

□

◆

A Computational Design Methodology for Tailored Fiber Placement Preforms

Daniel Rapping

Eric Zhou

Bert Liu

Michael Braginsky

Gyaneshwar Tandon



University of Dayton
Research Institute

Presentation Outline

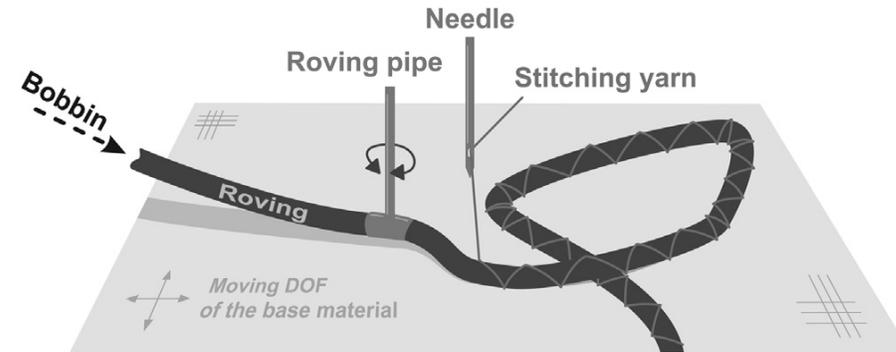
- Introduction to Tailored Fiber Placement
- IACMI Project 5.7: Tailored Fiber Placement for Complex Preforms
 - Motivation, Objectives, Team Members, Schedule
- Supporting Software Tools
 - Virtual Textile Manufacturing Suite (VTMS), BSAM 3D Stress Analysis Software System
- Analytical Tool Development
 - Mode I Fracture Toughness, Interlaminar Strength
- Summary
- Future Work
 - Preform Design for Sub-Elements, Bonded Joints and Complex Part Demonstration
- Acknowledgements

Introduction to Tailored Fiber Placement (TFP)

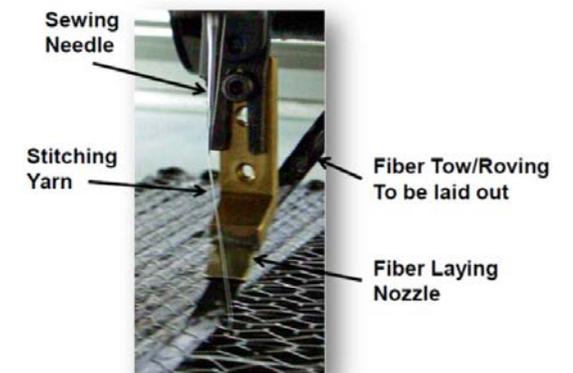
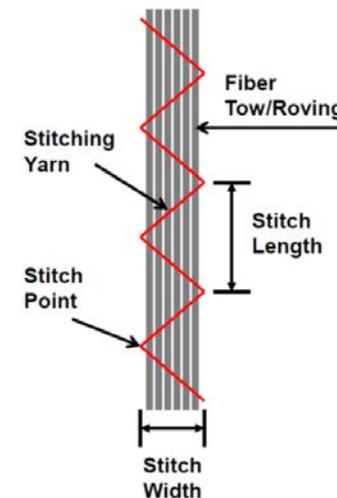


ZSK SGVA 0109

- 0.895m x 1.5m layfield
 - “Fast fiber lay”
 - Twin supply unit
 - Combination head: F, K, W type heads
-
- Embroidery-based technology
 - Automated tow steering process known as Tailored Fiber Placement (TFP)



Principle of TFP Process



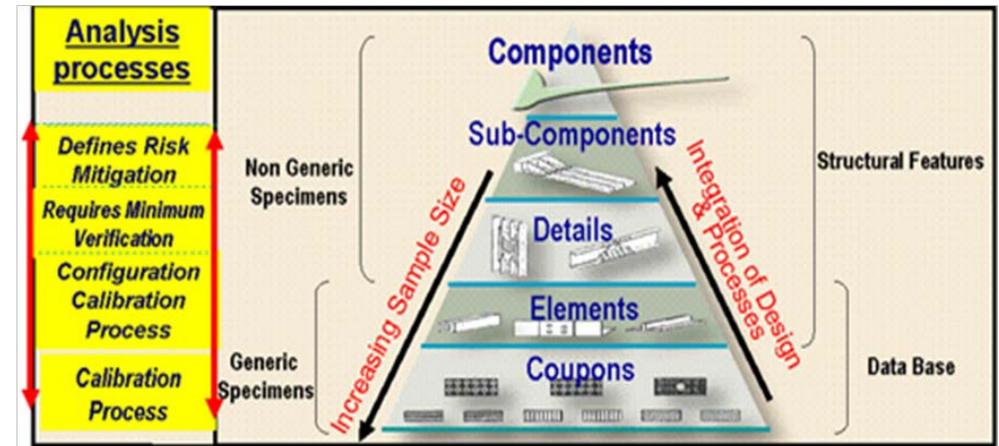
Project 5.7: Tailored Fiber Placement for Complex Preforms

Motivation

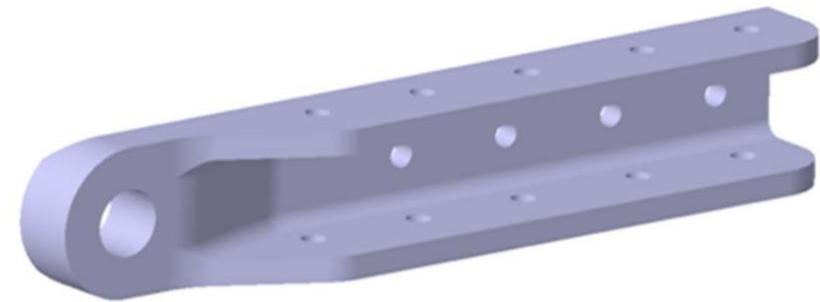
- Tailored Fiber Placement (TFP) offers a novel approach to optimize fiber architecture for the fabrication of complex, structural parts
- Technology not only offers new routes for weight reduction via metal substitution, it also offers cost reduction through minimization of material scrap and reduced labor.
- However, lack of commercial or non-proprietary structural performance data and robust analytical tools used to optimize fiber architecture and predict performance.
- This project is designed to develop the confidence and ability to take full advantage of TFP to fabricate primary, highly loaded structure and integrate features such as metallic fasteners.

Project 5.7 Objectives

- Development and demonstration of novel analytical tools applied to analysis of TFP preforms to be compared against commercial Finite Element Analysis (FEA) tools;
- Development and demonstration of a building block approach using coupons and sub-elements to optimize the design of a more complex component;
- Demonstration that optimized fiber orientation using TFP can exceed performance of conventional textile composite materials and can open new applications currently limited to metallic;
- Determine performance and cost benefits of the TFP process as compared to metallic and conventional textile composites.



Component Development via Building Block Approach



5.7 Project Partners

Organization

- Airbus
- Lockheed
- ZSK
- MSU
- UDRI

POC

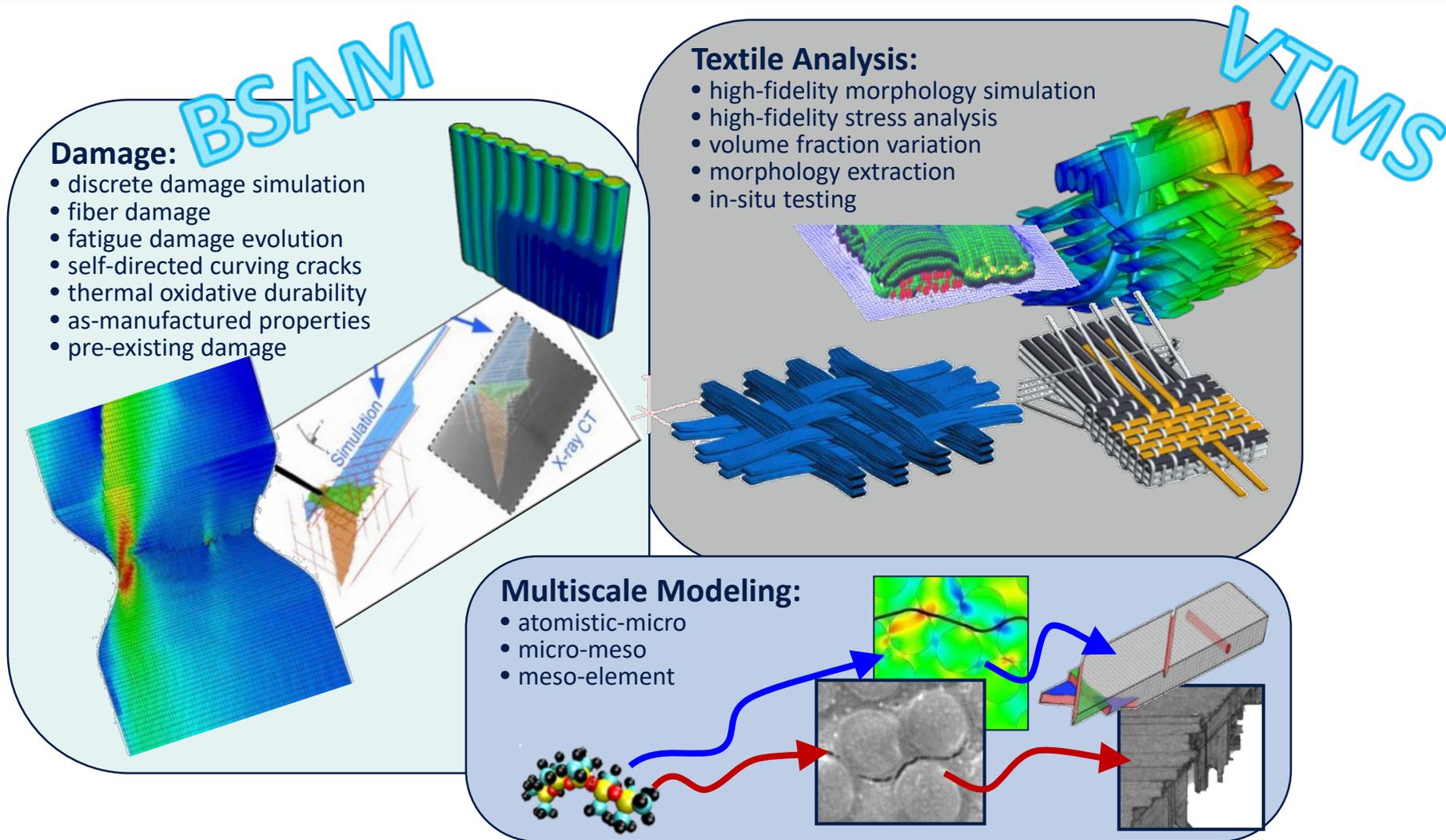
Amanda Simpson (amanda.simpson@airbus.com)
Bob Koon (robert.w.koon@lmco.com)
Nick Mattina (nick@zskmachines.com)
Mahmoodul Haq (haqmahmo@egr.msu.edu)
G. P. Tandon (gyaneshwar.tandon@udri.udayton.edu)

