

Dimensional Stability of Thin Ply Composites for Deployable Structures

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Dissertation Proposal

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Outline

Introduction

- Motivation
- Deployable composite booms
- Technology Risk

Research Objectives

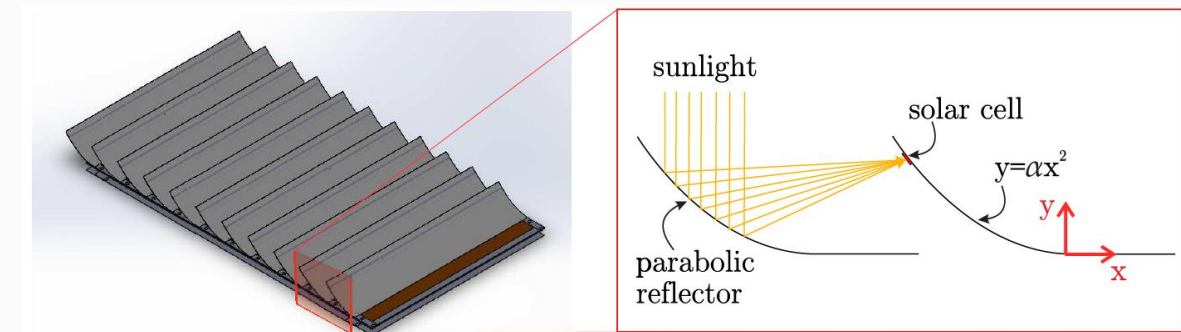
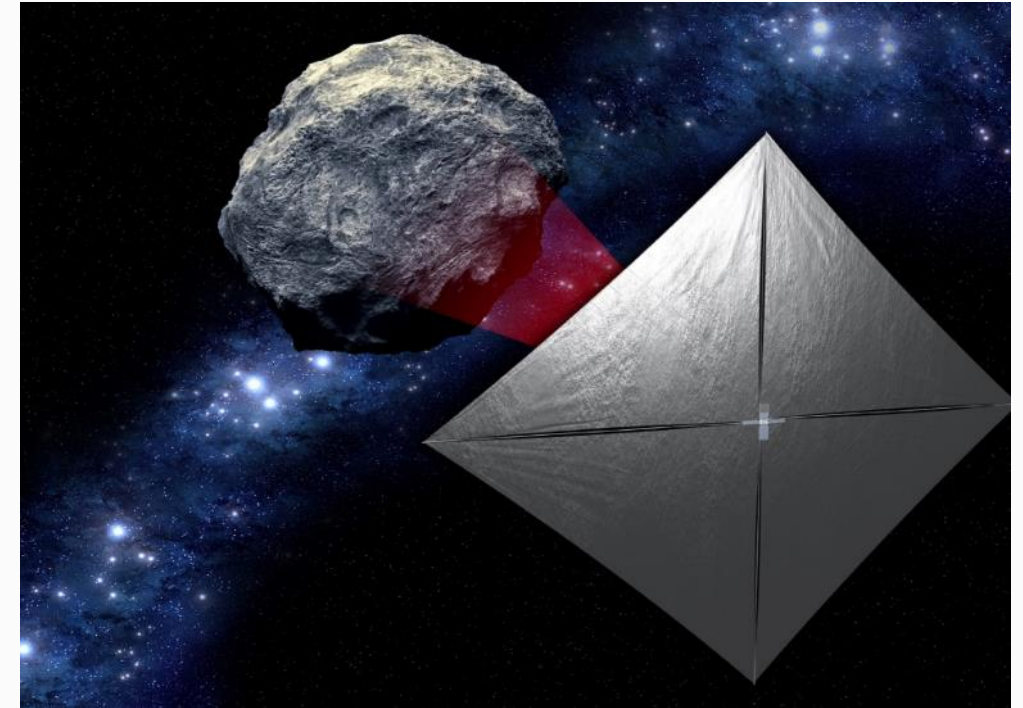
- Aim 1 – Determination of the dimensional stability of thin-ply composites during manufacturing
- Aim 2 - Determination of the dimensional stability of thin-ply composites during stowage

