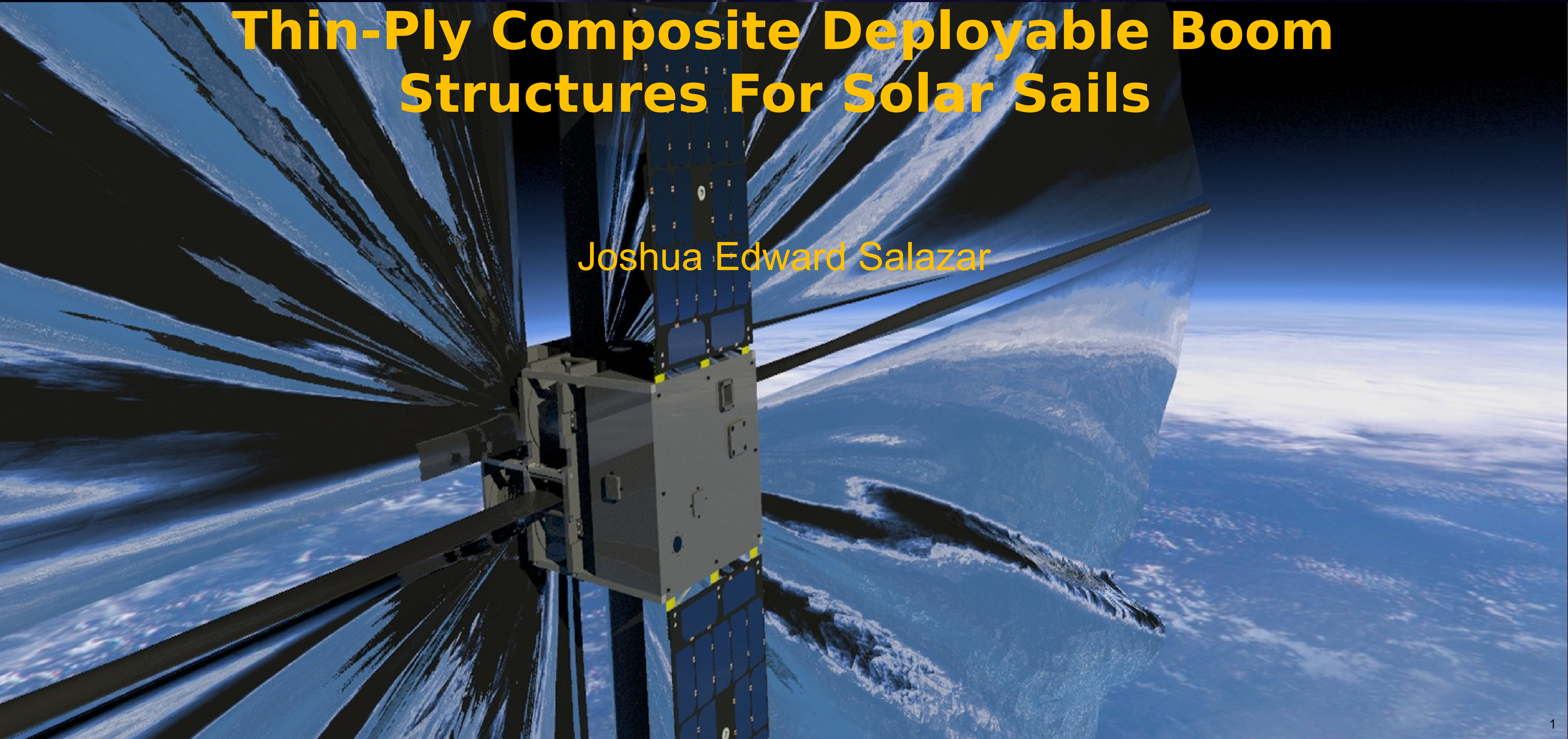
Thin-Ply Composite Deployable Boom Structures For Solar Sails

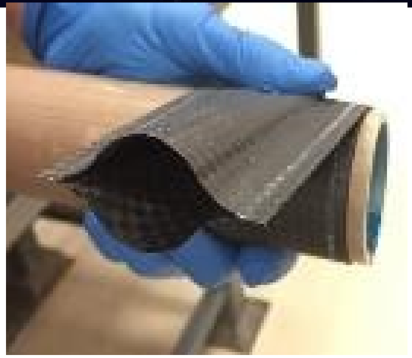
Joshua Edward Salazar



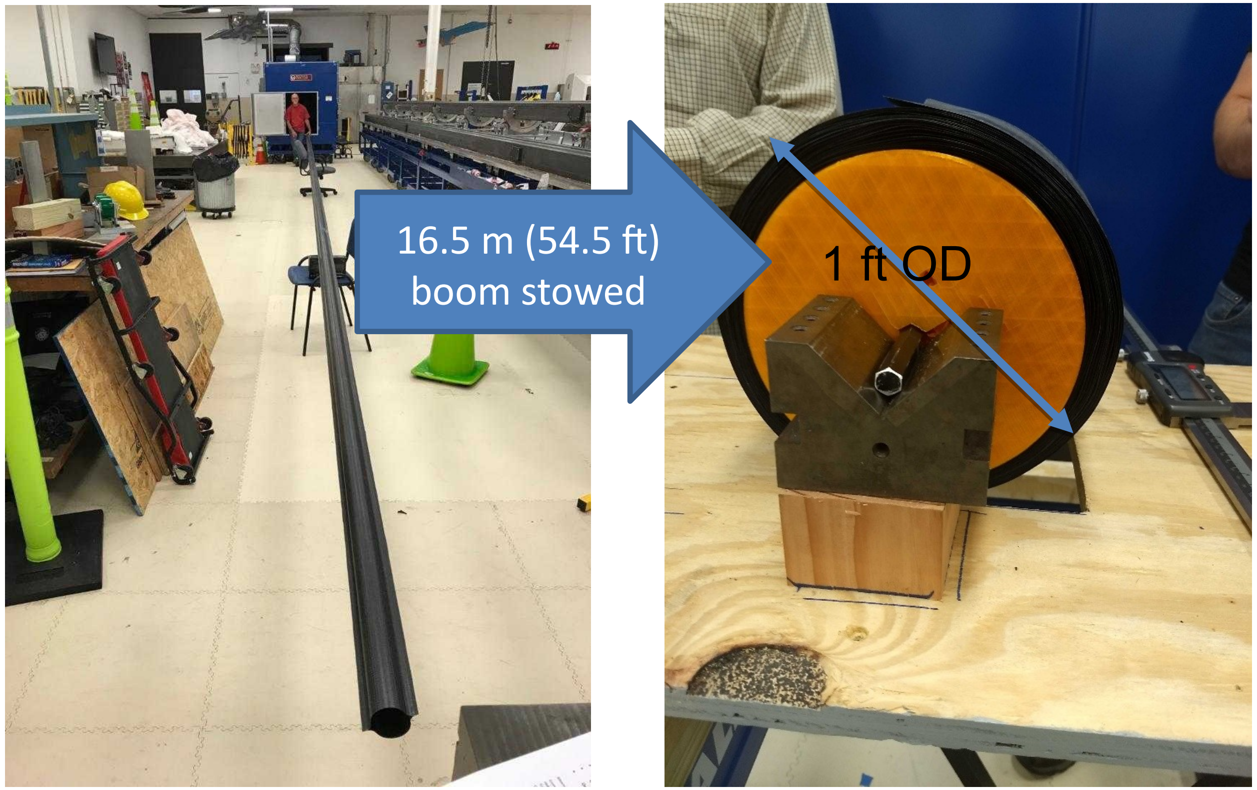
Thin-Ply Deployable Composite Booms

- Carbon Fiber Reinforced Polymers (CFRP) composites
- The Carbon fiber fabric is a spread tow fabric which allows Individual plies to be much thinner
- Single ply thicknesses around 30-60 um
- Laminate thicknesses around 120-300 um
- 54.5 ft boom stowed in less than 1 square foot

Rollable HSC booms under development at LaRC



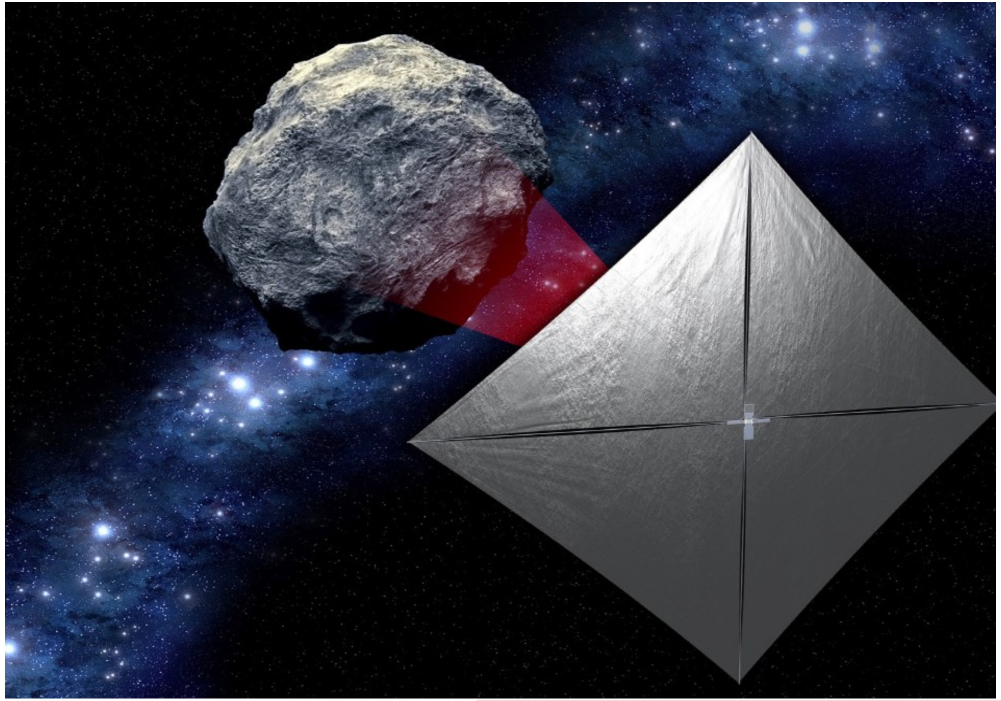
CTM boom partially rolled

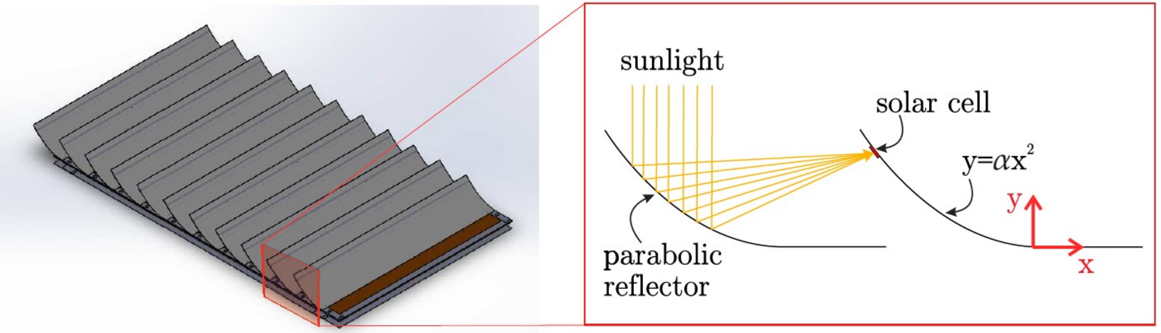


16.5 m (54.5 ft) boom stowed

Motivation and Applications

- Solar Sails:
  - Near Earth Asteroid (NEA) scout is a 6U cubesat mission set to fly with the SLS Orion EM-1 mission as a secondary payload.
  - 7.5 meter metallic Triangular roll able and collapsable (TRAC) booms
  - High CTE of metallic booms can cause deformations that severely limit the length of the booms
  - LaRC's Advanced Composites Solar Sail System (ACS3) 12U CubeSat solar sail flight demonstrator to fly in 2021 will have deployable composite booms.
- Drag sails to quickly de orbit satellites
- Deployable Antennas
- Parabolic reflectors
- Foldable panels / deployable surfaces