5.7 Project Schedule

Sub-Task	Title	Milestone	2019						2020						
			June	July	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	
5.7.1	Project Management		←												
5.7.2	Analytical Tool Development	Milestone 5.7.2.1: Achieve an optimum stitch design that increases the cohesive strength by at least 50% over unstitched baseline laminate	← <i>UDRI</i> (triangle at July, diamond at Dec) →												
		Milestone 5.7.2.2: Predict the ultimate strength and stiffness within 25% of the actual mechanical properties of the test element	← <i>UDRI</i> (spanning Oct 2019 to Feb 2020) →												
5.7.3	Preform Design for Sub-Elements	Milestone 5.7.3.1: Demonstrate that at least one sub-element TFP preform exceeds the strength of a traditional component by at least 10%.	← <i>UDRI, LM</i> (spanning Nov 2019 to Feb 2020) →												
		Milestone 5.7.3.2: Predict the ultimate strength and stiffness of the sub-element within 25% of the actual mechanical properties of the tested sub-element	← <i>UDRI, LM</i> (spanning Oct 2019 to May 2020) →												
5.7.4	Preforms for Bolted Joints	Go/No-Go 5.7.1: Demonstrate that an element TFP preform can exceed bearing strength of a textile based preform by at least 10% and a hardpoint insert provides an additional 10% increase over the TFP preform	← <i>UDRI, LM, MSU</i> (spanning Jan 2020 to May 2020) →												
		Milestone 5.7.4.1: Validate that the analytical models can predict the location of initial failure and predict the failure strength within 25% of measured value	← <i>UDRI, LM</i> (spanning Dec 2019 to May 2020) →												
5.7.5	Complex Preform Part Demonstration	Milestone 5.7.5.1: Demonstrate that a properly designed TFP part exceeds the tensile strength of a textile based preform by at least 10%.	← <i>UDRI</i> (spanning Feb 2020 to May 2020) →												
		Go/No-Go 5.7.2: Demonstrate that the TFP preforms for the complex parts will yield a 10% cost reduction or 25% weight reduction compared to a metallic part	← <i>UDRI, MSU</i> (spanning Feb 2020 to May 2020) →												

▲ Contract signed ◆ RTM6 resin delivered

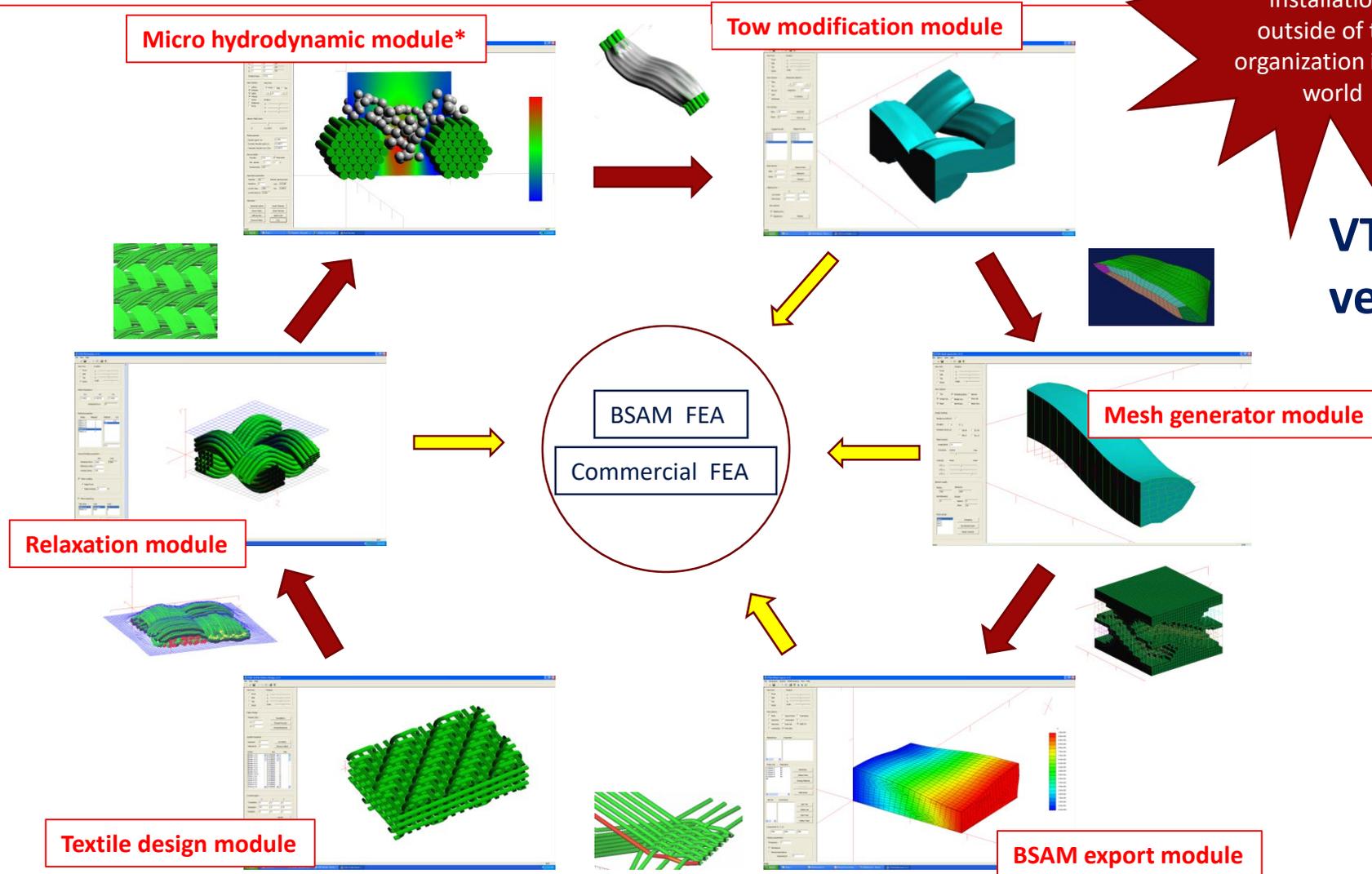
Supporting Software Tools



Virtual Textile Morphology Suite (VTMS)

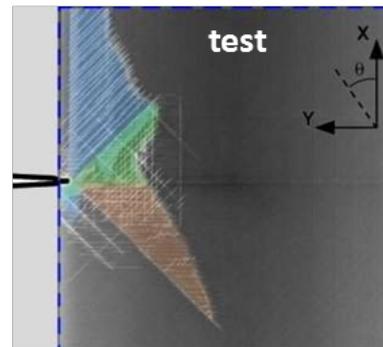
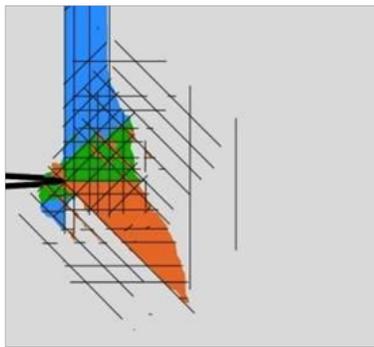
More than 80 installations outside of this organization in the world

VTMS
version 3.0



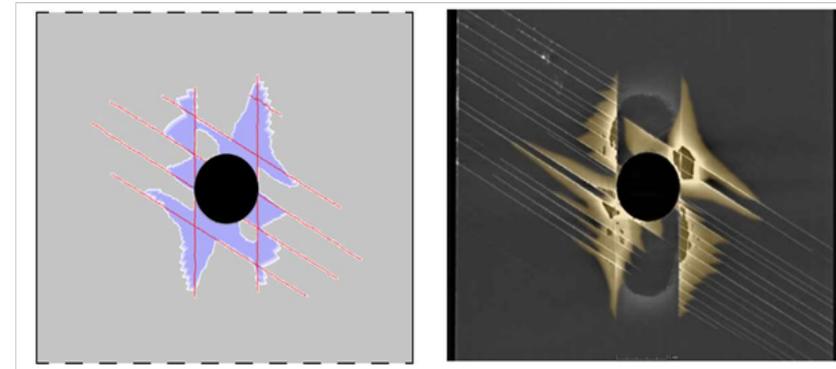
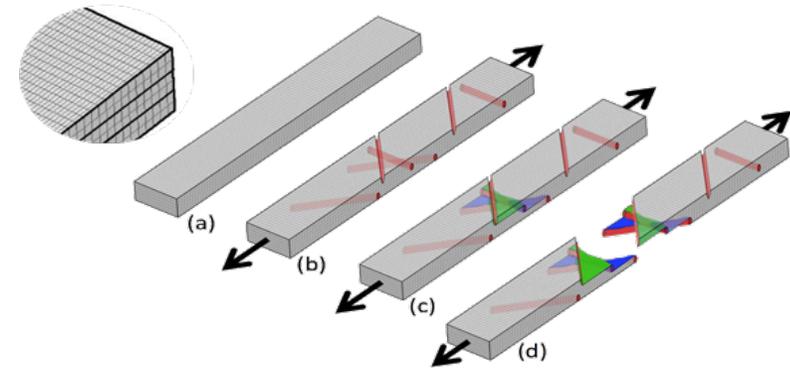
BSAM: 3D Stress Analysis Software System

- Crack insertion via:
 - Regularized X-FEM → “Rx-FEM”
 - Displacement discontinuity represented by step-function enrichment
- Integration schema is preserved
 - Cracks and delams behave well numerically!
- **Initiation** of crack via LaRC-04 (NASA) failure criterion
- **Propagation**: cohesive zone method (CZM)
- **Delamination**: propagation via CZM
- **Fiber failure** via Critical Failure Volume (RXCC) and **progression** via CDM (NASA)