Discussion

- Summary
- Timeline

Introduction and Motivation

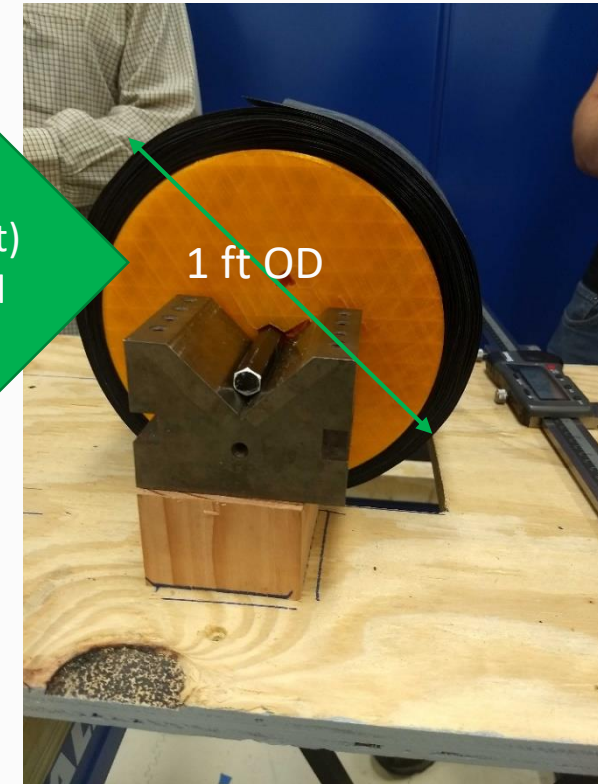
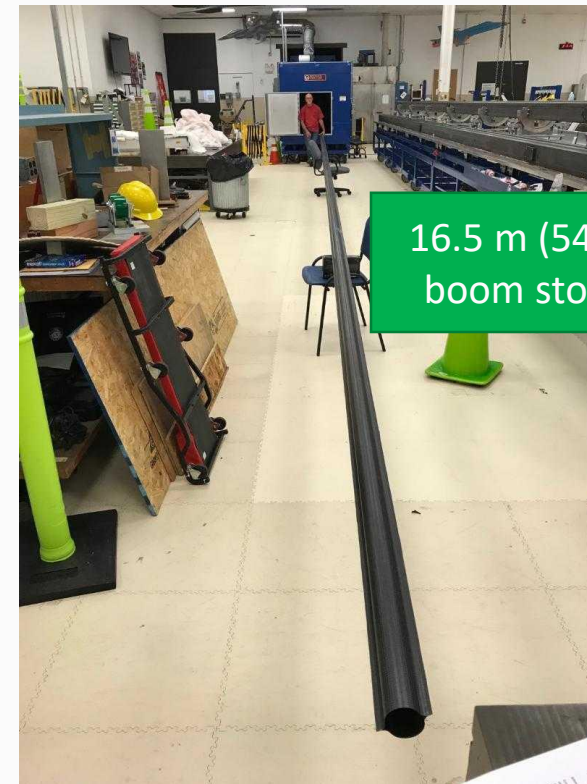
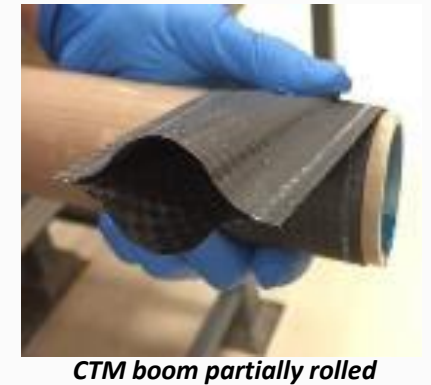
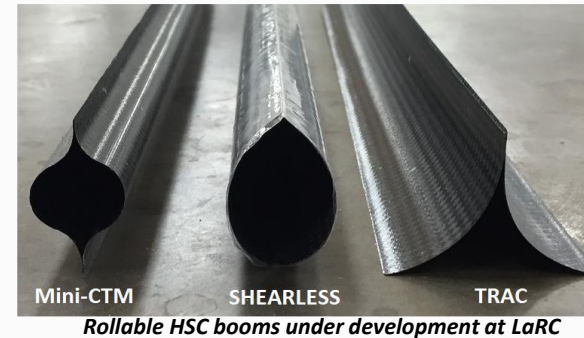
- Solar Sails:
 - Near Earth Asteroid (NEA) scout is a 6U cubesat mission set to fly with the SLS Orion EM-1 mission as a secondary payload.
 - 7.5 meter metallic Triangular rollable and collapsable (TRAC) booms
 - High CTE of metallic booms can cause deformations that severely limit the length of the 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., Et al, Cure-induced deformation of ultra-thin composite laminates, AIAA SciTech Forum, 8-12 (2018)