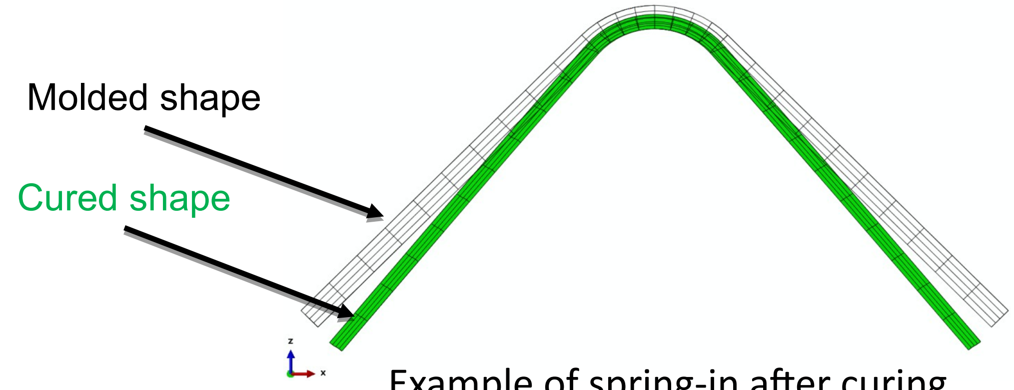


Bosi, F., Schlothauer, A., Pellegrino, S., Cure-induced deformation of ultra-thin composite laminates, AIAA SciTech Forum, 8-12 (2018)

Technology Risks

Technology Limitations:

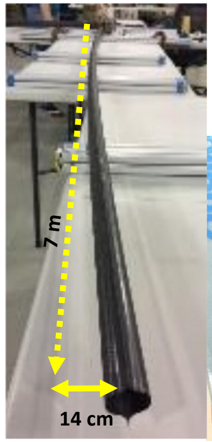
- **Loss of dimensional stability during manufacturing**
  - The manufacturing of high precision structures is limited by cure stresses causing relaxations and spring-in of curved parts
- **Loss of dimensional stability during stowage**
  - During stowage the composite is held in a high deformation state and is expected to have some amount of stress relaxation as a result of this. This stress relaxation can cause dimensional changes in the structure once released from stowage which could reduce load bearing capabilities
- Load bearing capabilities of thin-ply composite structures is highly dependent on cross section and length dimensions.
- The dimensional stability of both manufacturing and stowage need to be understood to utilize thin-ply deployable composites effectively



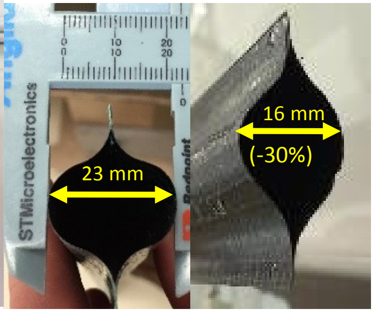
Example of spring-in after curing

Boom axial curvature (bow) developed after a one month stowage.

Note: Boom design and laminate not being used, shown here for illustrating the risk.



Boom flattens after prolonged stowage = 50% drop in buckling load



Research Objectives

1. Determination of the dimensional Stability during the manufacturing of thin-ply Composites

2. Determination of the dimensional stability of thin ply composites during stowage

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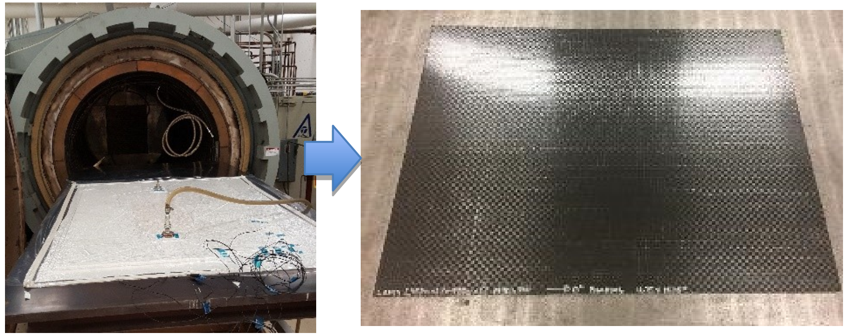
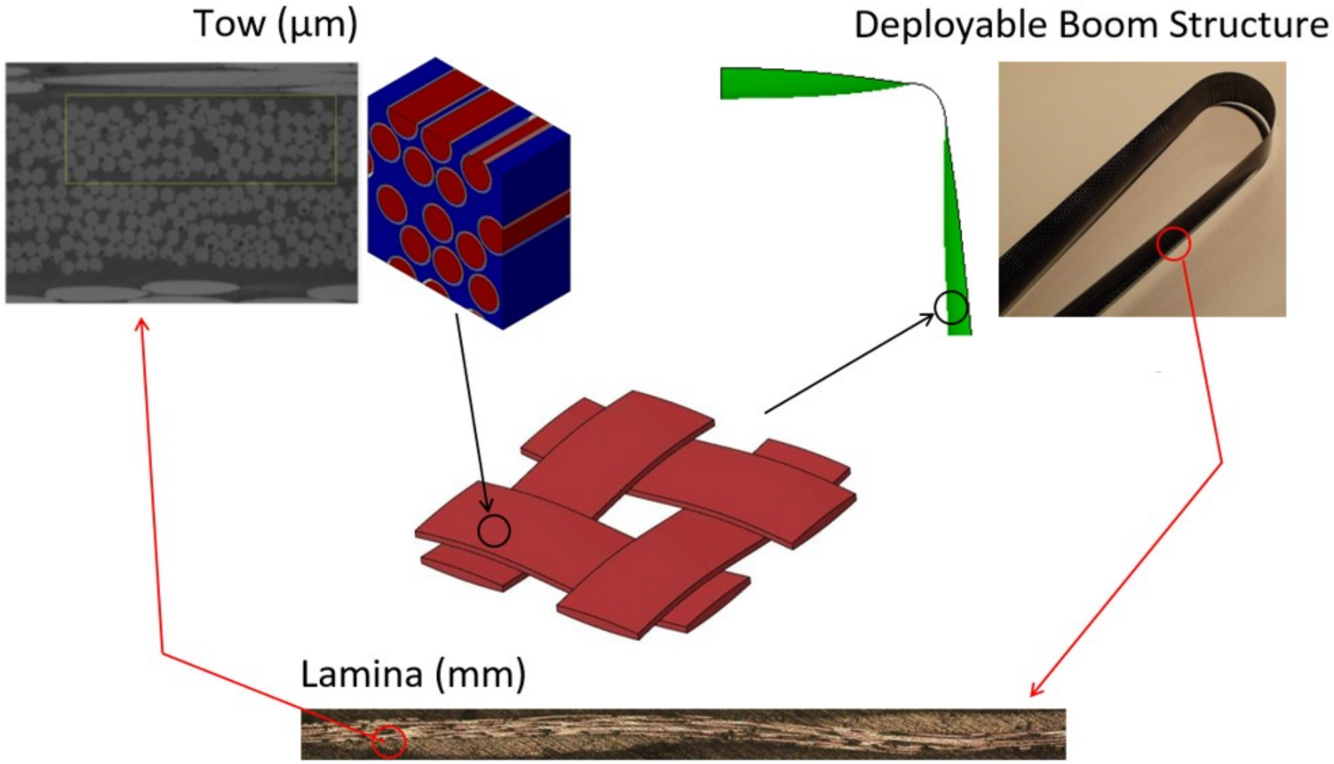
Composite Curing

- Carbon Fiber is impregnated with a viscous resin
- Composite is then placed under pressure and heat
- As the polymer resin cures it shrinks and hardens
- The combination of shrinking and pressure will also cause some amount of flow in the resin





Process Flow For Cure Deformation Analysis

Large number of polymer samples

DSC
Measures the amount of heat the polymer resin is absorbing as it cures

DMA
Mechanical and viscoelastic properties of polymer

Rheology
Can measure how the polymer resin's viscosity increases and how the polymer stiffens as it cures

Material Models & Properties

Cure Kinetics

$$\dot{x} = \frac{Kx^m(1-x)^n}{1+e^{C(x-x_{C0}-x_{CT}T)}}$$

$$K = Ae^{-\Delta E/RT}$$

Flow Compaction

$$\dot{u}_{i,i} - \left(S_{ij}P_{,j}/\mu\right) = 0$$

$$\sigma'_{ij,j} - P_{,i} = 0$$

Modulus development

$$E_r^{`} = \begin{cases} E_r^0 & T^* < T_{C1}^* \\ E_r^0 + \frac{(T^*-T_{C1}^*)}{(T_{C2}^*-T_{C1}^*)}(E_r^\infty - E_r^0) & T_{C1}^* < T^* < T_{C2}^* \\ E_r^\infty & T^* > T_{C2}^* \end{cases}$$

$$E_r = E_r^{`}[1 + a_{Er}(T - T_0)]$$

$$T^* = (T_{g_a} + T_{g_b}x) - T$$

$$T_{C1}^* = T_{C1_a}^* + T_{C1_b}^* T$$

Finite Element Analysis

Stress Deformation:

$$\Pi_P = U + \Omega$$

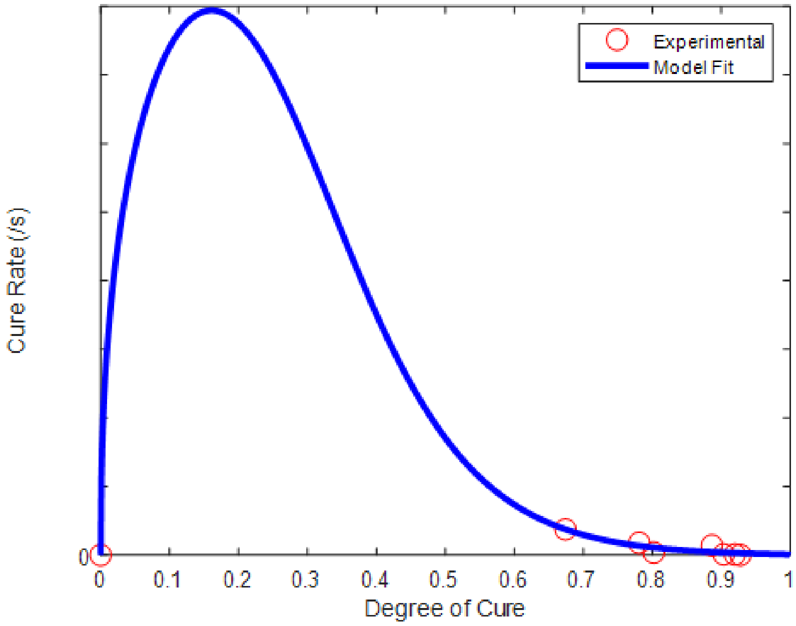
$$\Pi_P = \int_V \frac{1}{2}\varepsilon^T D\varepsilon \, dV - \int_V \varepsilon^T D\varepsilon_0 \, dV - \int_V \varepsilon^T \sigma_0 \, dV - \int_V u^T X \, dV - \int_S u_S^T q_S \, dS$$

