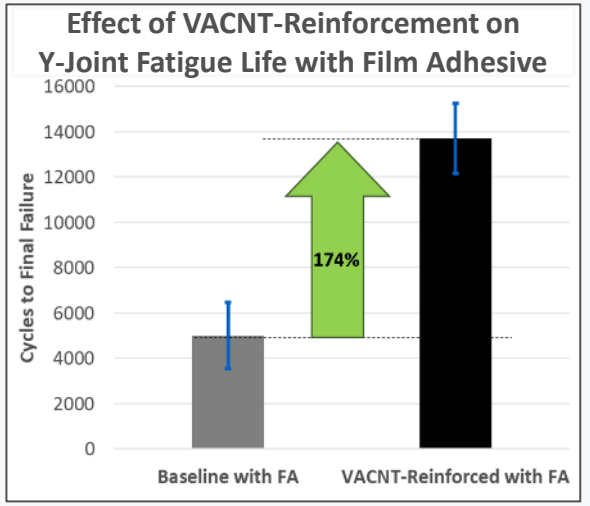
No Film Adhesive

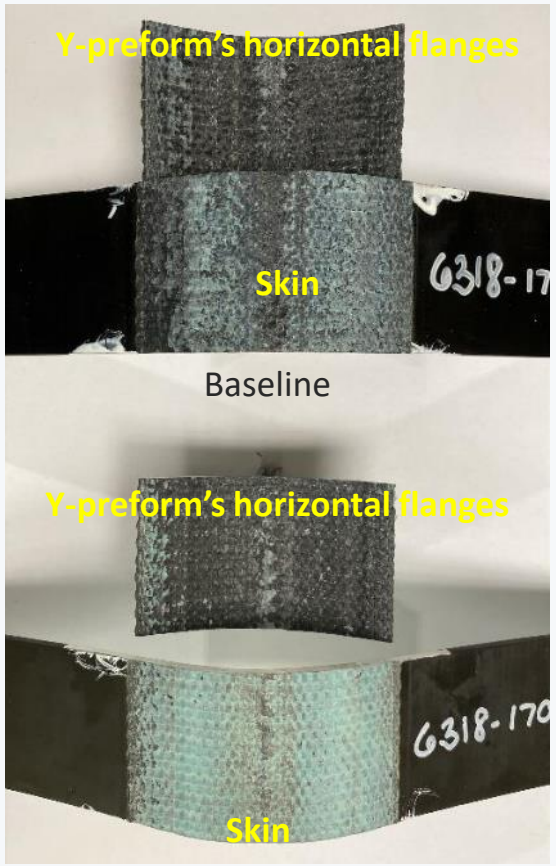




Global
VACNT-reinforced

With Film Adhesive

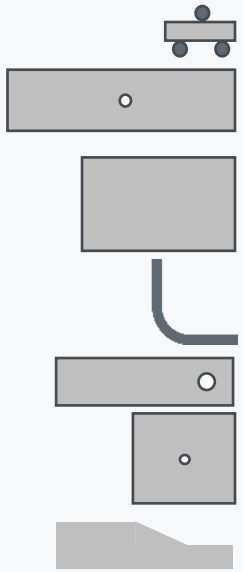




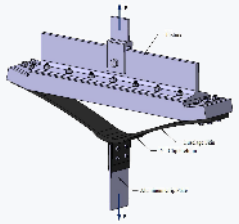
Global
VACNT-reinforced

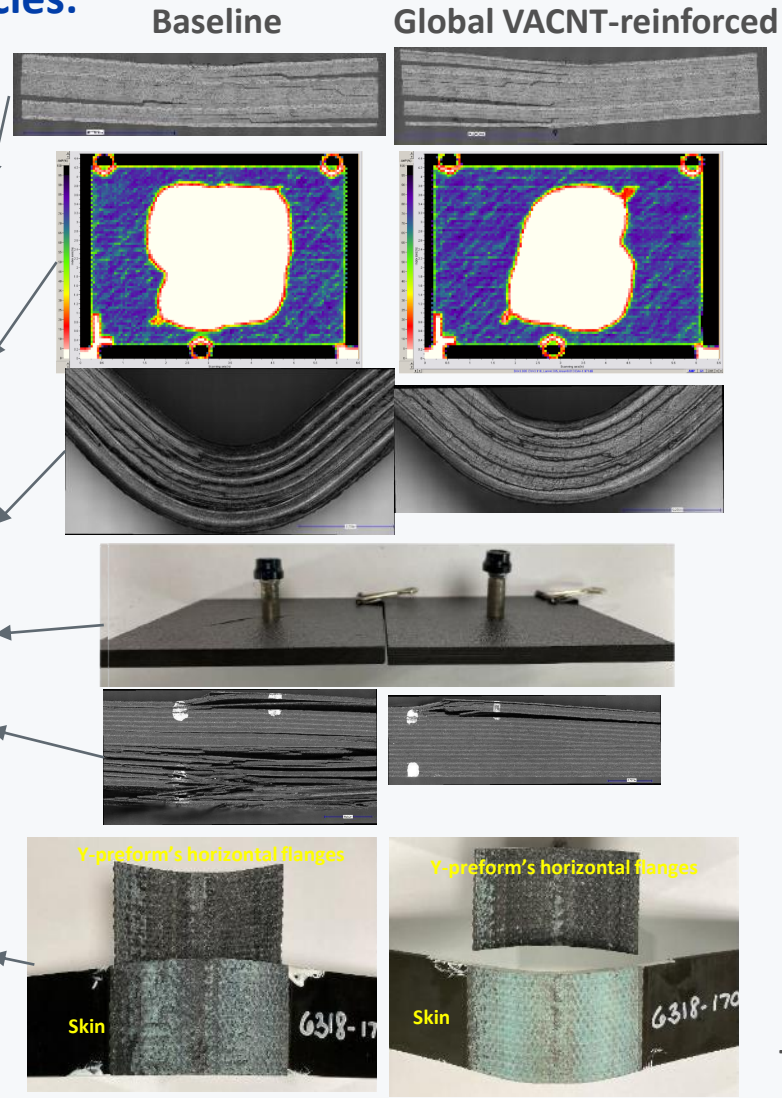
MECHANICAL RESULTS SUMMARY

Improvement of VACNT-reinforced over baseline (un-reinforced) articles:



Article	Property	Result (delta over baseline)
SBS	Static strength	+16%
	Fatigue life	+793%
OHC	Static strength	+3%
	Fatigue life	+77%
CAI	BVID Damage Size	-23%
	Residual compressive strength	+29%
Curved beam	Static ILT strength	-1%
	Fatigue life	Inconclusive (Pot. +110%)
Bearing	Static strength	+2%
Pull-through	Max. static load	+3%
Ply-drop	Fatigue cycles at initial failure	+49%
	Fatigue life (ult. failure)	+83%
Y-joint (skin/Y-preform co-cured)	Static pull-out load at initial failure	-4%
	Fatigue cycles at initial failure	-40%
	Fatigue life (two-part separation)	-38%
Y-joint (skin/Y-preform co-cured with film adhesive)	Static pull-out load at initial failure	+7%
	Fatigue cycles at initial failure	+202%
	Fatigue life (two-part separation)	+174%





TRL 4 Exit

KEY CONTRIBUTIONS

- **Integration of VACNT into production environment and process flow across**
  - Compatibility with cure, NDI, and inspection processes.
  - No impact on dimensions
  - Demonstrated mfg. integration onto a larger part – scaled to 10 ft-long joint article
- **Demonstrated material system dependencies**
  - Demonstration of the synergistic effect of adhesives with VACNT-reinforcement
- **VACNT reinforcement from UD to Woven Preform interface**
- **Demonstrated differences on selective vs global reinforcement to inform future tailoring**
- **Even smaller increases in static strengths are an indicator of considerable increases in fatigue life**
- **Reduced damage extent observed for many VACNT-Reinforced specimens**

RECOMMENDATIONS FOR FUTURE WORK

- Following the building block approach, study of the effect of VACNT-reinforcement on more detailed element and sub-component level articles.
- Further study on material system dependency of the improvements with VACNT reinforcement.
- Trade study for optimal introduction point of VACNT-reinforcement in part fabrication work-flow.
- Developing design rules to achieve target strength/life with optimal VACNT coverage.
- Study of environmental effects on the improvements due to VACNT reinforcement.
- Evaluation of multifunctionality of VACNTs. (e.g., efficacy in improving thermal and electrical properties.)

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