Thin- ply Deployable Composite Booms

- Carbon Fiber Reinforced Polymers (CFRP)
 - Carbon fiber – M30S plain weave (PW) fabric (Sakai Ovex)
 - Carbon Fiber – MR60H unidirectional (UD) fabric (Sakai Ovex)
 - Polymer Matrix – PMTF7 (Patz Materials and Technology)
 - Polymer Adhesive – EA 9696 (Henkel materials)
- 54.5 ft boom stowed in less than 1 square foot



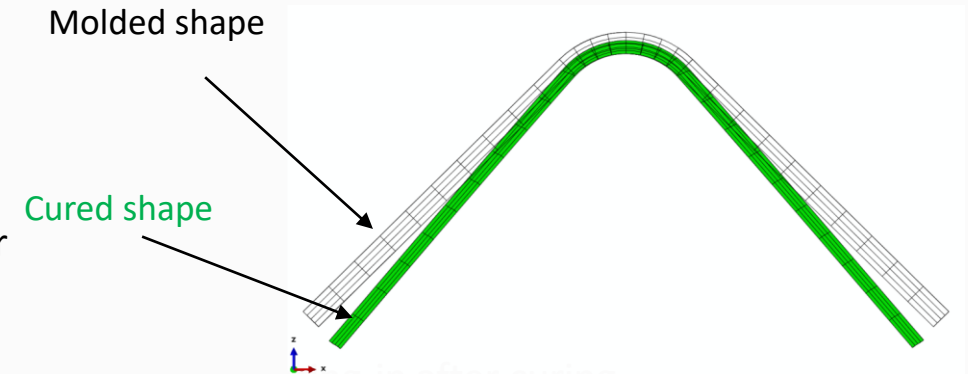
Technology Risks

• Loss of dimensional stability during manufacturing

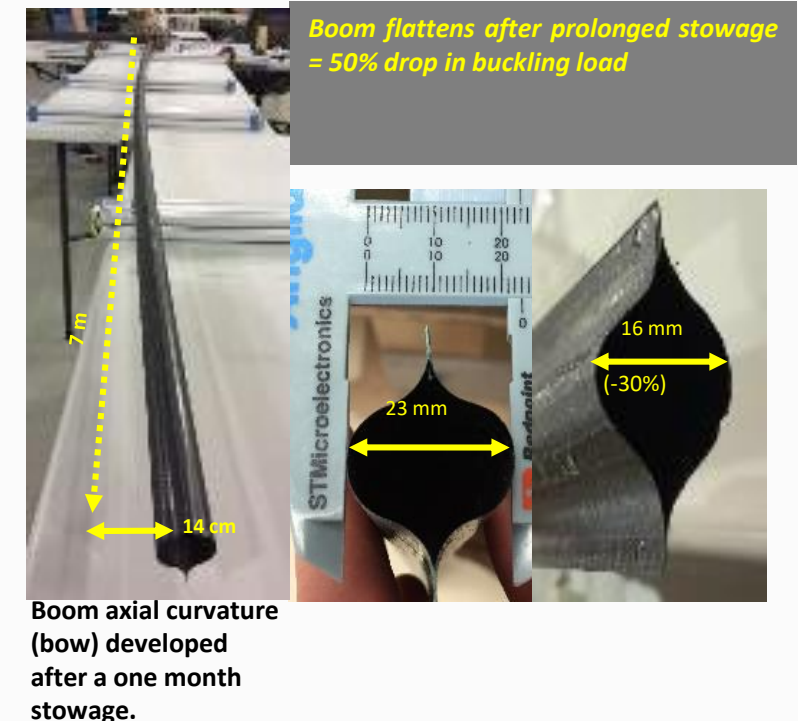
- During manufacturing carbon fiber that is impregnated with a polymer matrix is put under high pressure and heat to cure the polymer
- This curing process causes stress deformations
- The manufacturing of high precision structures is limited by cure stresses causing relaxations and spring-in of curved 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



Research Objectives

Aim 1. Determination of the dimensional stability of thin-ply composites during manufacturing

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

Research Objectives

Aim 1. Determination of the dimensional stability of thin-ply composites during manufacturing

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

Properties of Cure Deformation

- Thermo-chemical
 - Cure Kinetics
 - Heat of Reaction
 - Glass Transition
 - Density
 - Specific Heat Capacity
 - Thermal Conductivity
- Flow Compaction
 - Initial Fiber Volume Fraction
 - Fiber Bed Compaction
 - Resin Viscosity
- Stress Deformations
 - Elastic/viscoelastic constants
 - CTE
 - Cure Shrinkage