Fracture Mechanics Framework for Composites

Matrix Cracking and Delamination

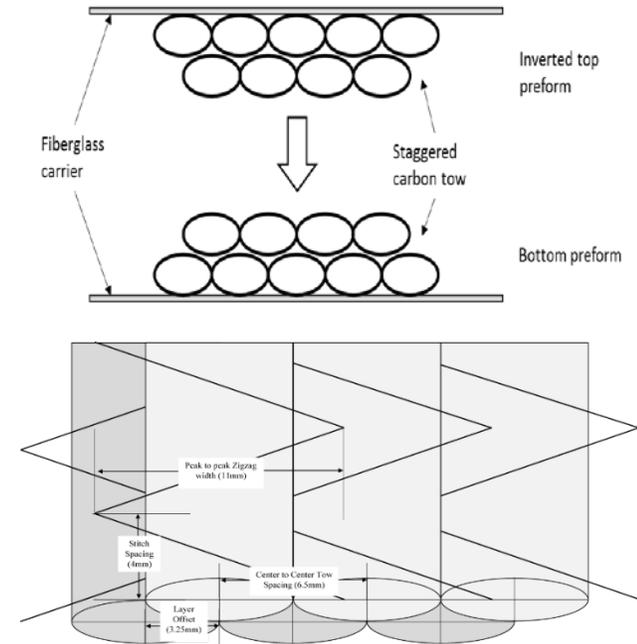


Tension-tension fatigue, 200,000 cycles

$[60 / 0 / -60 / 60 / 0 / -60 / 60 / 0 / -60]_s$

Flat TFP Preforms

- Previous work by UDRI regarding stitching:
 - Work presented at CAMX 2018
- Specimens fabricated using:
 - Zoltek 50k tow, EPON 862, 40 tex Kevlar thread
- 4 laminates constructed.
 - 1 unstitched, 3 various stitch densities
- Fiber path is 0° fiber using two layers of carbon tow per half, tow spaced at 6.5mm apart.
 - 2nd layer offset by 3.25mm
- Stitch tension upper is 2.1 N, lower thread tension 0.65 N.
- Peak to peak zigzag of 11 mm to hold tow in place.



	Preform 1	Preform 2	Preform 3
Preform Stitch Spacing (mm)	4.4	4.0	3.6
Joining Stitch Spacing (mm)	3.7	3.5	3.3
Per Layer (stitch/sq.cm.)	3.5	3.8	4.3
Through Center (stitch/sq.cm.)	7.3	8.2	9.2
Through Layer 1 (stitch/sq.cm.)	14.3	15.9	17.7
Through Layer 2 (stitch/sq.cm.)	10.8	12.0	13.5

Influence of Stitch Density on Mechanical Performance

Mode I Fracture Toughness (ASTM D5528)

Stitch density	G _{1c}
Unidirectional	0.718
90% (7.3/cm ²)	1.686
100% (8.2/cm ²)	2.288
110% (9.2/cm ²)	1.965

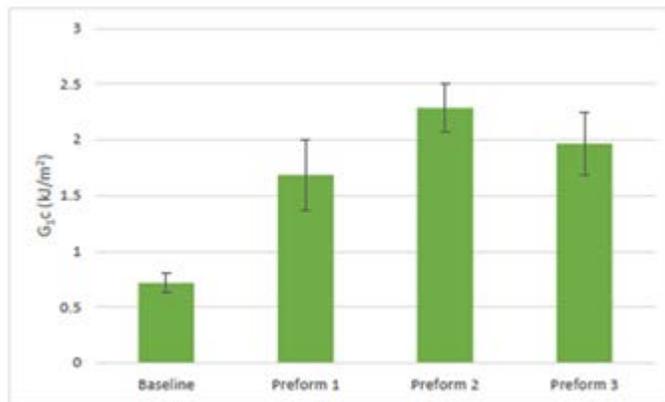
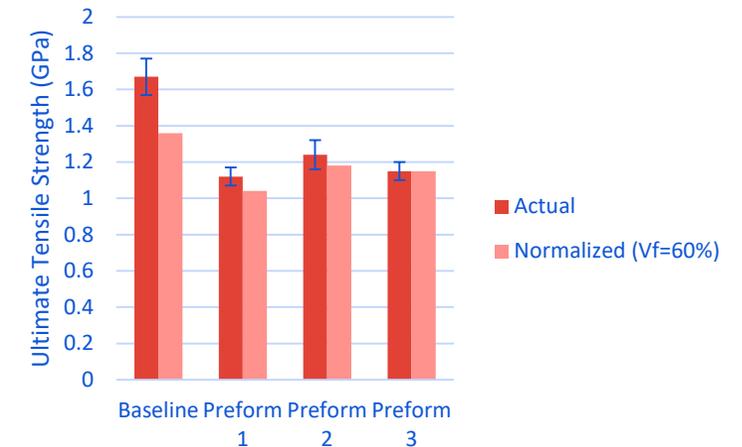
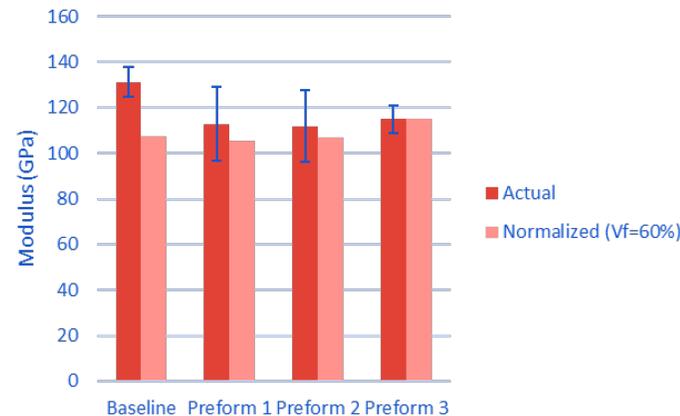


Figure 9. Average fracture toughness of test laminates

Uniaxial Tension (ASTM D3039)

Modulus	GPa	UTS	GPa
Baseline	107.28	Baseline	1.36
Preform 1	105.35	Preform 1	1.04
Preform 2	107.1	Preform 2	1.18
Preform 3	114.87	Preform 3	1.15



- **Mode I fracture toughness improved by more than 50%**
- In-Plane Modulus is relatively unchanged
- Small knockdown in uniaxial strength

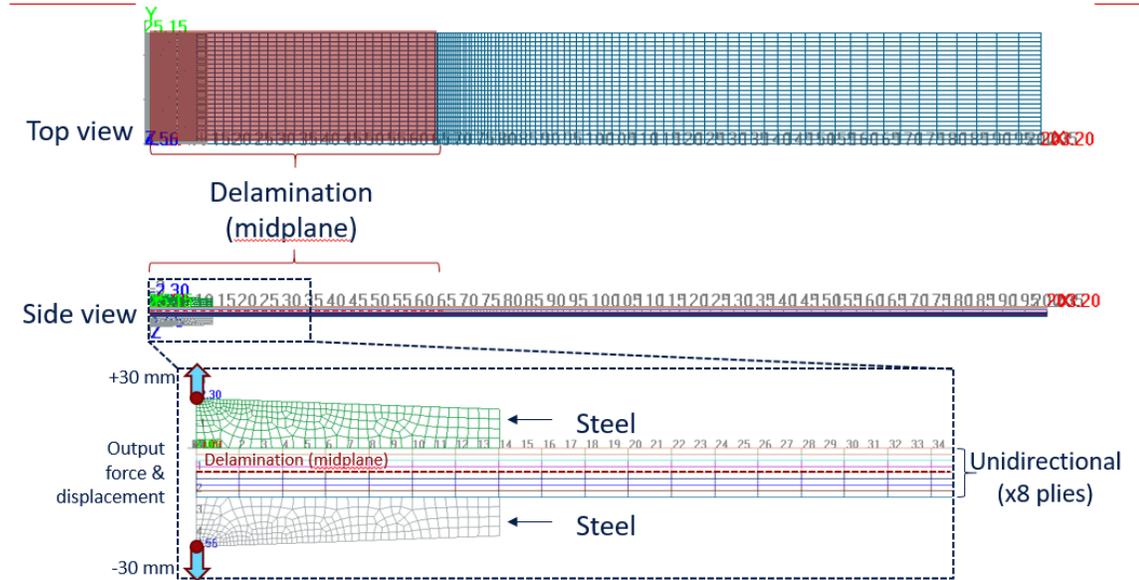
Computational Model Set Up: Mode I Testing (DCB)

Initial model (ASTM)

Modified



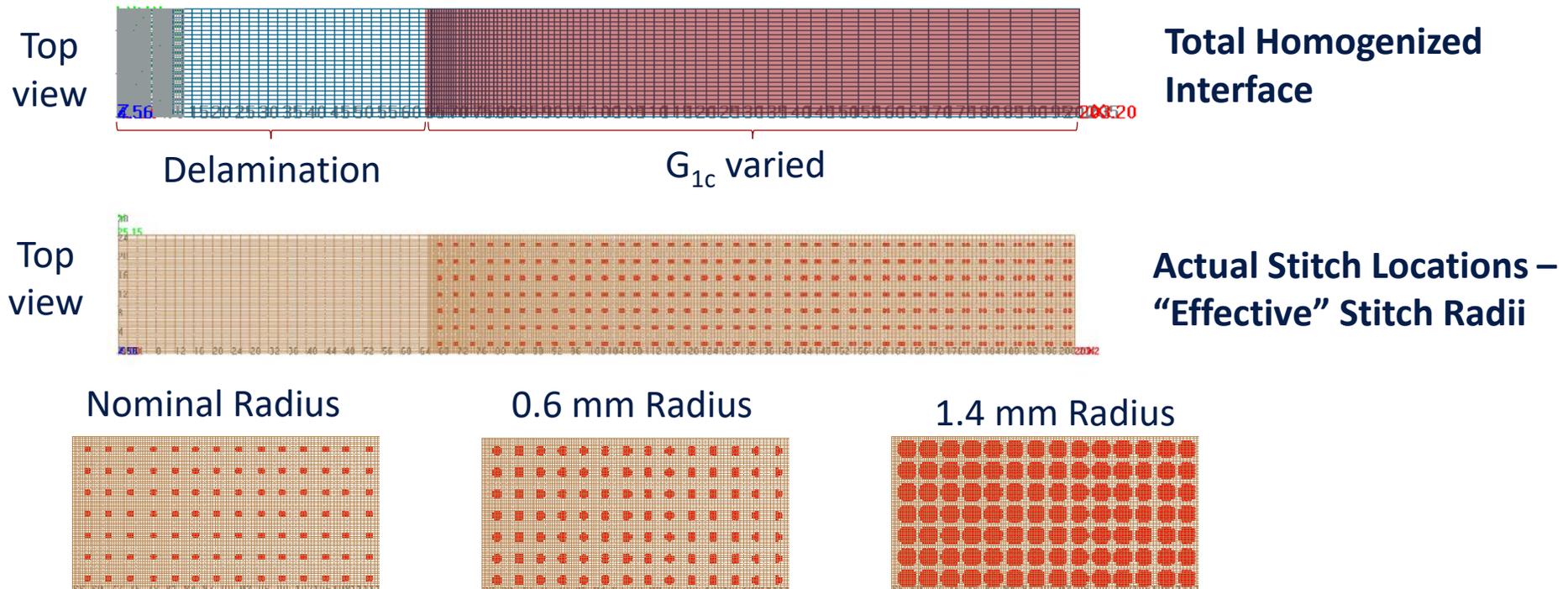
1 inch



Preliminary Model Discussion

- Modeling each stitch discretely
- Model “1D” element embedded in location of stiffness to modify strength of interface
- First order approximation – Homogenized cohesive interface
 - Additional models could have “discrete” stitch regions
- Fiber orientation of tow applied on element by element basis to capture “TFP” architecture effect
- Material properties combination of measured values and R.O.M approximations from literature.