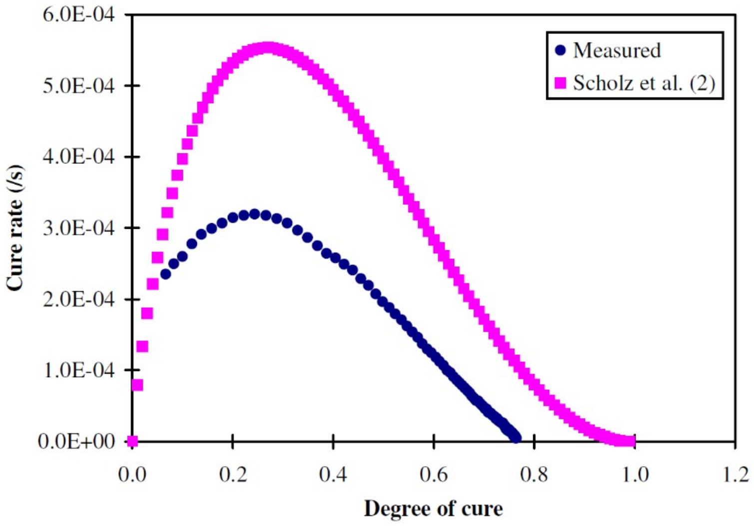
Degree of Cure Curve fitting

- Data obtained gives degree of cure vs time
- Slope between two point gives cure rate
- Plot cure rate vs degree of cure
- Fit model to experimental data

$$\dot{x} = \frac{K x^m (1-x)^n}{1 + e^{C(x - x_{C0} - x_{CT} T)}}$$

$$K = A e^{-\Delta E / RT}$$





ref: Hubert, P., Johnston, A., Poursartip, A., Nelson, K. Cure kinetics and viscosity models for Hexcel 8552 epoxy resin, 46th International SAMPE Symposium and Exhibition, 2341-2354 (2001).

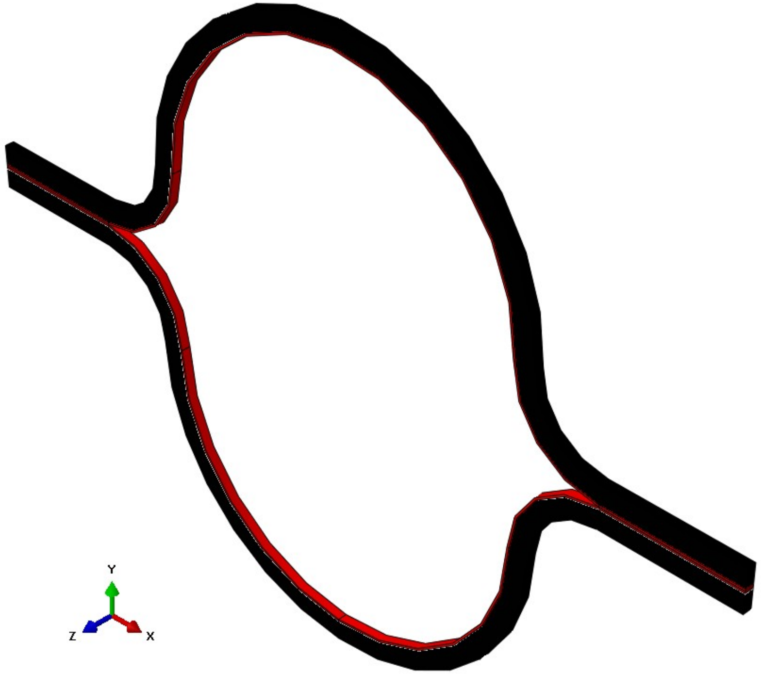
Parameter
Activation Energy (ΔE) - J/mole
Pre-exponential cure rate coefficient (A) - 1/s
First exponential constant (m)
Second exponential constant (n)
Diffusion constant (C)
Critical degree of cure at T = 0 K (x_{C0})
Increase in critical resin degree of cure with temperature (x_{CT}) – 1/K

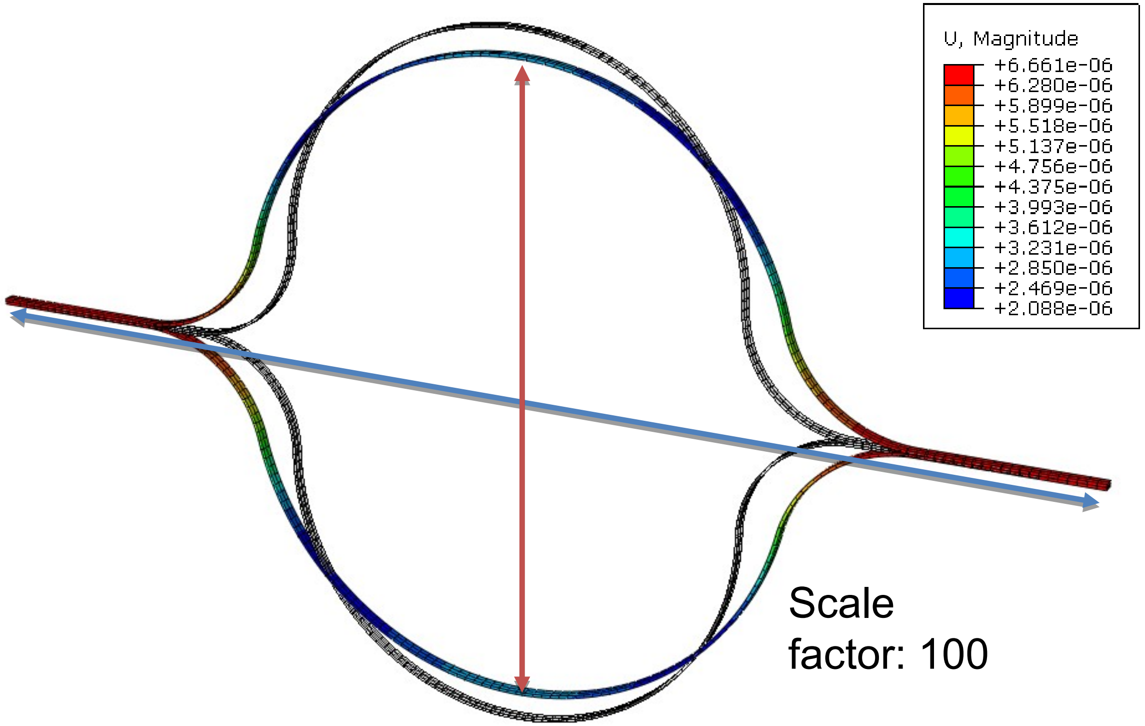
Preliminary FEA results Abaqus+COMPRO Results

Analysis Steps

1. Thermo-chemical
2. Stress deformation
3. Tool removal and relaxation

Horizontal Change = 0.013 mm
Vertical Change = -0.006 mm
Area Change = 0.269 mm^2





Scale factor: 100

Research Objectives

1. Determination of the dimensional Stability during the manufacturing of thin-ply Composites
2. Determination of the dimensional stability of thin ply composites during stowage

Background & Motivation

Previous tests developed for understanding the behavior of thin-ply composite flexures have limitations.

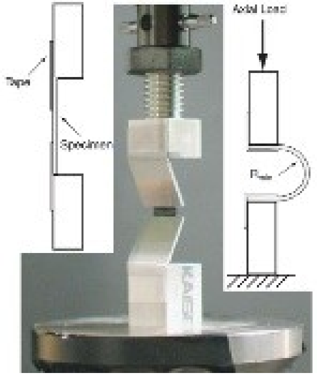
Simple Vertical Test with tape hinges is prone to gravity-induced lateral loads and moments that tend to produce coupon/tape shear distortion at large rotation angles or induced curvatures.

Platen Test generates a small localized region of high curvature in coupon apex, well away from coupon ends, that result in uncharacteristically high failure curvatures. The moment and stress over the coupon is highly non-uniform requiring complex structural analyses to interpret test results.

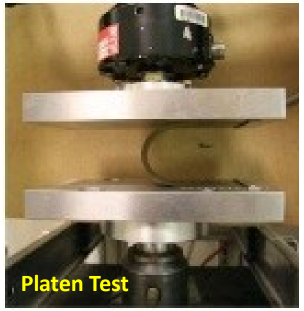
- Used for determining upper limit on maximum coupon curvature or for computing strains and stresses at failure.
- Not used to assess bending stiffness as it does not represent well the pure bending states of most thin-ply composite structures.

Large Deformation Four-Point Bending (LD-FPB) subjects the coupon to a pure bending stress state, and used to measure bending stiffness including fiber nonlinear effects.

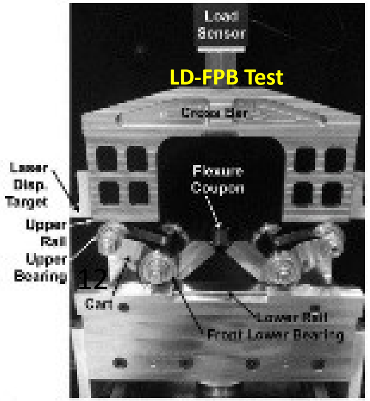
- However, the abrupt transition from flat to curved causes premature failure at test grips (stress concentration).
- Hence, not normally used for bending strength and strain to failure evaluation.



Simple Vertical Test



Platen Test



LD-FPB Test

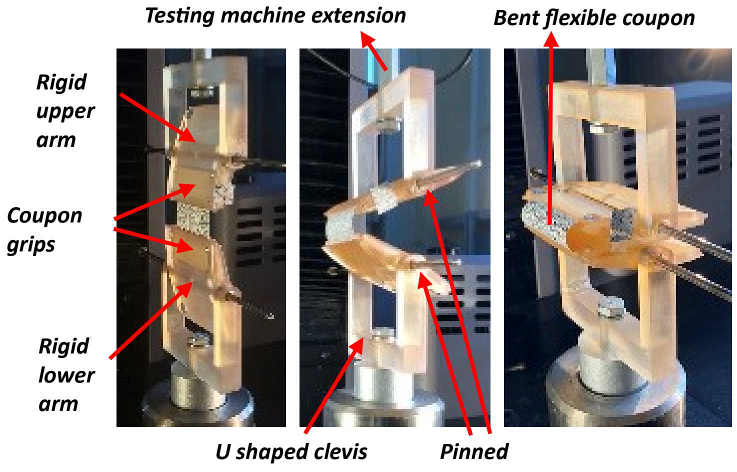
Column Bending Test (CBT)

- CBT method initially developed by Opterus R&D and evaluated and refined for very thin composite flexures at Opterus R&D and LaRC: Fernandez, Murphey, AIAA 2018-0942.

- Test setup consists of double-symmetric, weight-balanced rigid fixtures arms pinned inside a clevis, which firmly clamp the specimen at an offset distance from the pin axis.