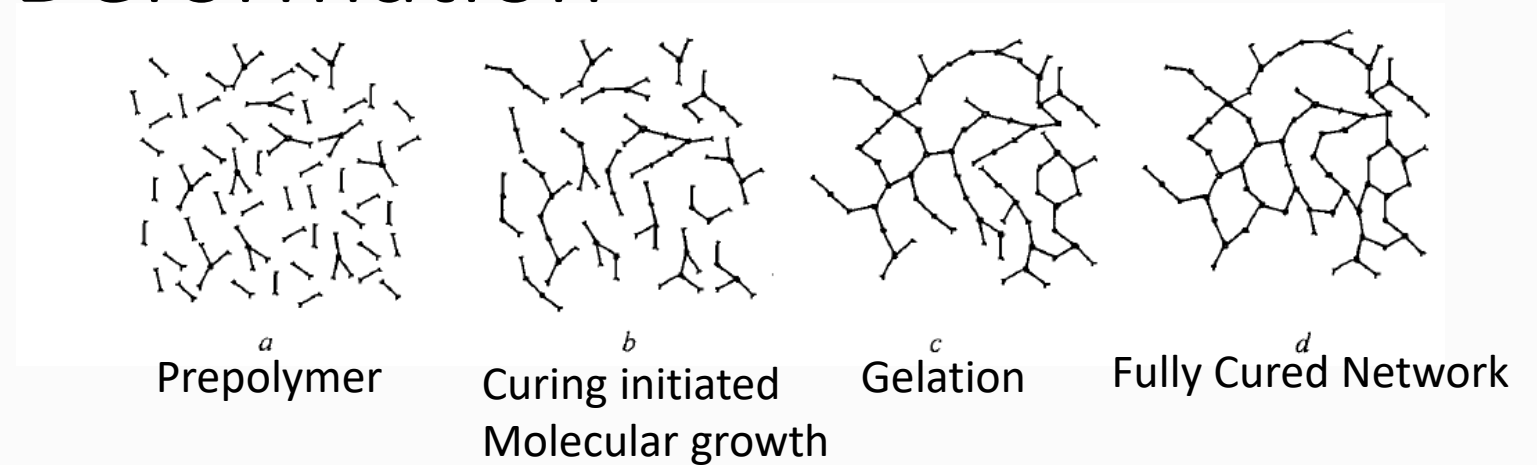
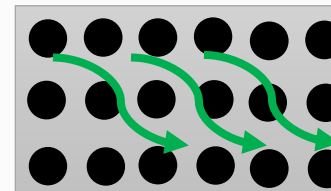
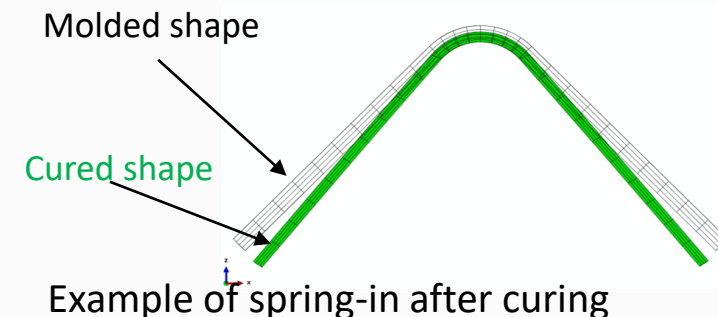