Different Model Construction Types



- Different stitch densities were simulated by varying mid-plane's G_{1c} (from experimental data) for homogenized model
- Different stitch densities were directly input into the “effective” stitch radii model – with effective radii varying from 0 to 1.4 mm
 - requires a “theoretical” calculation of toughness for both approaches

Toughness Analytical Estimate

Initial Model Assumptions

- Consider each ply as homogenous orthotropic
- “Stitch” is stretched straight across span of specimen thickness
- Utilize generic Kevlar stitching thread properties
- Crack growth is self similar
- Linear-Brittle fracture response, with fracture leading to release of all strain energy in stitch after breaking
- Utilize principle of energy super position

$$G_{IC-Eff\ Fib} = \sigma_{stitch} * \epsilon_{stitch} * \frac{\# \text{ Fibers}}{\text{Unit Area}} * A_{fiber} * t_{total\ laminate\ thickness}$$

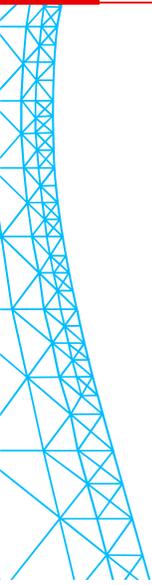
$$G_{IC-Total} = G_{IC-Effective\ of\ matrix} + G_{IC-Effective\ for\ total\ area\ of\ fiber\ breaking}$$

G_{IC} (kJ/m²)

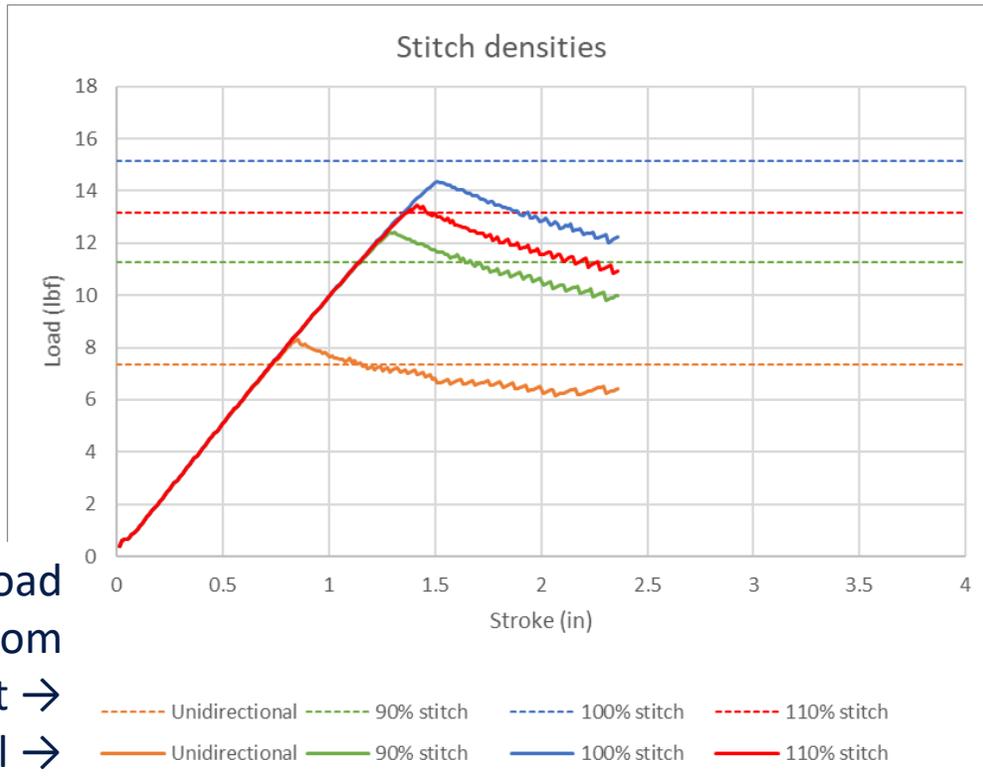
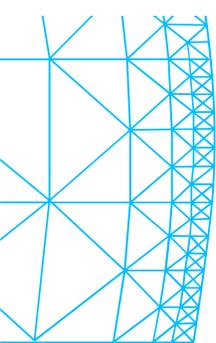
Preform	Measured	Calculated
Baseline (unstitched)	0.718	N/A
Preform 1 (7.3 stiches/cm ²)	1.686	2.272
Preform 2 (8.2 stiches/cm ²)	2.288	2.464
Preform 3 (9.2 stiches/cm ²)	1.986	2.677

- ❑ Analytical model over predicts measured toughness currently
- ❑ Upper bound estimate neglecting porosity, fiber pull-out and other potential defects

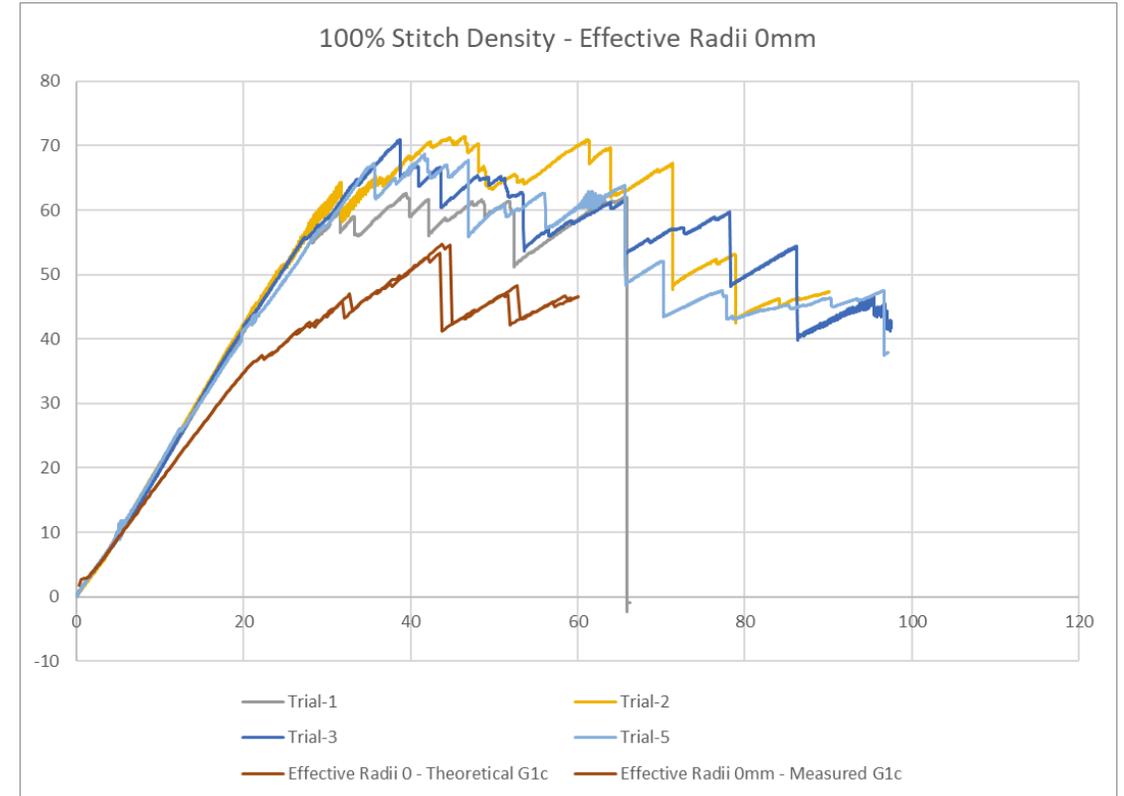
Load-Displacement Response under Mode I Testing



Avg peak load from experiment →
Model →

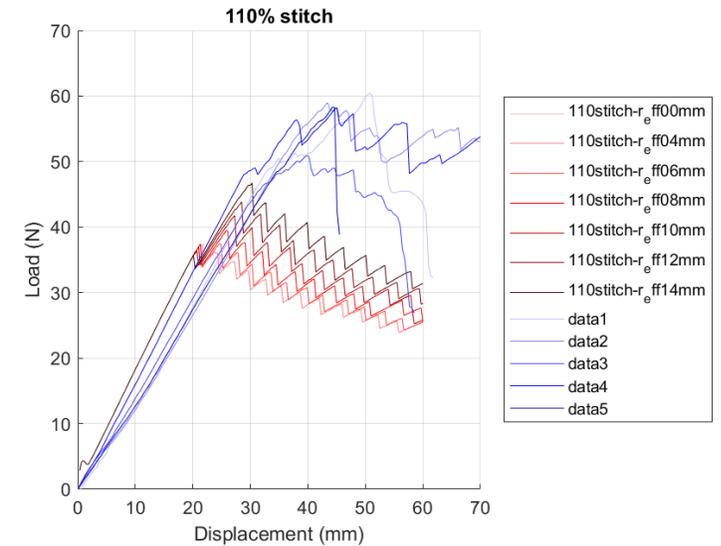
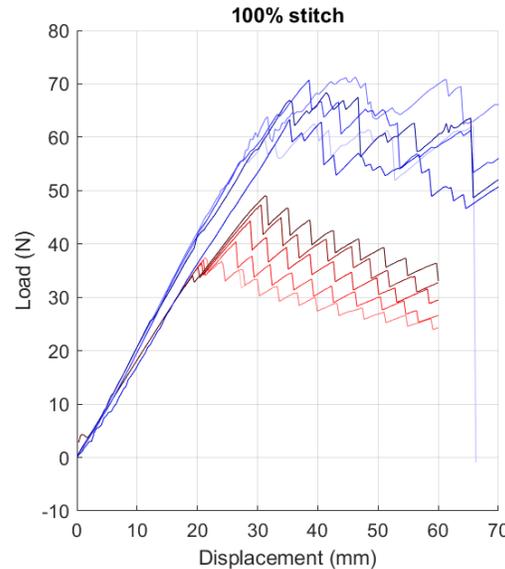
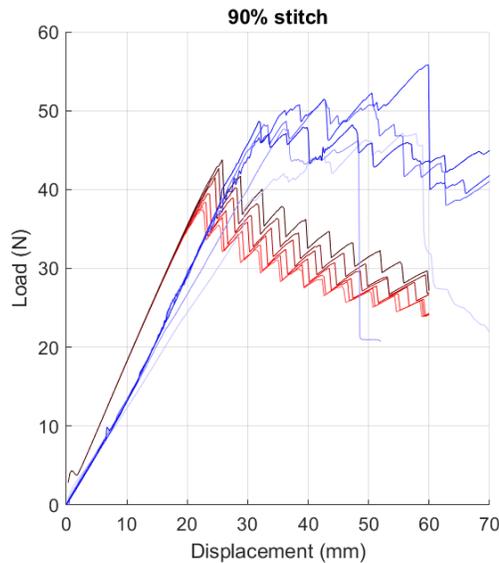