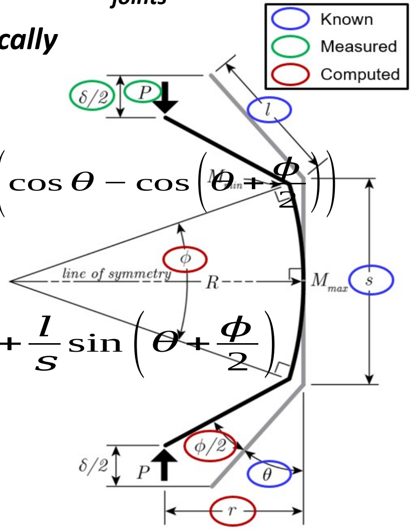
- As the fixture move vertically towards each other applying a compression force, they rotate causing a bending moment in the coupon.

- Combines best features of previous tests:
  - Vertical setup **compatible with uniaxial load frames**.
  - **Generates a max stress state at the coupon center** (as in platen test) but only decreasing it to 80-90% of the max at the grips (and not 0%).
  - Because a larger volume of material is subjected to high stress, the **results are more representative of pure bending stress than in platen test**.
  - Stress state is mostly uniform, as in large deformation four point bending test (LD-FPB), allowing **simple kinematic analysis** to estimate moment and curvature: **constant curvature assumption**.
  - Since curvature is slightly reduced at grips, **failure likely to occur in coupon apex** (as opposed to LD-FPB) for tests seeking bending strength and failure strain.



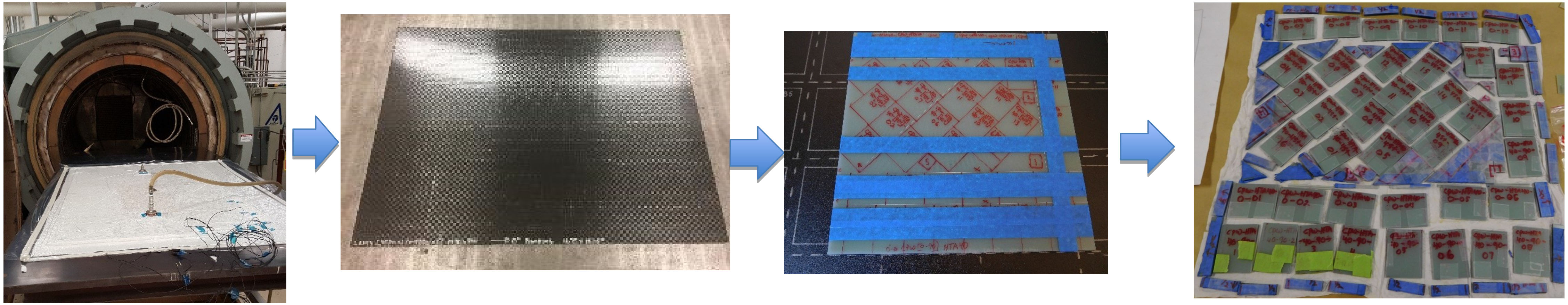
CBT Kinematics: numerically calculating and

$$\begin{cases} \dfrac{\delta}{s}=1-\dfrac{2}{\phi}\sin\dfrac{\phi}{2}+2\dfrac{l}{s}\left(\cos\theta-\cos\left(\theta+\dfrac{\phi}{2}\right)\right) \\ \kappa=\dfrac{\phi}{s} \\ \dfrac{r}{s}=\dfrac{1}{\phi}\left(1-\cos\dfrac{\phi}{2}\right)+\dfrac{l}{s}\sin\left(\theta+\dfrac{\phi}{2}\right) \\ M_{max}=Pr \\ M_{min}=Pl\,sin\left(\theta+\dfrac{\phi}{2}\right) \end{cases}$$



Output: Bending Stiffness D^*_{11} =

Material Preparation



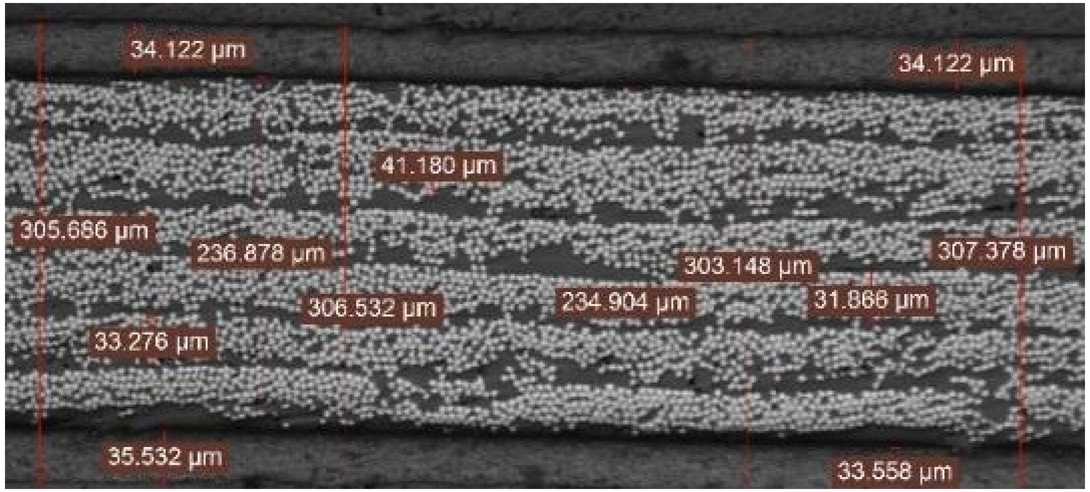
Test Coupon fabrication and painting

- Laminates are cured in an autoclave at 14 psi and 350^{o}F and cut via water jet
- Coupons were wiped down with Isopropyl alcohol and hung on the painting rack
- The samples were painted with up to two coats of a matte white commercial aerosol spray paint
- After at least 12 hours, the samples were painted with Aeroglaze Z306 Flat Black Polyurethane paint mixed with Aeroglaze 9958 thinner using a detailing airbrush

Material Preparation

Polishing, Imaging & Micrographs

- After allowing the paint to dry for at least 24 hours the coupons were polished in the polishing lab in building 1205
  - Coupons were polished with 600, 800, and 1200 grit sandpapers at a constant 120 rpm
- The coupons were then imaged using the inverted Leica optical microscope at 100x, 200x, and 500x
  - 100x images were used to stitch together multiple images for a larger image of the sample
  - 500x images were used to calculate the fiber volume fraction



Thin-ply laminates studied

Label	Laminate	# Coupons tested	Avg thickness (µm)
M30S PW_45_x4	$[\pm 45PW]_4$	4	250 ± 10
M30S PW_0_x4	$[0\text{-}90PW]_4$	4	250 ± 10
LAM1_0_x6	$[\pm 45PW_2/0UD_2/\pm 45PW_2]$	5	330 ± 10
LAM1_90_x6	$[\pm 45PW_2/90UD_2/\pm 45PW_2]$	5	330 ± 10

Doubled the laminate layup (2x thickness) for ease of testing. Data is then scaled down.

Material (fiber/resin)	Spread-tow Fabric Form	Width (mm)	FAW (g/m²)	Ply AW (g/m²)	FVF (%)	Cured Ply Thickness (µm)	E_1 (GPa)	E_2 (GPa)	ν_{12}		Vendor (fiber / resin)
MR60H/PMT-F7	UD	50	38.0	63.4	56	40 ± 3	174.4	8.4	0.259	6.4	Sakai Ovex / Patz M&T
M30S/PMT-F7	PW	1000	61.0	89.7	54	60 ± 3	94.2	94.2	0.026	3.9	Sakai Ovex/ PatzM&T

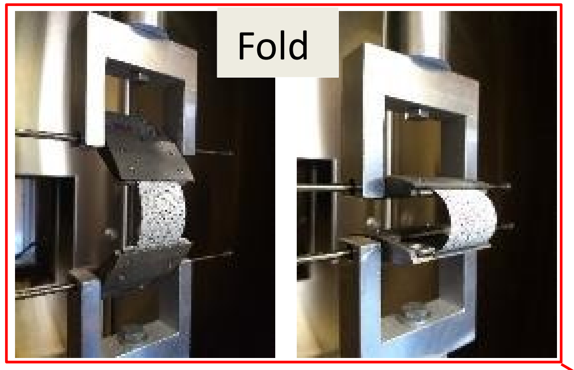
Preparing Coupons for Testing

- Coupons were installed in CBT fixtures with pre determined gage lengths depend on material and laminate
- The CBT fixtures were then installed in the thermal chamber and it was set to testing temperature and allowed to equilibrate for 90 minutes
- MTS Load is zeroed at half the weight of the CBT clamps and coupon after they were installed

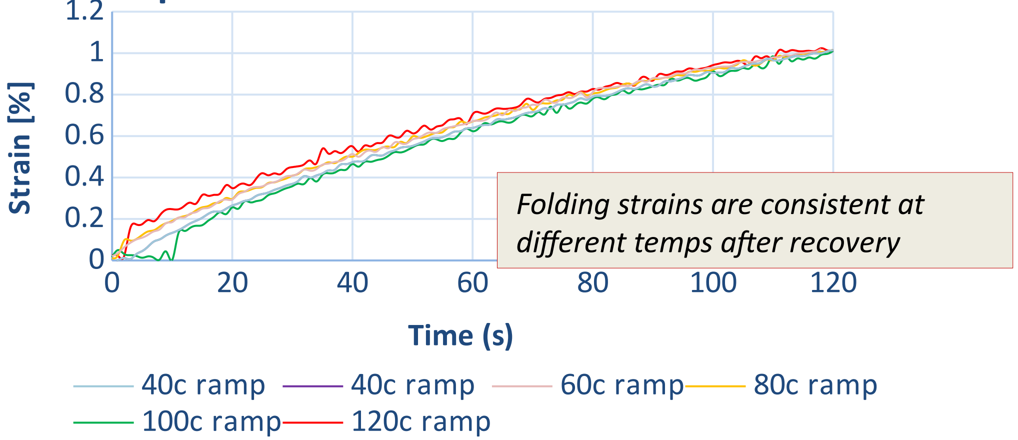
CBT Test Procedure for Viscoelastic Characterization

Test parameters adopted in this study

Temperature	40, 60, 80 ,100, 120°C
Temp. steady state time	1.5 h
Fold/unfold rate	12 mm/min
Fold/unfold time	2 min
Estimated surface strain	1%
Relaxation time:	6 h
Recovery Time	2 h
Total test time	48 h