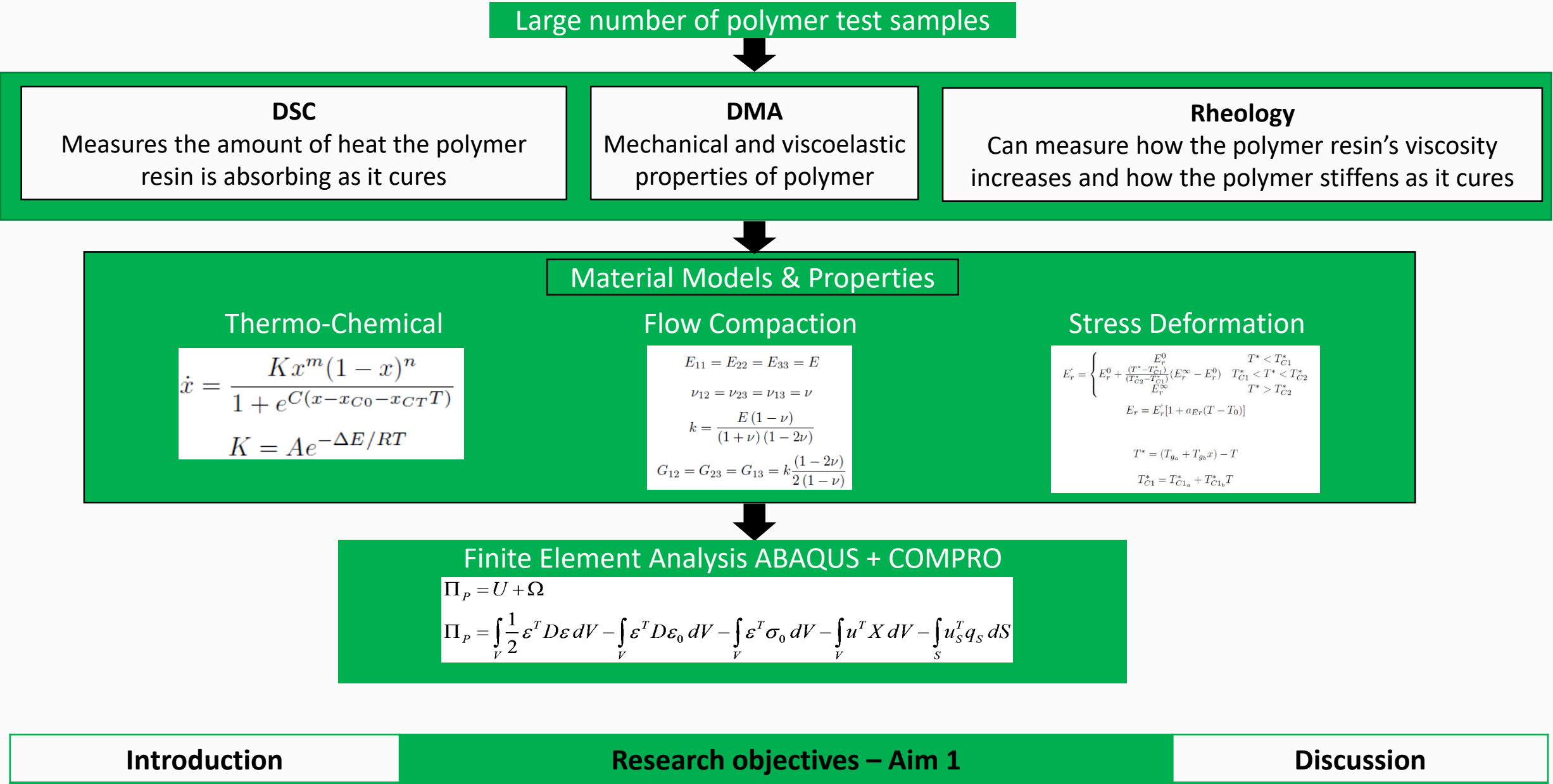
Figure reprinted from Berglund and Kenny, 1991



Resin flow and fiber bed compaction results from Cure temperatures and pressures and resin shrinkage



Cure deformation modeling process



Thermo-Mechanical Testing

- TGA
 - Thermogravimetric analyzer
 - Measures change in mass over time as temperature changes
- DSC
 - Differential Scanning Calorimetry
 - Measures heat flow in a material
 - Heat flow can be from thermal transitions or curing
- Rheology
 - Measures mechanical properties of a material over different temperatures
- DMA
 - Dynamic Mechanical Analysis
 - Measures the dynamic and time dependent mechanical properties of a material by applying sinusoidal loading



Aim 1. Determination of the dimensional stability of thin-ply composites during manufacturing

Aim 1.1 – Thermo-Chemical Model Development

Aim 1.2– Flow-Compaction Model Development

Aim 1.3 – Stress Deformation Model Development

Aim 1.4 – Stress Deformation Finite Element Analysis

Aim 1.5 – Stress Deformation Analysis Verification

Aim 1. Determination of the dimensional stability of thin-ply composites during manufacturing