Totally Homogenized Interface



Nominal Stitch Density "Effective"
Nominal Radii Interface

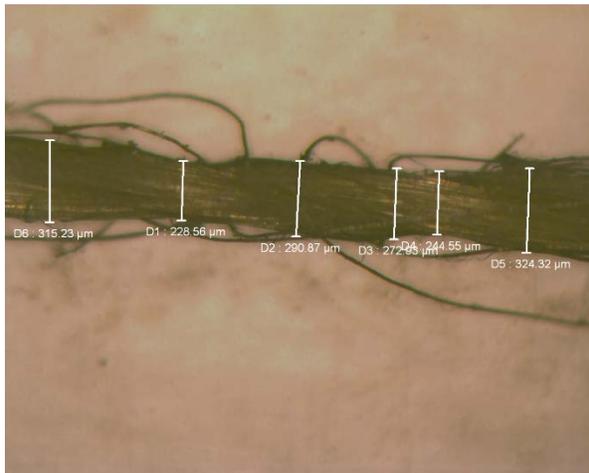
Impact of Effective Radii on Model Response



- As expected having a lowered Y_t in the regions of stitches lead to a lower peak value being predicted
- Models still show better potential to capture load fluctuations in experimental testing compared to homogenized response
- Kevlar Thread tested and preliminary data was incorporated into models looking at the variation of Y_t

Kevlar Stitching Thread Test Data

- Kevlar thread tested to estimate tensile strength
- Using ASTM D7269 Stress at Break Estimated: 1909 MPa
 - Back Calculation of stitch diameter of 188 microns
- Need to determine how to scale effective impact on Y_t in model given that even a “nominal” stitch radii captured in the model is larger than 188 microns

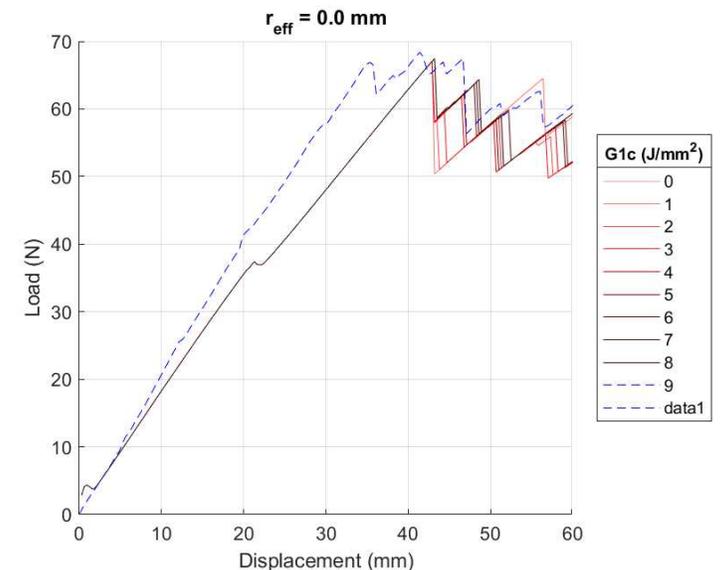
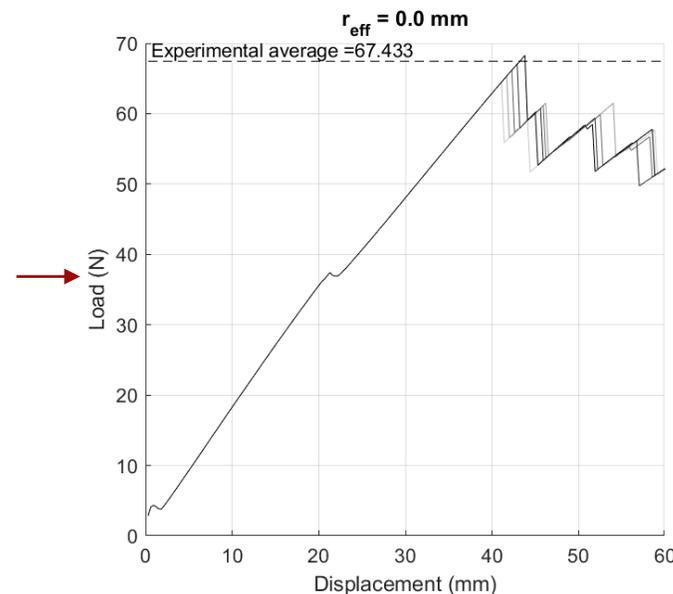
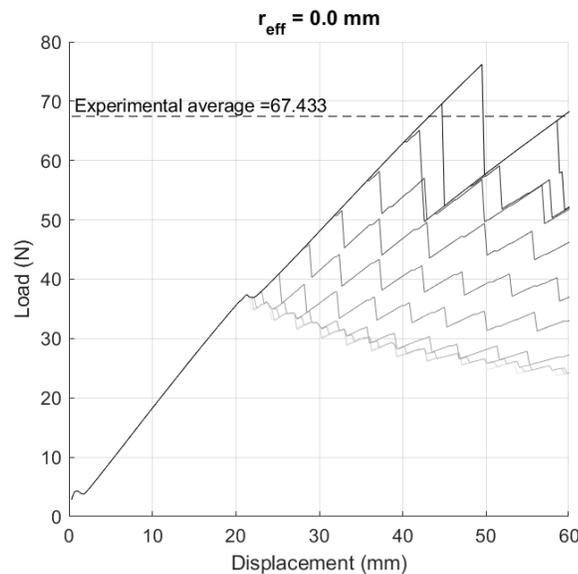


Results Table 1

	Specimen label	Dist. Between Grips (in)	Maximum Tensile extension (in)	Maximum Load (lbf)	Gripping Method	Failure Location
1	Thread 1	2.00	0.26790	11.78453	Bollard Grips	Gage
2	Thread 2	2.00	0.26158	11.67793	Bollard Grips	Gage
3	Thread 3	2.00	0.28926	12.18514	Bollard Grips	Gage
4	Thread 4	2.00	0.24841	11.62563	Bollard Grips	Gage
5	Thread 5	2.00	0.24393	12.34414	Bollard Grips	Gage
	Mean	2.00	0.26222	11.92347		
	Std Dev	0.00	0.02	0.32		
	Coeff of Var %	0.00	6.85	2.70		

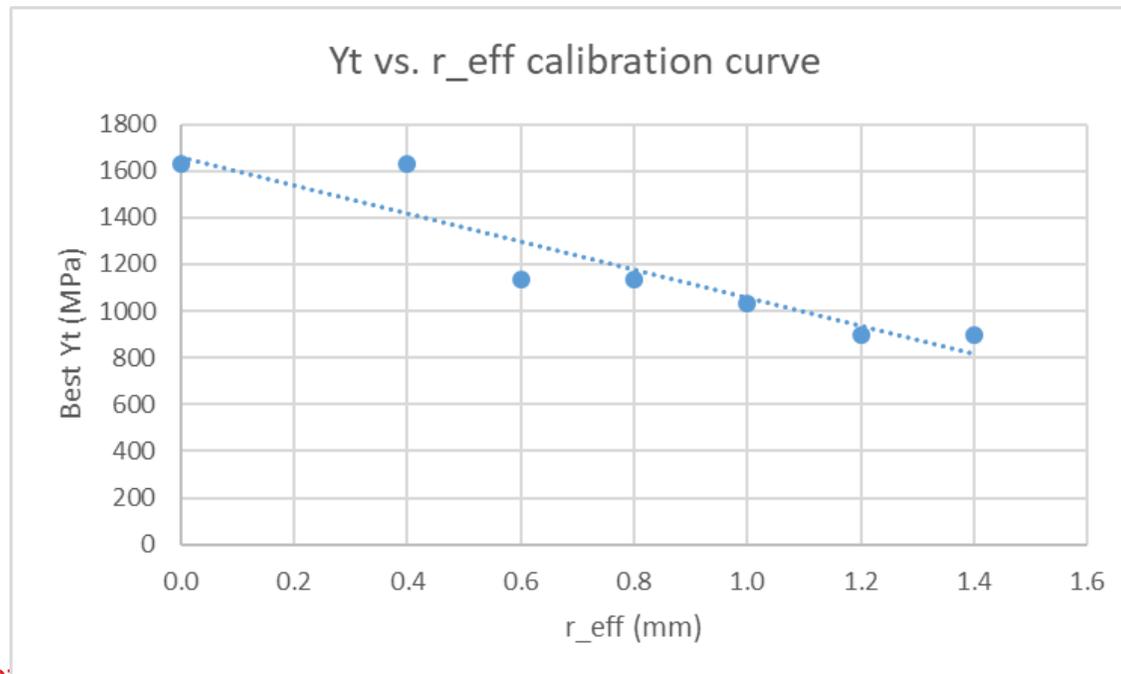
Determination of Y_t Based on “Effective” Stitch Radii – 100% Stitch Density