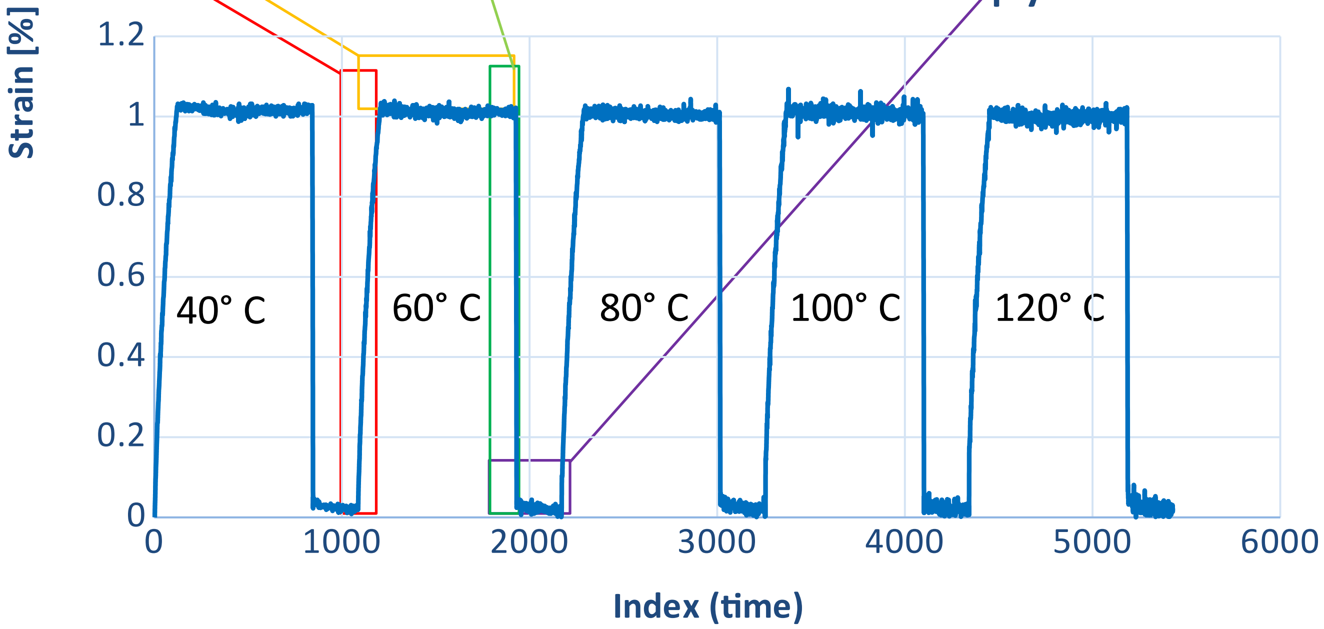


DIC tension-side strains during folding at temperatures 40°C - 120°C



Folding strains are consistent at different temps after recovery

DIC tension side strains at 40°C-120°C for 4-ply 45° M30S PW

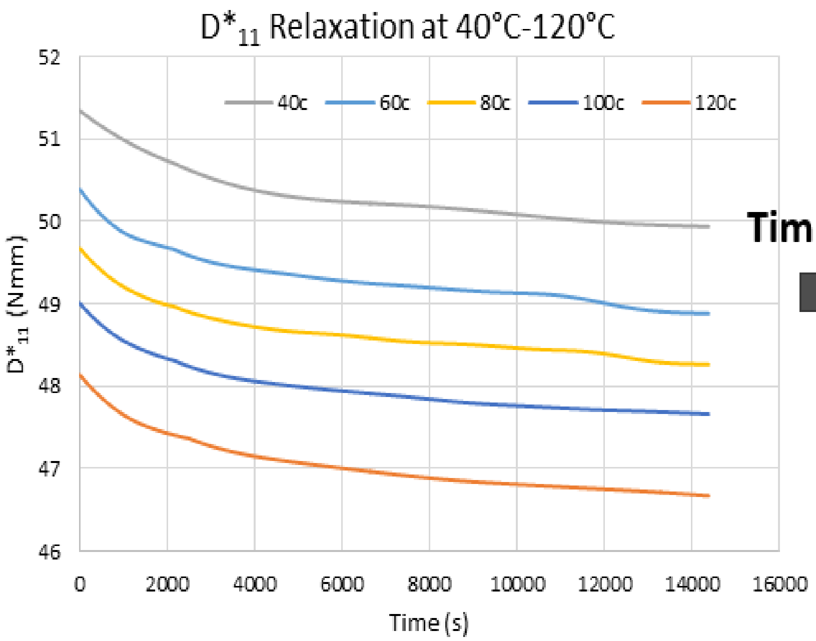


Composite Bending Viscoelastic Characterization

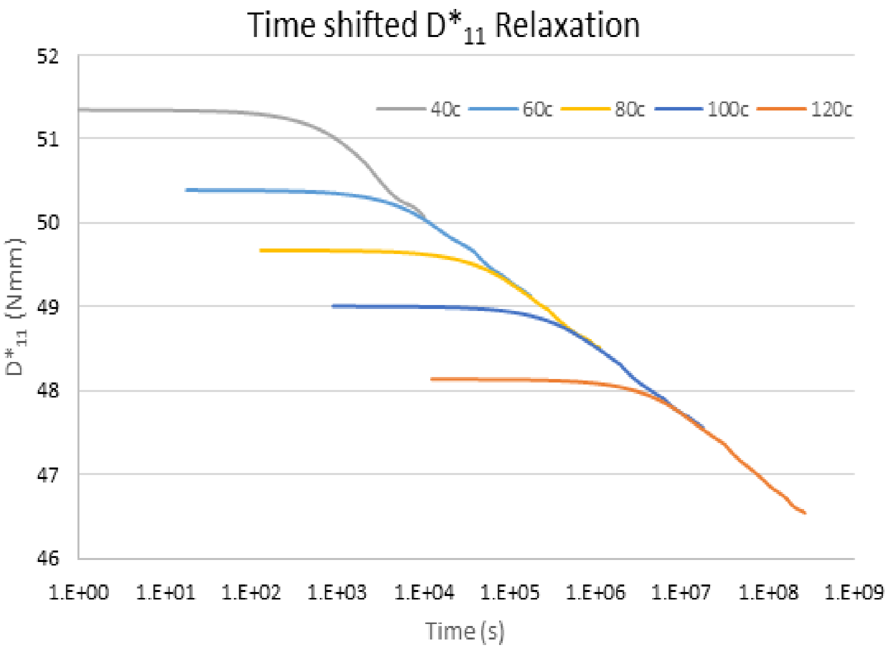
- **CBT Bending relaxation tests of 4-ply ±45º PW (M30S/PMT-F7) laminate performed at 40 - 120 ºC in 20 ºC increments.**

- **Bending relaxation data shifted to form a master curve at 40 °C (expected max stowage temperature) using Time-Temperature-Superposition Principle.**

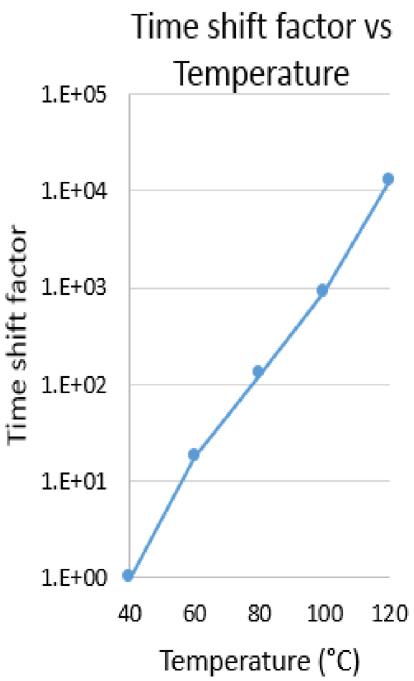
- **High degree of linearity of log of time shift factor vs temperature curve indicates that the CFRP material behaves like a thermorheological one allowing the TTSP to be used for accelerated relaxation testing.**



Time shift



(Log time scale)



Composite Bending Viscoelastic Characterization

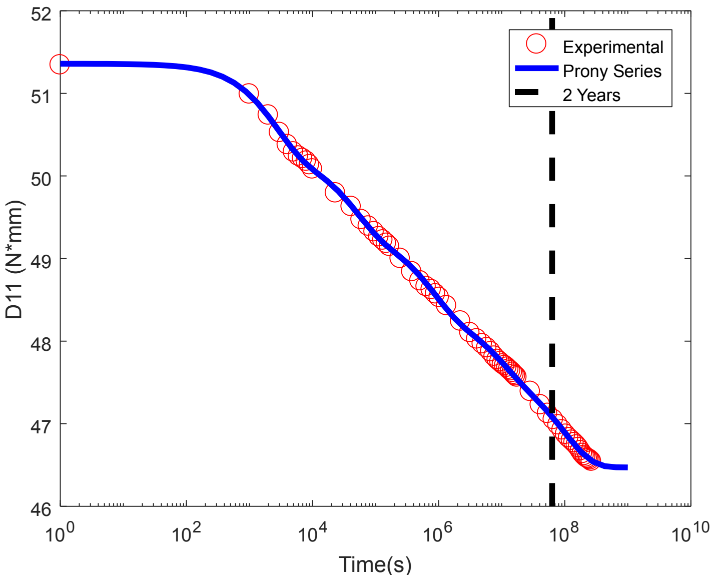
Prony Series Fitting to experimental and simulated bending relaxation master curves at 40 °C. Prony terms can be used to validate/update finite element model (FEM) under development.

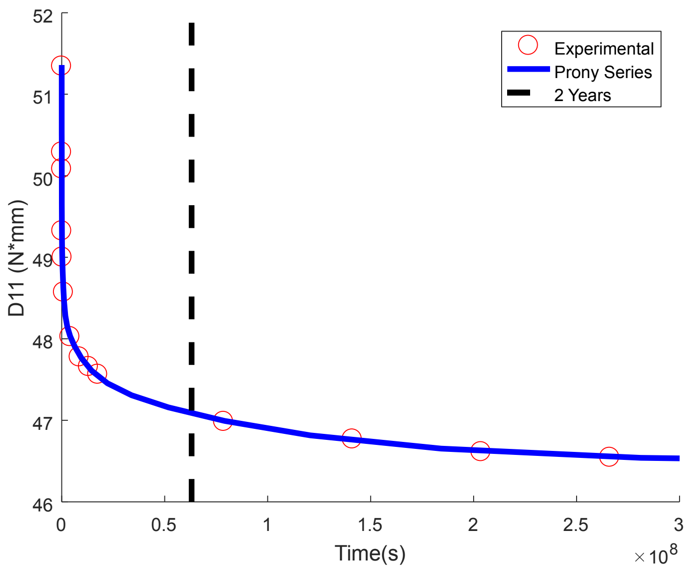
9-term Prony fit of the pseudo stiffness (D^*_{11} *(t)* =) terms shown for one ±45° PW sample.

The long-term coefficient ($D^*_{11,}$) is similar (4% off) for the test and FEM fit.

Shifted test data allows to evaluate material response 2 years (6.3+E7 sec) out, which is the maximum stowage time required for boom application. The FEM can predict past 2 year mark.

Prony series coefficients $D*_{11} = D*_{11,\infty} + \sum_{k=1}^{n} D*_{11,k} * e^{-\frac{t}{\rho_k}}$





9-term Experimental data fit			9-term FEM Numerical model fit		
	(s)	(Nmm)		(s)	(Nmm)
	---	46.4701		--	48.3955
1	0.04	0.1179	1	1.89E+01	0.6081
2	0.05	0.0032	2	1.00E+02	0.8042
3	49.40	4.4409E-14	3	1.00E+03	0.8195
4	441.02	3.8166E-08	4	2.00E+04	0.7250
5	2.58E+03	1.1046	5	1.00E+05	0.4394
6	4.64E+04	0.9509	6	1.95E+06	0.4431
7	7.67E+05	0.9736	7	1.77E+07	0.5439
8	9.09E+06	0.7079	8	1.74E+08	2.4962
9	1.0000E+08	1.1508	9	1.38E+09	0.0308

Thin-ply Composite Viscoelastic Characterization Summary

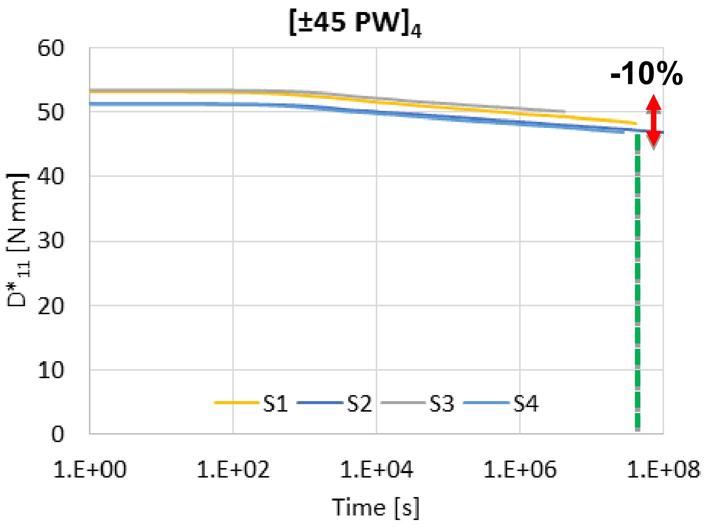
Bending relaxation data for all samples was normalized by the thickness of the thicker coupon in each batch.