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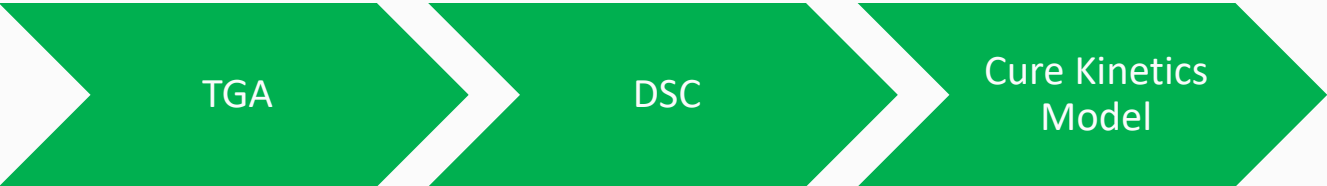
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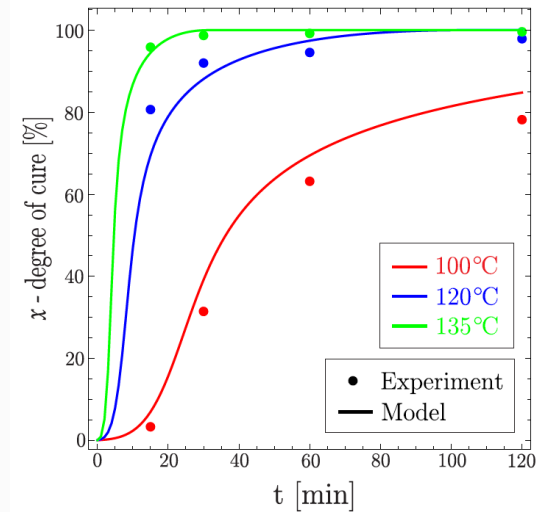
Cure Kinetics Model Development

- TGA + DSC for material characterization
- Cure Kinetics model development



- | | | |
|---|---|---|
| <ul style="list-style-type: none">• Decomposition Temperature (1% mass loss)• Limit for DSC to prevent contamination | <ul style="list-style-type: none">• Sweep Test (3°C/min, -40°C→295°C)• Identify temperatures during curing (exothermic heat flow)• Time-limited Isothermal tests• Measure degree of cure as function of time | <ul style="list-style-type: none">• Least Squares fit used to fit degree of cure model• Degree of cure model verification• Degree of cure model implementation in ABAQUS+COMPRO |
|---|---|---|

$$\frac{d\alpha}{dt} = \frac{K\alpha^m(1-\alpha)^n}{1 + e^{C\{\alpha - (\alpha_{C0} + \alpha_{CT}T)\}}}$$
$$K = Ae^{(-\Delta E / RT)}$$



Parameter	Value	Comments
Activation energy	$\Delta E = 66.5 \text{ kJ/gmole}$	Calculated from slope of line of $\ln(d\alpha/dt)$, vs. $1/T$
Pre-exponential cure rate coefficient	$A = 1.53 \times 10^5 / \text{s}$	Calculated from weighted least squares analysis
First exponential constant	$m = 0.813$	Calculated from weighted least squares analysis
Second exponential constant	$n = 2.74$	Calculated from weighted least squares analysis
Diffusion constant	$C = 43.1$	Accounts for rate of shift from kinetics to diffusion control
Critical degree of cure at $T = 0 \text{ K}$.	$\alpha_{C0} = -1.684$	Note that this parameter is invalid below 35°C since degree of cure cannot be negative
Constant accounting for increase in critical resin degree of cure with temperature	$\alpha_{CT} = 5.475 \times 10^{-3} / \text{K}$	When α approaches α_c at a given temperature, cure rate slows dramatically as the reaction becomes diffusion-controlled.

Bosi, F., Et al, Cure-induced deformation of ultra-thin composite laminates, AIAA SciTech Forum, 8-12 (2018)

Cure Kinetics Preliminary results

- Data obtained gives degree of cure vs time
- Slope between two point gives cure rate
- Plot cure rate vs degree of cure
- Least Squares Fit model to experimental data
 - 160 C isotherm, needs to be done for other temperatures

$$\alpha = \frac{H_T - (H_T - H_{ISO})}{H_T} = \frac{H_T - H_R}{H_T}$$

H_T = Total Enthalpy of reaction

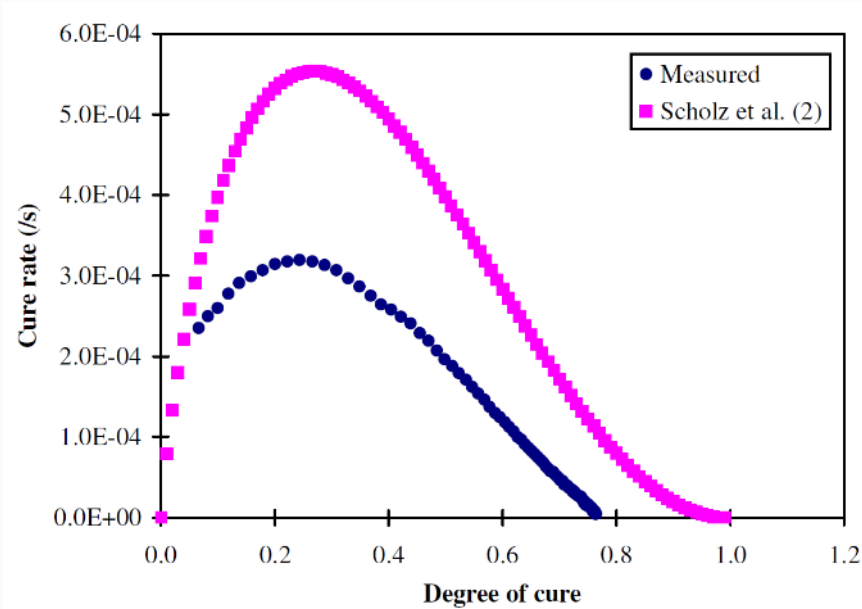
H_{ISO} = Enthalpy of isothermal curing reaction