- 7 r_{eff} 's were selected for exploration through modeling
 - 0.0, 0.4, 0.6, 0.8, 1.0, 1.2, and 1.4 mm
- For each r_{eff} , Y_t was varied until the peak load matches experimental average, then G_{1c} was explored for its impact on qualitative performance of model (i.e. “goodness” of comparison to experimental data)
- At the end, calibration curves will be generated to identify best Y_t and G_{1c} for any given r_{eff}



Effective Stitch Radii “Calibration” Curve

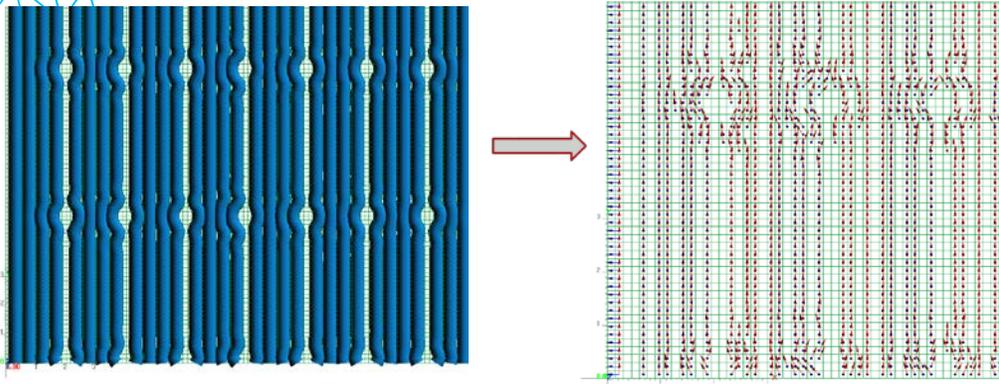
- Process discussed produced a “calibration” curve for varying Y_t as a function of “effective” stitch radii in order to capture peak load of experimental data
 - Points that exhibit same Y_t with differing effective radii indicates that mesh density was low enough that changing radii didn’t change number of nodes captured in cohesive zone region
 - For final calibration would require a dense enough mesh to capture the impact of small variations of effective radii



Fitting parameters:
 $y = -602.89x + 1660.1$
 $R^2 = 0.8565$

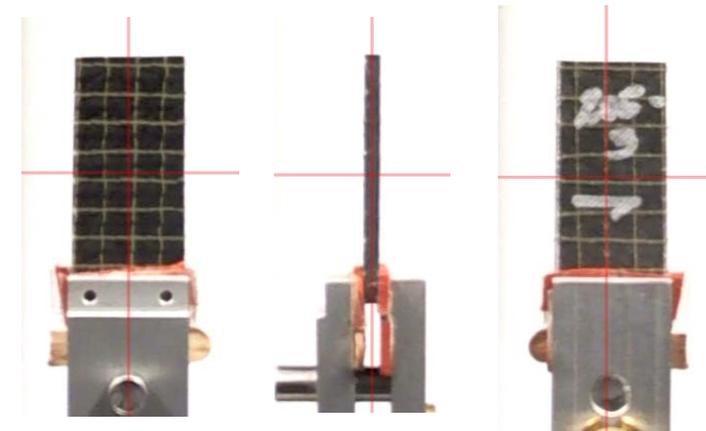
Capturing Fiber Distortions from Stitching Leading to Modulus Variations

- Many factors impact potential fiber distortion
 - head movement and stitching speed, tension of thread holding tows in place, movement during infusion etc
- Model can incorporate variations in fiber orientation based on “theoretical” model or from measured data
- Sample with “nominal” or 100% stitch density Micro-CT’ed



Theoretical Fiber Path with Distortions –
Overlaid on Model

- 0/90/0 panel
- Kevlar stitches in diamond-grid pattern
- ~10 micron resolution



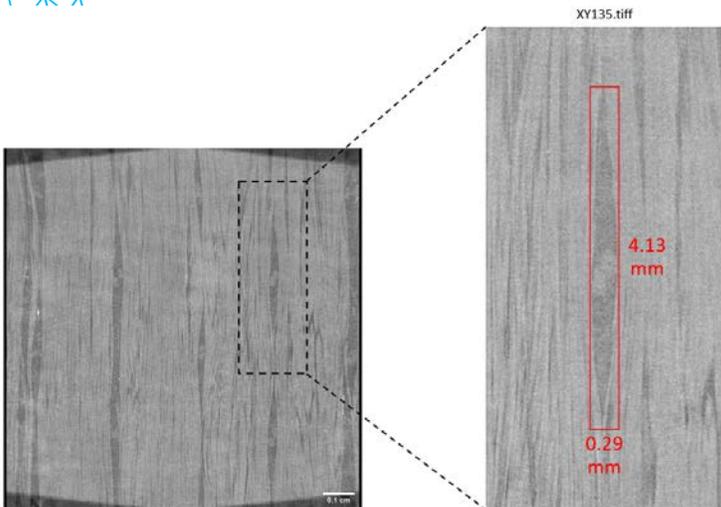
X-Ray CT Characterization



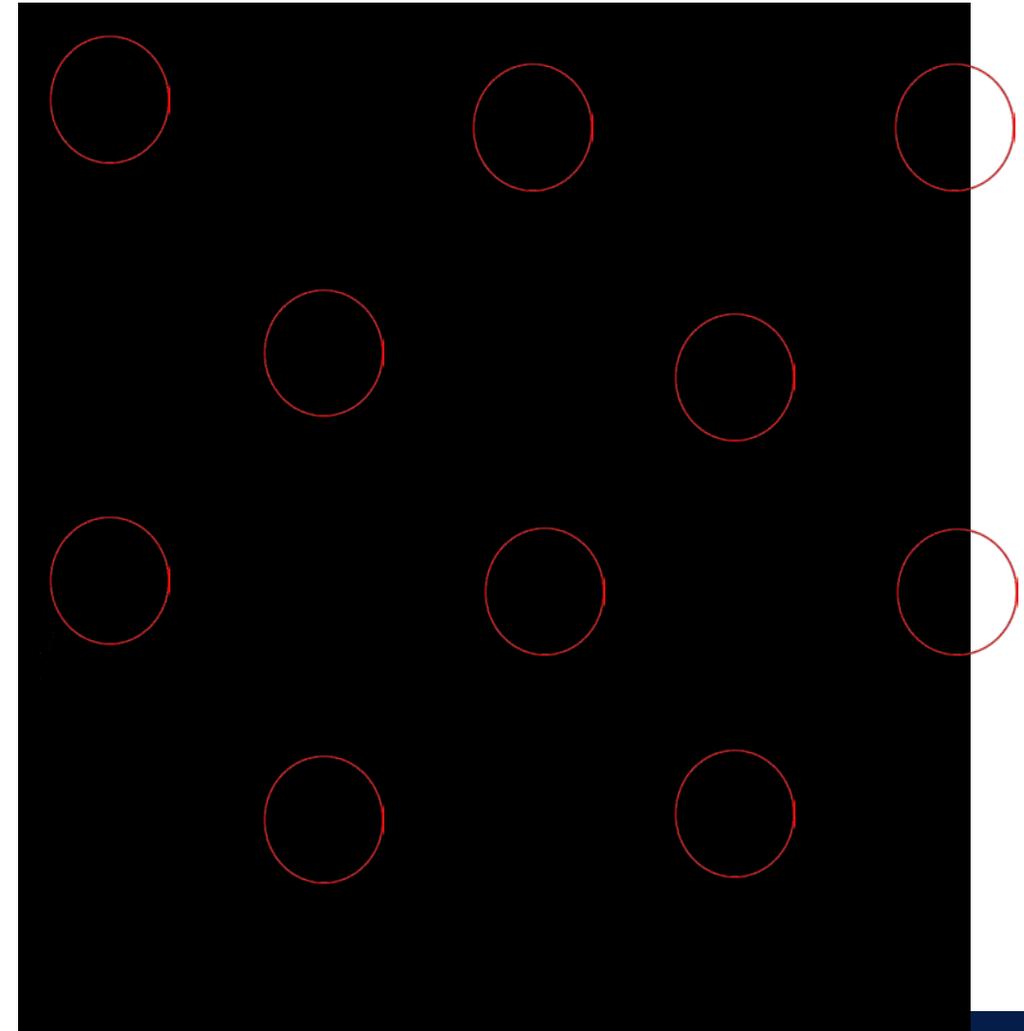
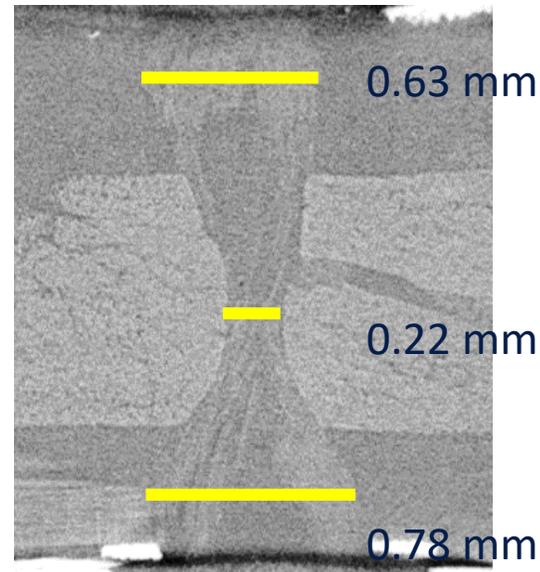
XY plane

- 0/90/0 panel
- Kevlar thread “parts” the carbon fiber
- Carbon fiber “pinches” the Kevlar thread
- Measurements made on “diameter” of Kevlar through the thickness and have shown large amounts of variation