The sample-to-sample thickness variability is acceptable and results show low standard deviations with [±45PW/0/±45 PW] laminate data having the largest spread given the large effect of the central 0° UD ply thickness on the laminate D^*_{11} value and its higher variability.

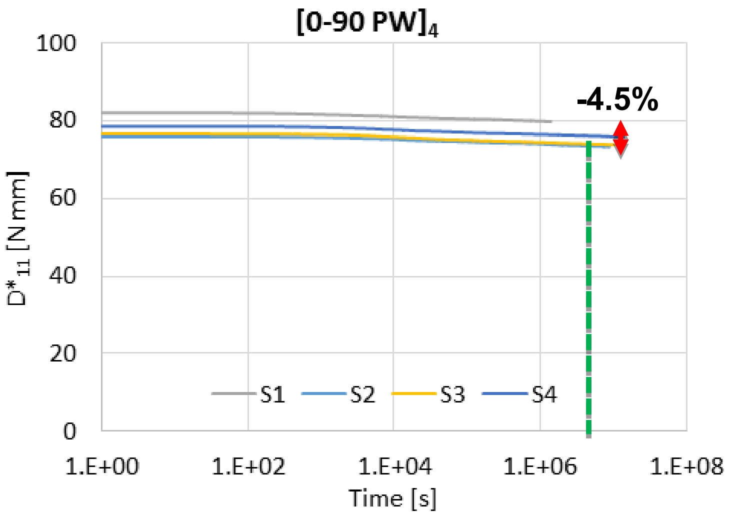
Most relaxation on ±45° PW laminate (10%), followed by [±45PW/0/±45 PW] laminate (6%) due to the viscoelastic matrix of the surface plies being highly loaded in shear as coupon gets bent axially.

0-90° PW relaxes the least (4.5%) due to elastic fibers oriented in the principal loading 1-direction.

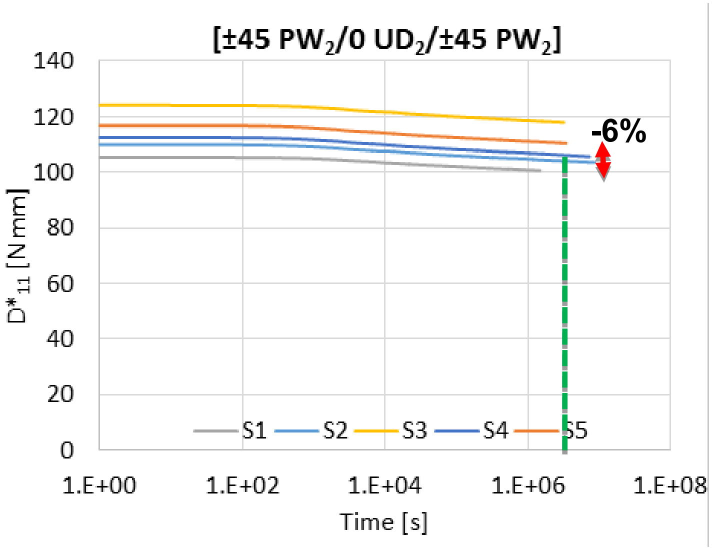
The ±45° PW laminate showed the largest shift factors resulting in higher relaxation times, while the others had similar time predictions.



[±45 PW]$_4$



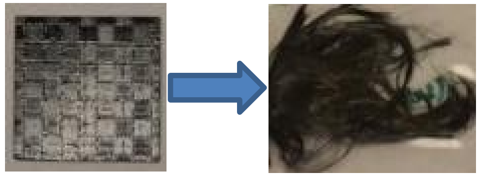
[0-90 PW]$_4$



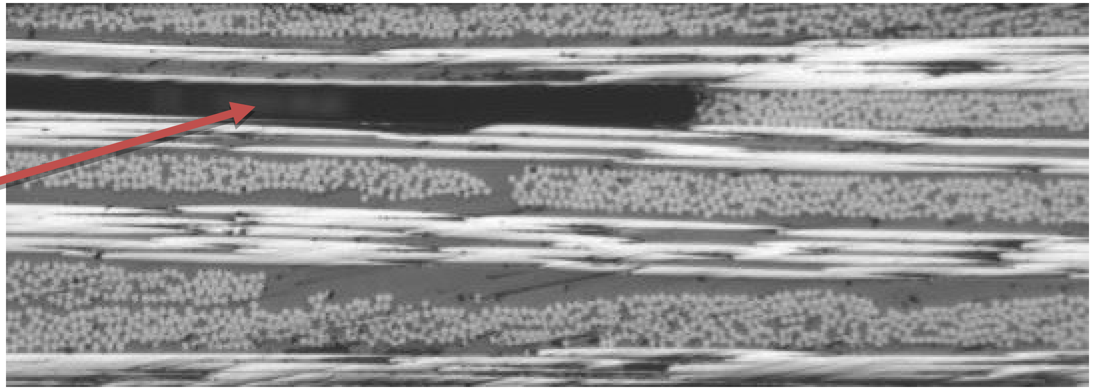
[±45 PW$_2$/0 UD$_2$/±45 PW$_2$]

Composite Fiber Volume Fraction Variance

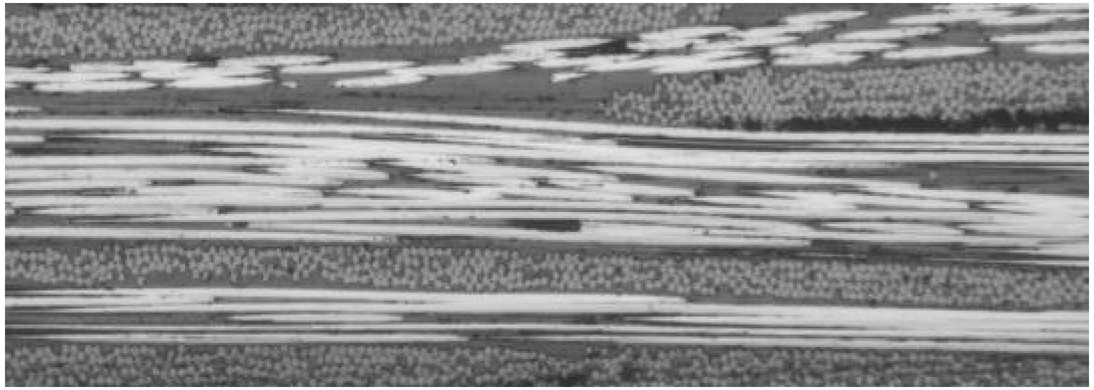
Fiber Volume Fraction - Jin Ho Kang and Brian Grimsley
Acid digestion method (ASTM 3171-15)
Procedure: (1) Heat in sulfuric acid at 280˚C for 3 hours
(2) Heat in hydrogen peroxide at 280˚C for 3 hours
(3) Vacuum filtering / rinse with DI water & Acetone
(4) Drying and measure weight the fiber



	Sample 1	Sample 2
D11	82 N*mm ⇧	76 N*mm ⇩
Thickness	0.241 mm ⇧	0.234 mm ⇩
FVF	60.4% ⇩	62.4% ⇧
RVF	38.4%	38.5%
Voids	1.2% ⇧	-0.9% ⇩

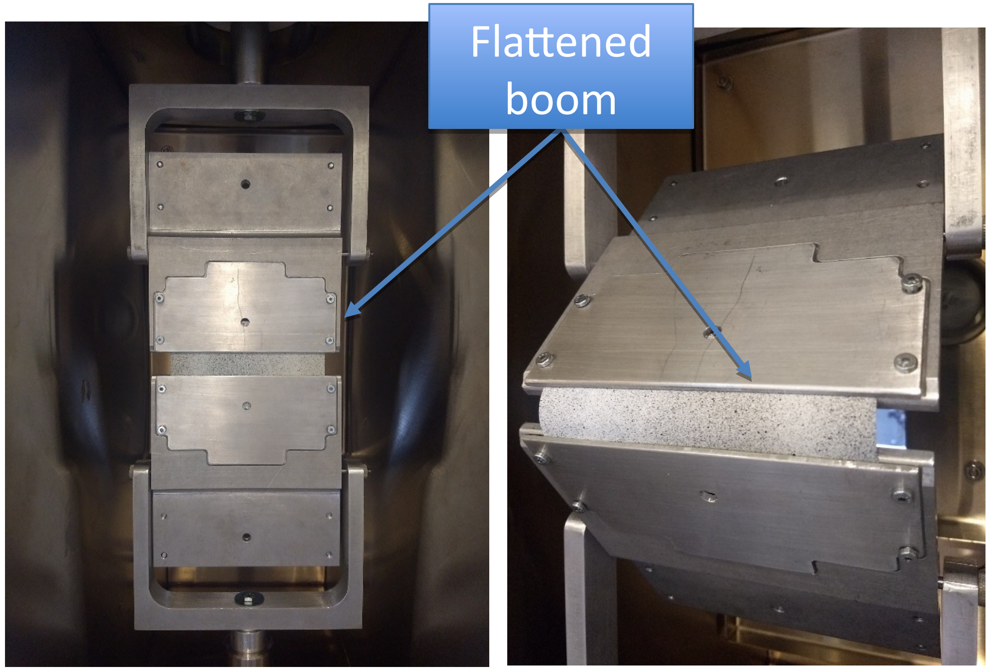


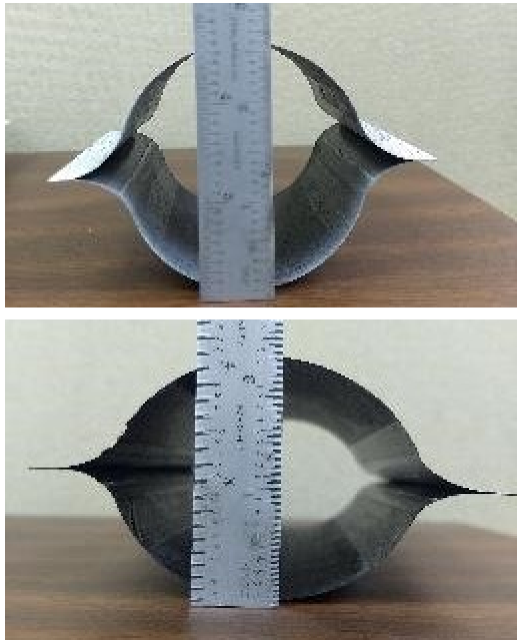
More voids and increased thickness moves fibers away from neutral axis