H_R = Residual enthalpy

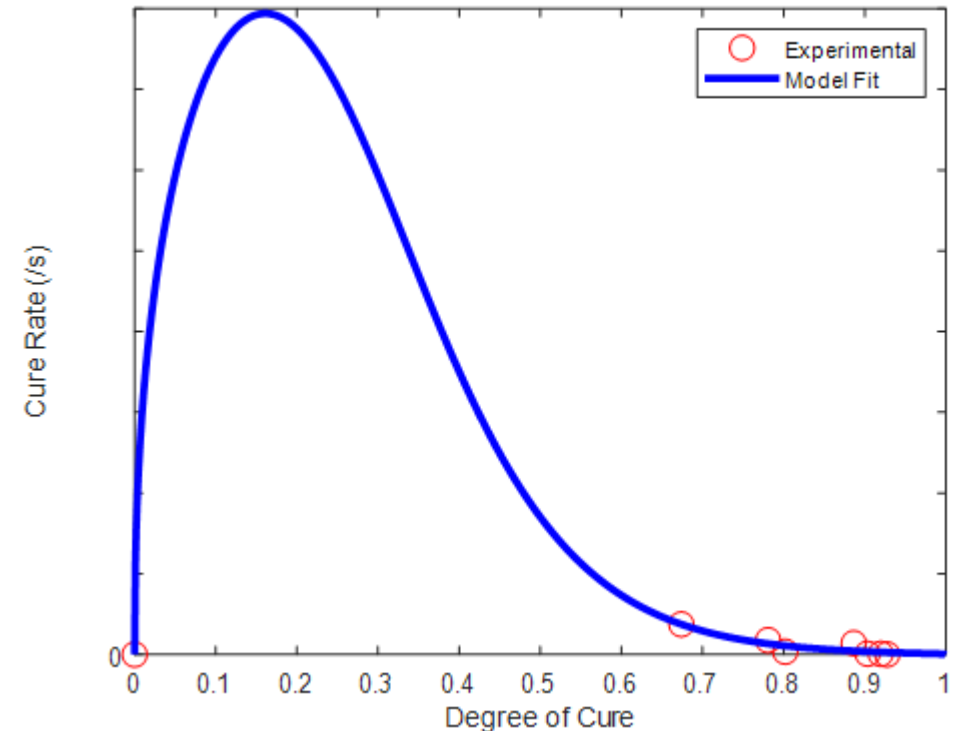
$$\frac{d\alpha}{dt} = \frac{K\alpha^m(1-\alpha)^n}{1 + e^{C\{\alpha - (\alpha_{C0} + \alpha_{CT}T)\}}}$$

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

Parameter	Symbol
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	α_{C0}
Constant accounting for increase in critical resin degree of cure with temperature	α_{CT} (/K)



Hubert, P., Et al Cure kinetics and viscosity models for Hexcel 8552 epoxy resin, 46th International SAMPE Symposium and Exhibition, 2341-2354 (2001).



Introduction

Research objectives – Aim 1.1 Thermo-Chemical Model

Discussion

Other Material properties

- Specific Heat Capacity
 - Represented as a function of Temperature and Degree of cure with weighted coefficients a_{cp} and b_{cp}
- Other material properties for the polymer matrix (density and CTE) are modeled in a similar fashion

$$C_p = C_{p0} + a_{cp}(T - T_0) + b_{cp}(\alpha - \alpha_0)$$

$$CTE = CTE_{nom} + a_{CTE_r}(T - T_0) + b_{CTE_r}(\alpha - \alpha_0)$$

$$\rho = \rho_{nom} + a_{\rho}(T - T_0) + b_{\rho}(\alpha - \alpha_0)$$

Johnson, A (1997), "An Integrated Model of the Development of Process-Induced Deformation in Autoclave Processing of Composite Structures" P.H.D. Thesis, University of British Columbia.