Still from Video – XY Plane

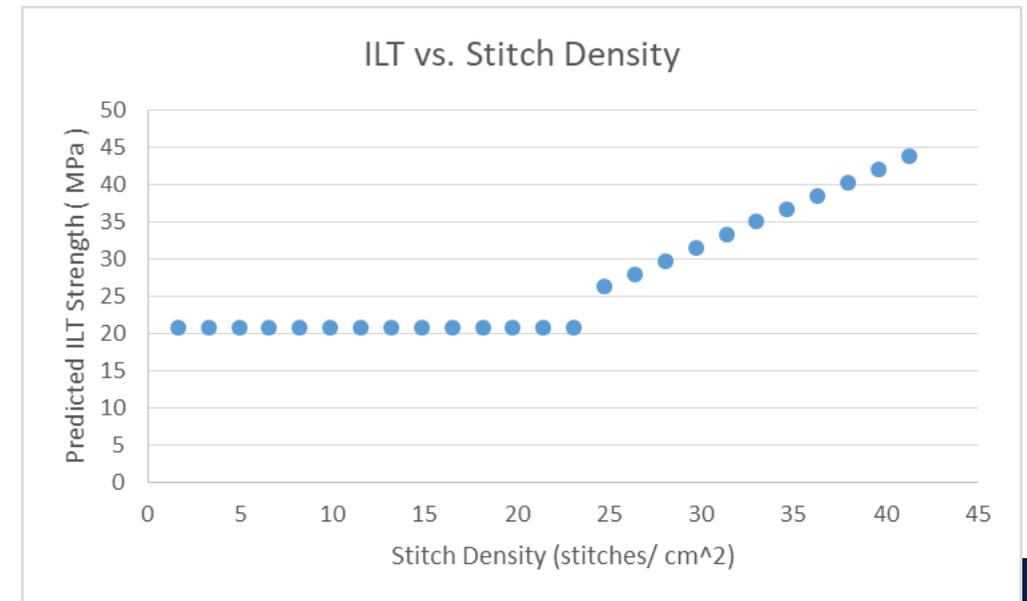
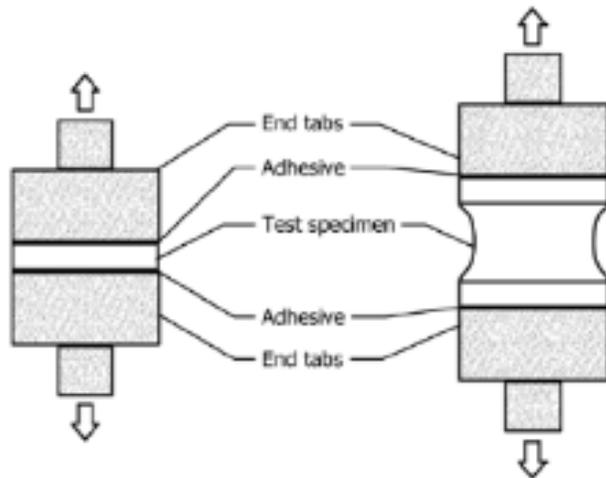


Still Frame – XZ Plane



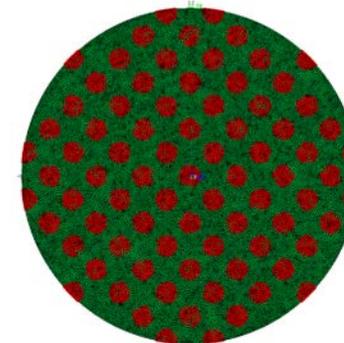
Preliminary Interlaminar Tension Calculations

- ILT specimens fabricated with “nominal” 100% stitch density and tested
 - ILT results showed no improvement in ILT strength with nominal stitch density
 - Baseline unstitched specimen failed at 20.76 MPa \pm 0.39 MPa
 - Stitched with Nominal Density failed at 20.09 MPa \pm 1.57 MPa
- Based on this method to “estimate” required stitch density to see 50% improvement devised thinking of matrix and threads as a series of springs in parallel – requires 32 stitches/cm²



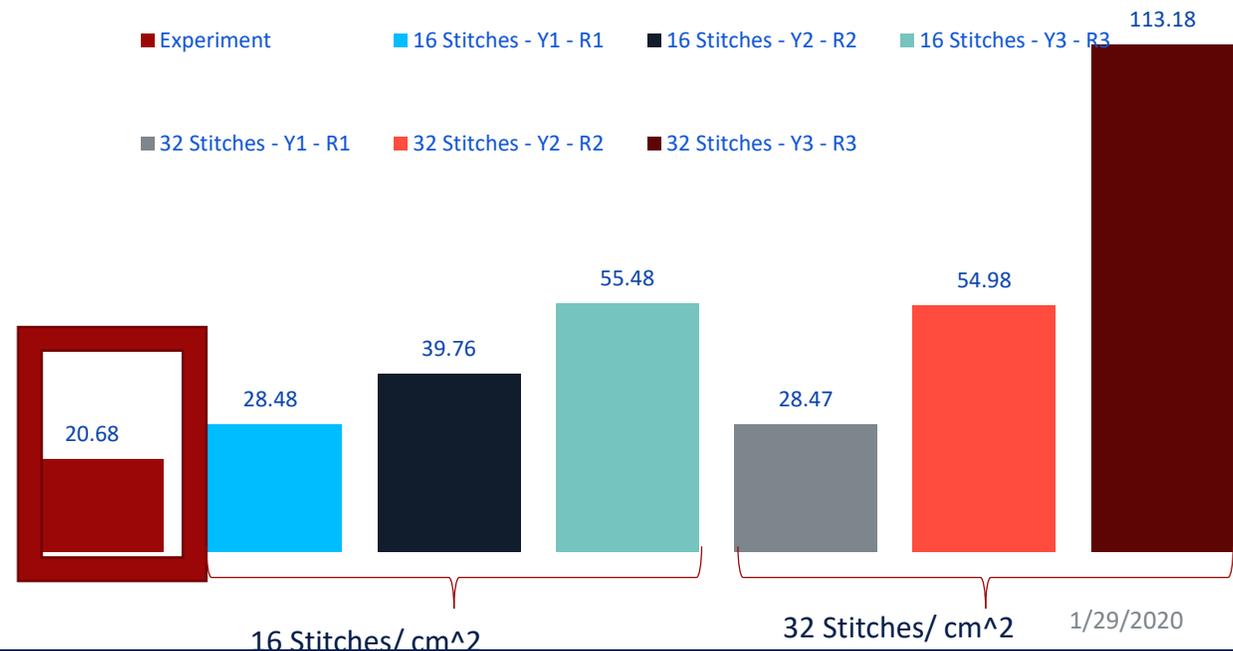
ILT Modeling and Future Testing

- ILT specimens are being fabricated with the increased stitch density to determine if it will increase ILT strength by at least 50%
- An interim model constructed of ILT to look at modeling test specimen
 - Utilized 3 different “effective” radii – and 3 different Y_t parameters from previous “calibration” curve and toughness values
 - Radii: 0 mm, 0.6 mm, 1.2 mm
 - Y_t : 1660.1 MPa, 1418.9 MPa, 1177.8 MPa
- Model shows potential drastic improvements, requires experimental data to validate predictions extreme scenario of 4 fold increase in ILT not expected to occur (Y_t3 R3)



Sample ILT Interface – 16 Stitches/cm² R=1.2 mm

ILT Strength (MPa) as a Function of Stitch Density



SUMMARY

➤ Modeling work simulating Mode I fracture of Zoltek 50k / EPON 862/ Kevlar composites

- Model has shown the ability to capture the experimental response (**Mode I fracture toughness improved by more than 50%**)
- Demonstrated sensitivity to specimen thickness, modulus, G_{1c} , and difference between modeling discrete stitch regions vs. a homogenized interface
- Model explored impact of Y_t or Interlaminar tensile strength on both homogenized interface models and nominal “stitched” region models (with pseudo random stitch locations)
- Implemented and tested automated method for generating effective stitch regions based on stitch locations produced by TFP machine
- Explored impact of local fiber distortion due to Kevlar stitching on in-plane modulus

➤ Interlaminar Tension (ILT) Test Specimens

- ILT didn't see any improvement over baseline material at nominal stitch density of 8.2 stitches/cm²
- From calculations expect 50% ILT strength improvement at stitch density of 32 stitches/cm²

➤ Tested Kevlar Stitch thread for information on strength

Work-in-Progress

Fabrication/Testing

- Fabricated new test panels with stitch density of 16 and 32 stitches per cm² for X-ray CT to quantify fiber distortion (as well as an ILT specimen with Epon 862)
 - Explored impact of polyester holding stitch on spreading of fiber
- Fabricate spiral “doilies” to be put into prepreg lay-up and test in-bearing strength for Lockheed
- Fabricate baseline DBS test specimens without z-stitching
- Begin infusing property generating test articles with RTM6

Analysis

- Conduct analysis of DCB with 32 stitches to predict response, do this for ILT “puck” as well
- Collect RTM6 data from Hexcel and literature to begin modeling work of DBS configurations
- Begin modeling of DBS and varied stitch locations to predict impact of stitching
- Begin modeling of Angled Bracket 4 point bend to predict impact of stitching

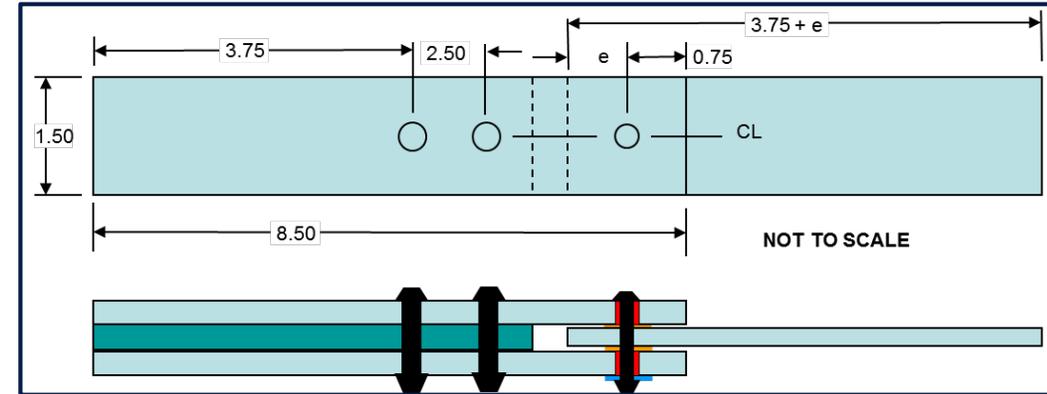
Future Work

❑ Milestone 2: Test Double Bearing Shear using CALE 1 Nominal Dimensions (modify to be 4.0D)

- Finalized plan to test quasi-isotropic laminates
[45/90/-45/0]_{2s}, [45/-45/02/90]_{2s}
- Test according to ASTM D5961 Proc A
- Reaction skins would be hardened steel
- Working to identify hardened steel for bolts, nuts, etc.
- Will test baseline laminate without z-stitching to show improvement of stitching

❑ Milestone 3: Second round of testing would look at effect of stitching on angle bracket