Boom CBT Testing

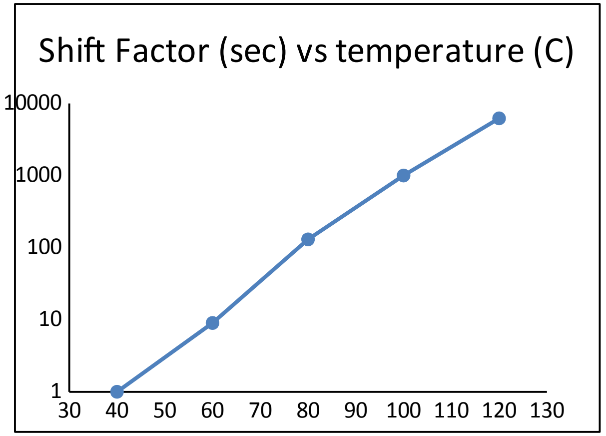
- Boom is painted white and speckled with black paint then cut into 6 inch sections
- CBT clamps are placed against flat surfaces for alignment while inserting boom
- 1 inch gage blocks are used to separate the clamps while inserting and clamping a section of the boom
- The test has 5 repeated steps:
    - Steady state, creep at 0 load – 92 min
    - Cross head lowering – 2 min
    - Relaxation, constant displacement – 360 min
    - Unloading to 0 load - ~2min
    - Recovery, creep at 0 load – 120 min

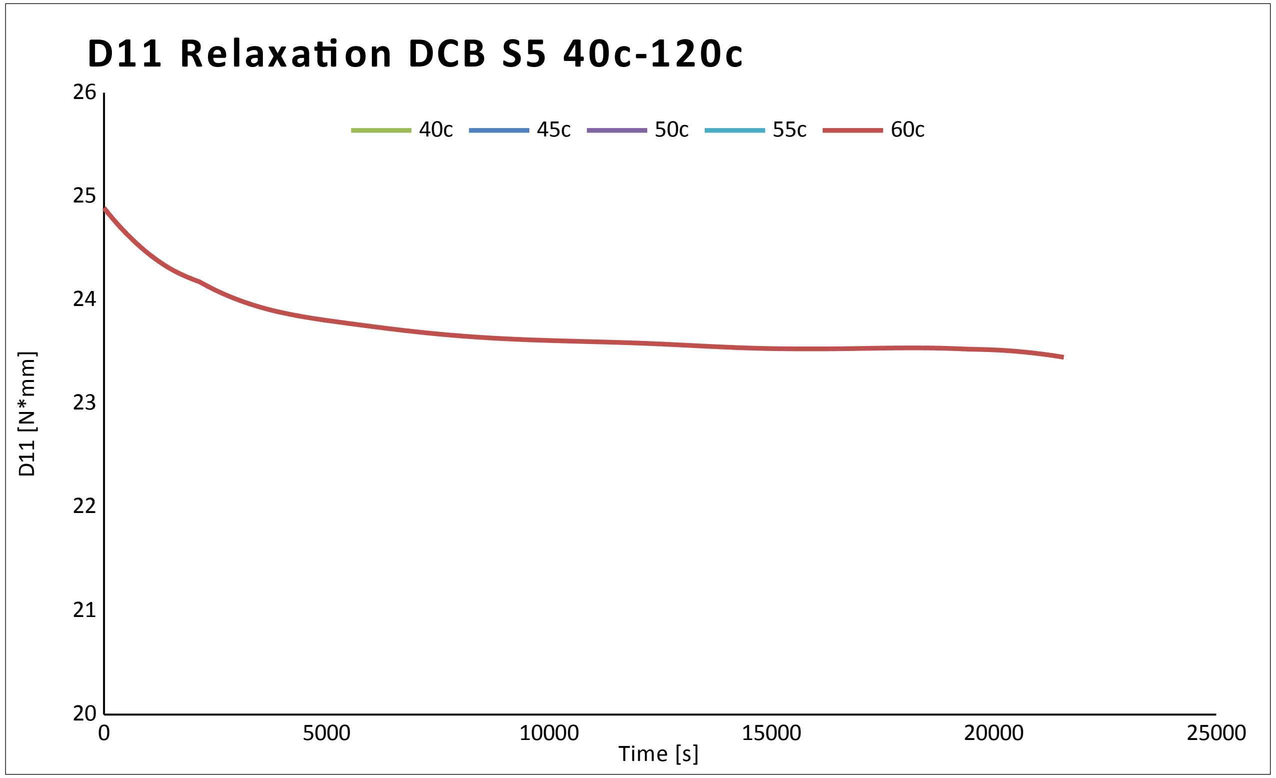


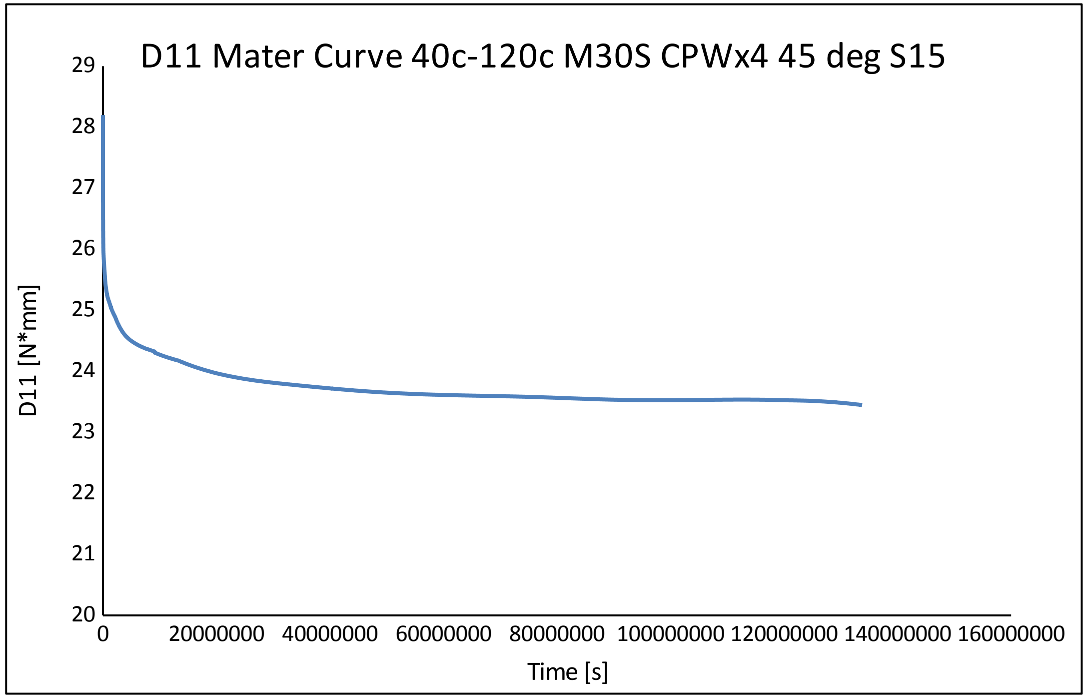


Boom CBT Relaxation Test Results

- The bending relaxation results from the CBT are shown below
- The data shown has been filtered due to noise in the testing process
- The Relaxation curves where then shifted to 40c using the shift factors on the right to produce the master curve
- The Master curve shows a Reduction in D11 by 4.75 N*mm in about 4 years at a curvature of 0.04 mm^{-1}

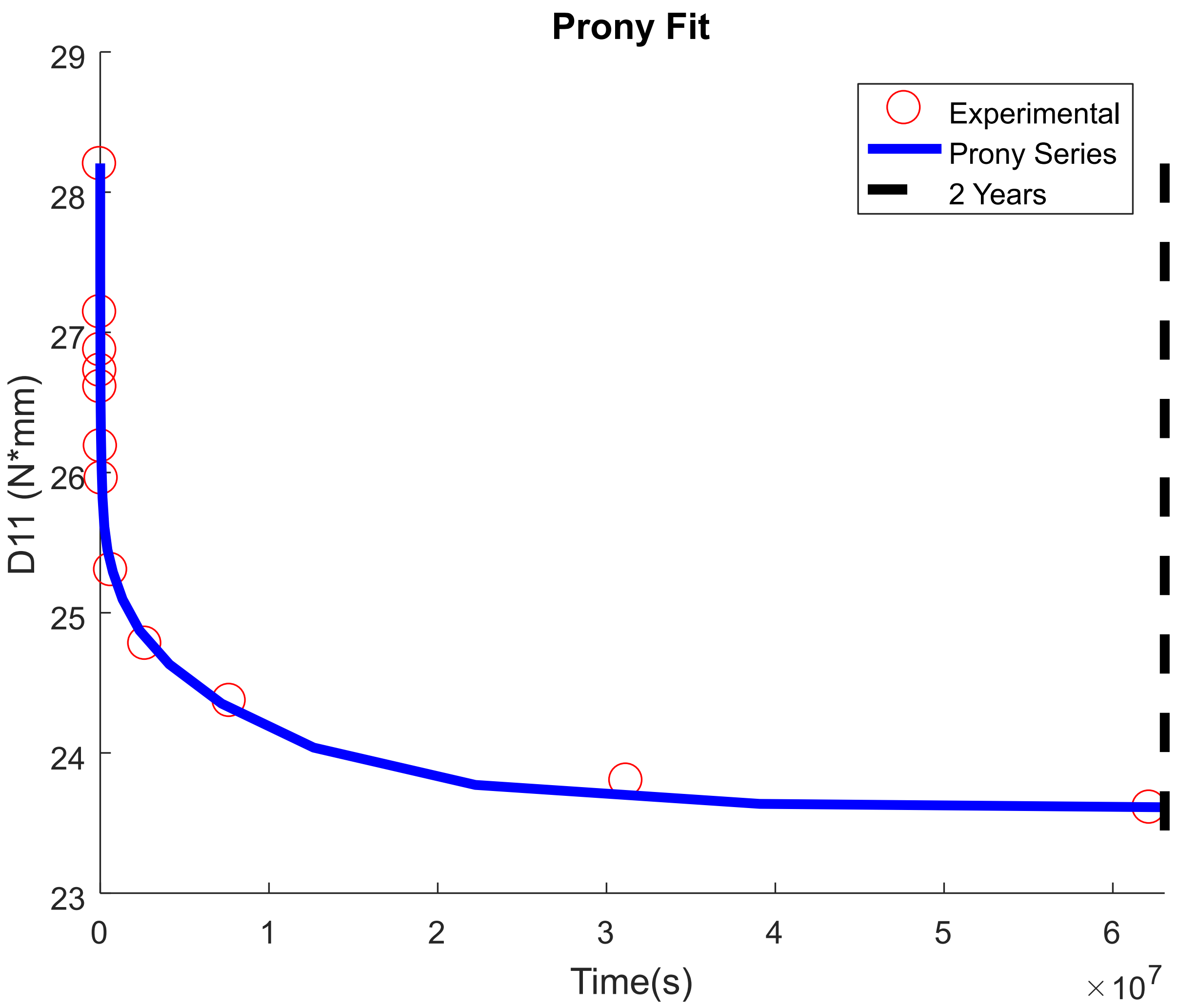






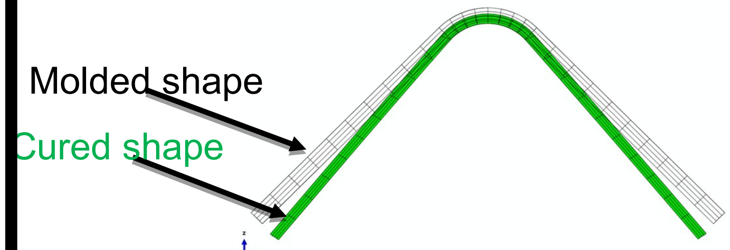
Boom CBT Bending stiffness Model curve fitting

- A Prony series was fit to the master curve using the method of least squares
- The Prony series is fit to the data for up to 2 years at 40c
- The D11 Prony coefficients and time constants are shown below

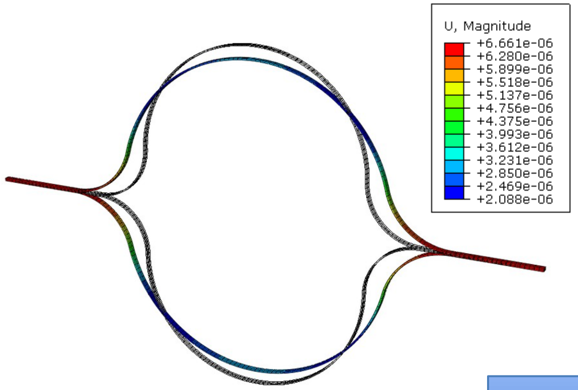


Summary

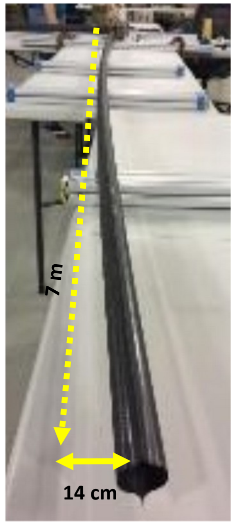
Dimensional stability of thin-ply composites post curing

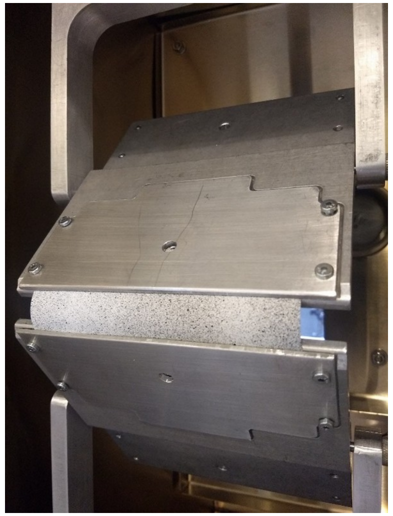


Example of spring-in after curing

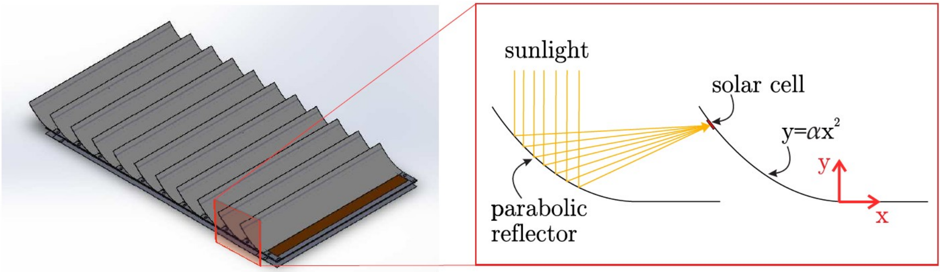


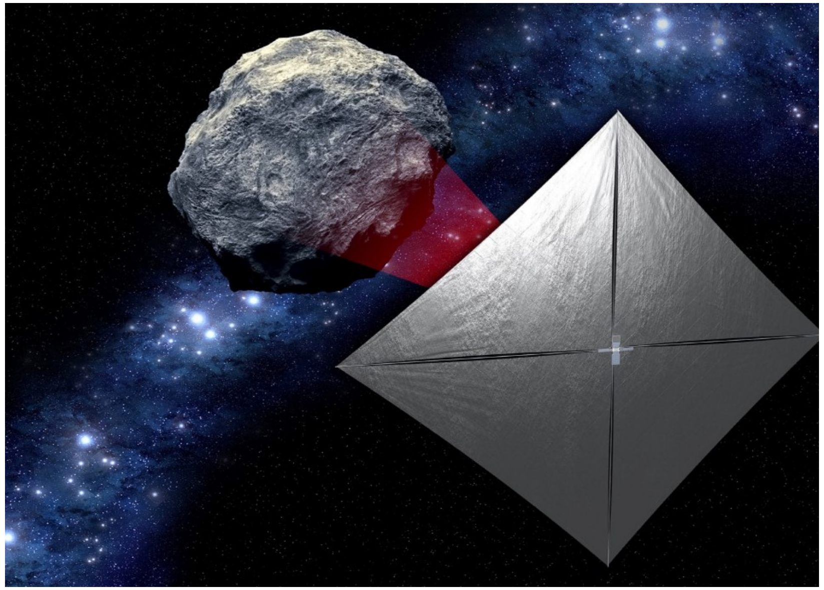
Dimensional stability of thin-ply composites post stowage





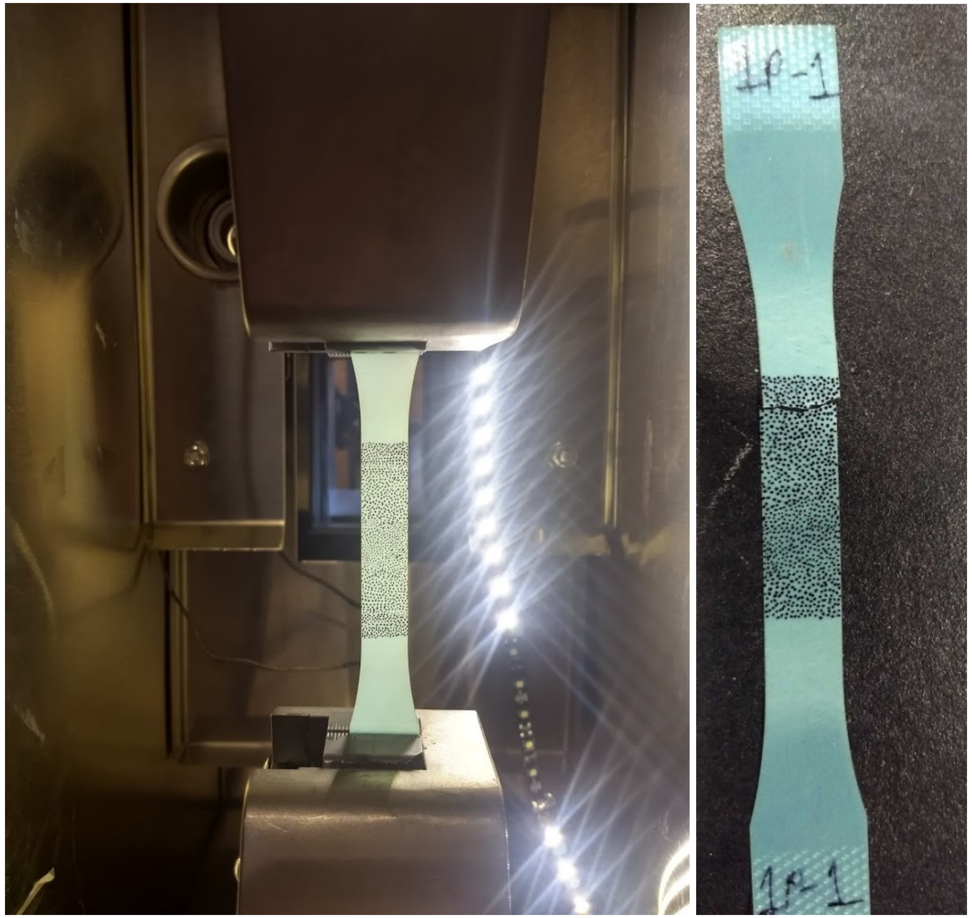
Improved thin ply deployable composite structures



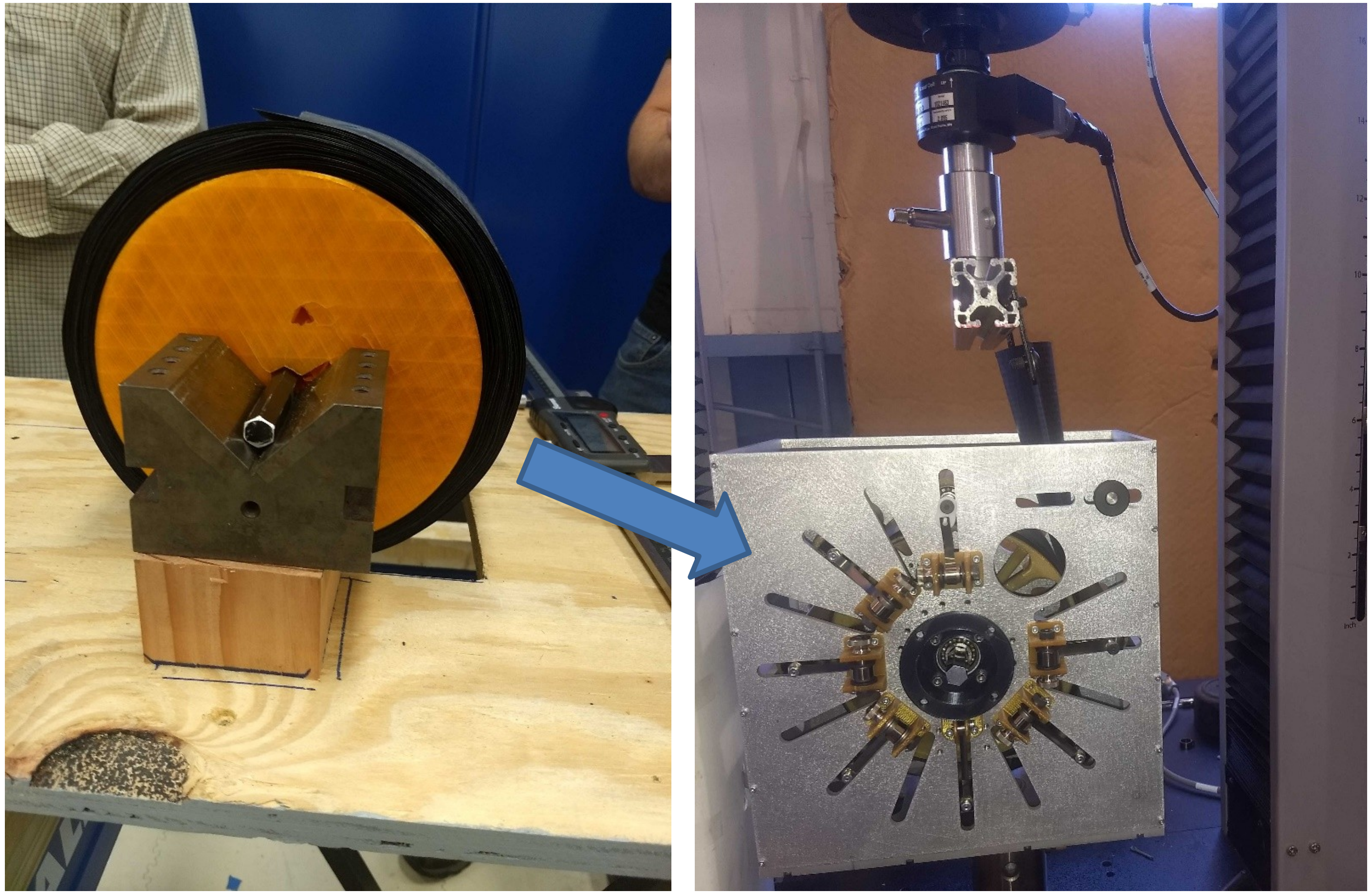


Future Work

Adhesive Testing



Full Scale Boom Stowage Testing



Thank you!

Questions?