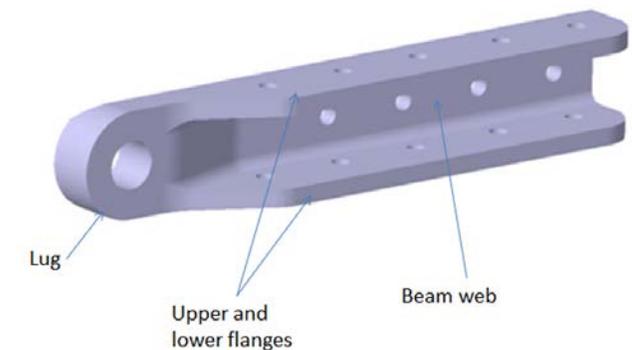
- Bracket with 4 Point bend test to look at impact of stitching on radial portion (1/4" radius)
- Test according to ASTM 6415
- Explore ability to prevent damage growth critical to complex part



Double Bearing Shear (DBS)



Angle bracket



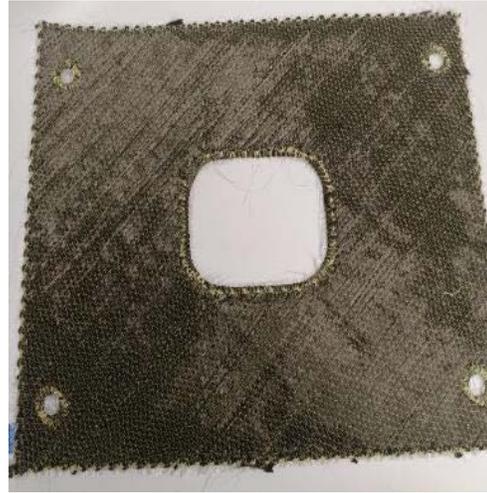
Notional complex part

ACKNOWLEDGEMENTS

- Brian Rice
- Scott Huelskamp
- Ray Rawlinson
- Jayson Lotz
- Mathew Cameron
- Caleb Tanner
- Jeff Nangle
- Nathan Ball
- Brian Said

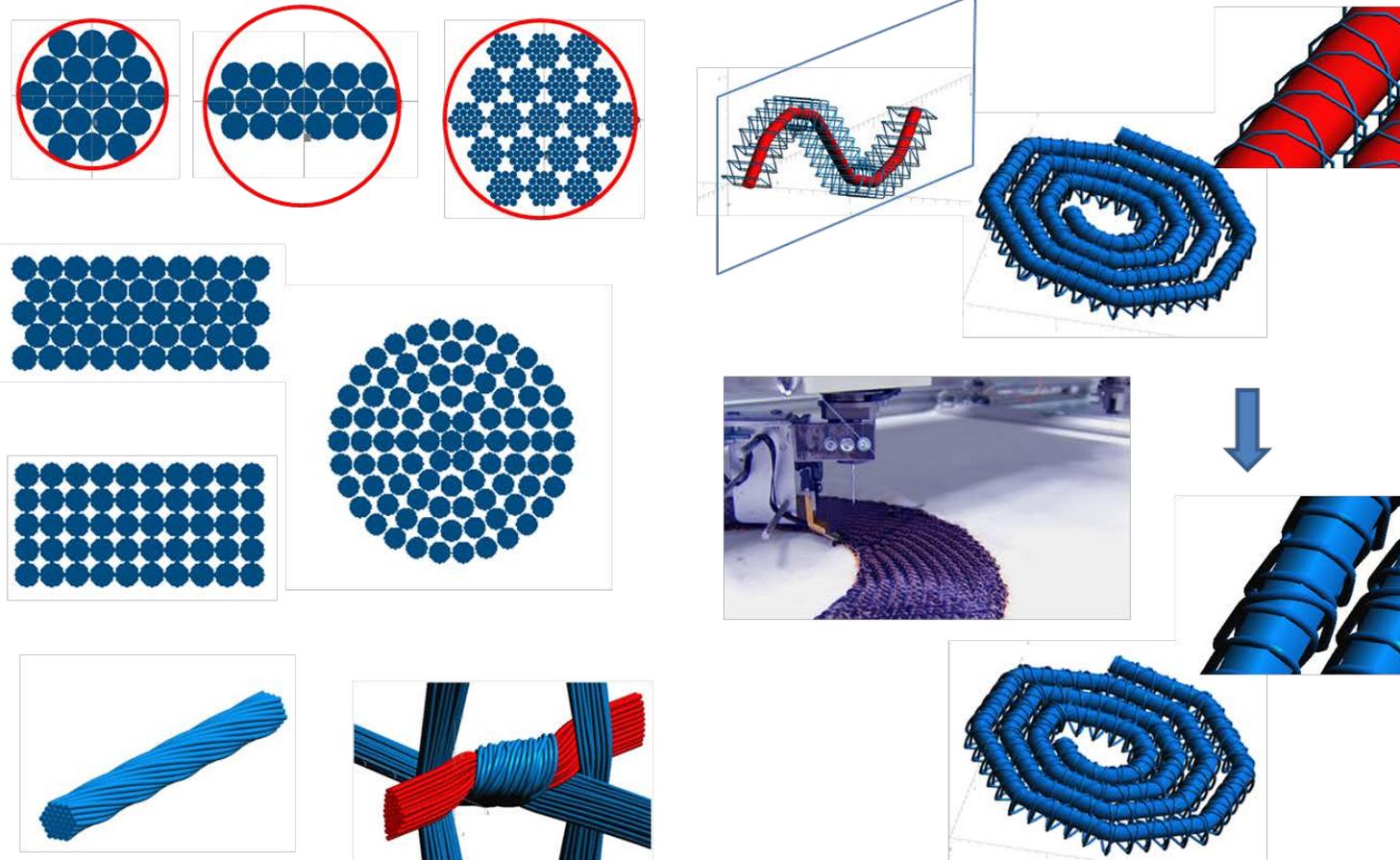
BACK-UP SLIDES

UDRI Preforms



Fiber Packing Patterns

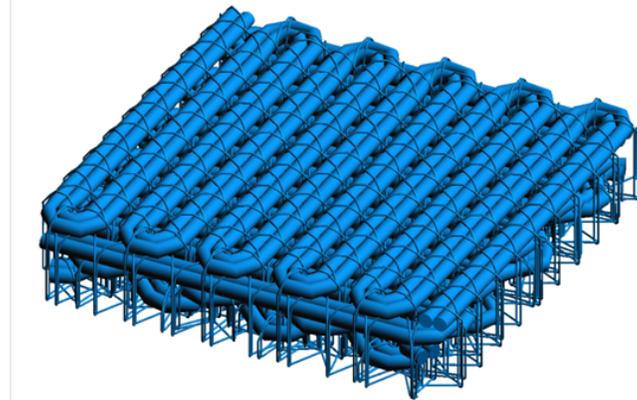
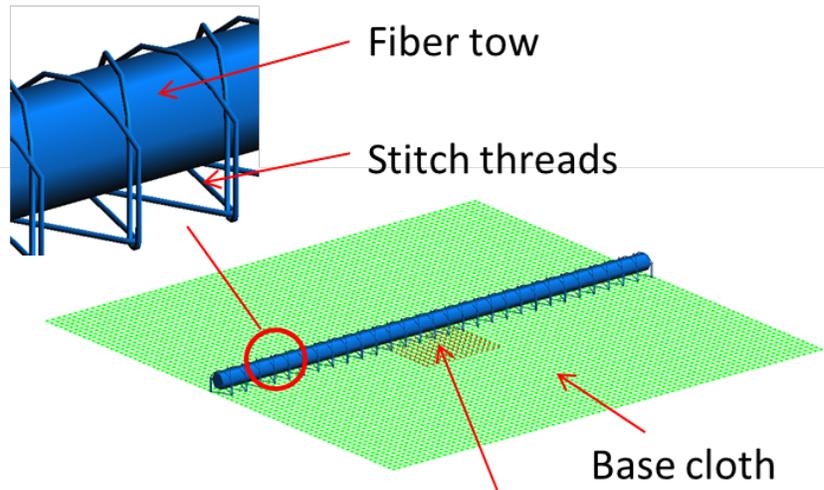
Initial configure of Laystitch created by VTMS
Tow path is created using Sketch feature in VTMS



Twisted fiber bundle

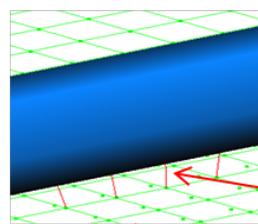
Final configure of Laystitch after relaxation

Draping Simulation of Laystitch in VTMS



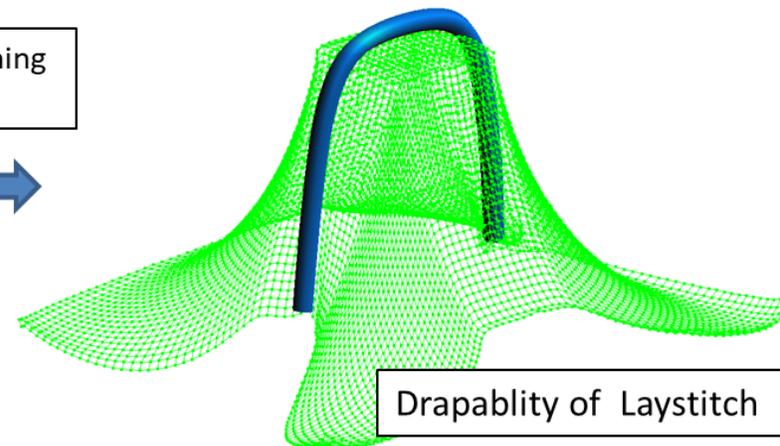
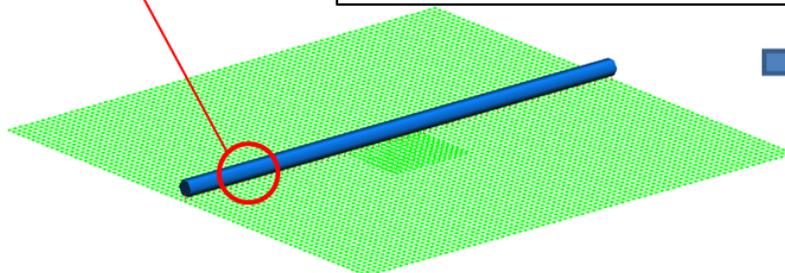
Basic concepts :

1. Fiber tows are reinforcements to the base cloth
2. Stitch threads glue fiber tows to the base cloth
3. Draping of the base cloth with fiber reinforcements.



Rigid mold

Stitch threads are replaced by stitching bonds (node-to-node) for simplicity



Fiber Orientation and Volume Fraction of A Stitched TFP Laminate For Homogenization Approach