Aim 1. Determination of the dimensional stability of thin-ply composites during manufacturing

Aim 1.1 – Thermo-Chemical Model Development

Aim 1.2– Flow-Compaction Model Development

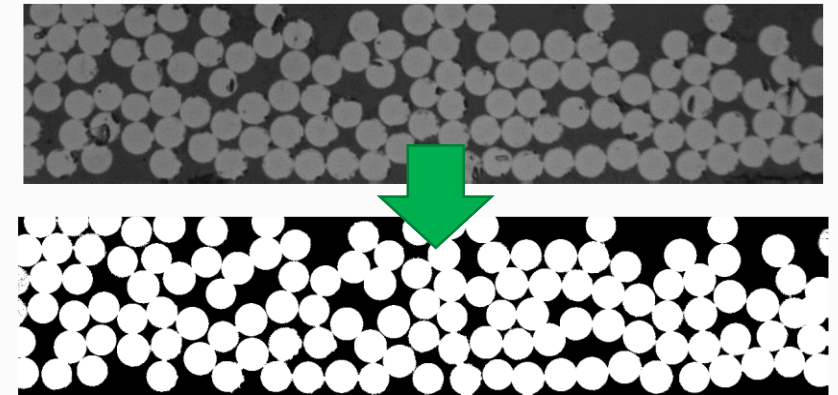
Aim 1.3 – Stress Deformation Model Development

Aim 1.4 – Stress Deformation Finite Element Analysis

Aim 1.5 – Stress Deformation Analysis Verification

Flow Compaction

- Initial Fiber Volume Fraction
 - Can be determined via micrographs or with volume and mass measurements
- Fiber Bed Compaction
 - Fiber bed assumed to be homogenous isotropic linear elastic material
 - Bulk and shear modulus calculated from Young's modulus and poison ratio
- Resin Viscosity
 - Same model used in the thermo-mechanical model



Fiber volume fraction from micrographs

$$\begin{aligned}E_{11} &= E_{22} = E_{33} = E \\ \nu_{12} &= \nu_{23} = \nu_{13} = \nu \\ k &= \frac{E(1 - \nu)}{(1 + \nu)(1 - 2\nu)} \\ G_{12} &= G_{23} = G_{13} = k \frac{(1 - 2\nu)}{2(1 - \nu)}\end{aligned}$$

Fiber bed mechanical properties

Viscosity

- A generalized version of previously developed viscosity models
- Allows for multiple Arrhenius type of relations and a quadratic term in the exponent.
- The model was implemented for CYCOM 890RTM epoxy resin

$$\mu_1 = A_1 \cdot e^{\frac{E_1}{RT}}$$

$$\mu_2 = A_2 \cdot e^{\frac{E_2}{RT}}$$

$$\mu = \begin{cases} \mu_1 + \mu_2 \cdot \left(\frac{x_{gel}}{x_{gel} - x} \right)^{(A+Bx+Cx^2)} & x < x_{gel} \\ \mu_{max} & x \geq x_{gel} \\ \mu_{max} & \mu > \mu_{max} \wedge \mu_{max} Flag = 0 \end{cases}$$

Symbol	Number	SI Units
A_1	1	Pa s
E_1	2	J/mol
A_2	3	Pa s
E_2	4	J/mol
R	5	J/mol/K
x_{gel}	6	None
A	7	None
B	8	None
C	9	None
μ_{max}	10	Pa s
$\mu_{max} Flag$	11	None

Khoun, L. (2009), "Process-Induced Stress and Deformations in Woven Composites Manufactured by Resin Transfer Moulding", PhD Thesis, Department of Mechanical Engineering, McGill University, Montreal, Quebec, Canada

Aim 1. Determination of the dimensional stability of thin-ply CFRP during manufacturing

Aim 1.1 – Themo-Chemical model development

Aim 1.2– Flow-Compaction model development

Aim 1.3 – Stress Deformation model development

Aim 1.4 – Finite Element Analysis

Aim 1.5 – Analysis Verification

Cure Shrinkage

- Determines cure shrinkage strain, V_r^S
- α_{c1} is the onset of resin cure shrinkage
- α_{c2} is the end of resin cure shrinkage
- A is a coefficient for nonlinear relationship between cure shrinkage and degree of cure

$$\begin{aligned} V_r^S &= 0.0 & \alpha < \alpha_{c1} \\ V_r^S &= A * \alpha_S + (V_r^{S\infty} - A) * \alpha_S^2 & \alpha_{c1} \leq \alpha < \alpha_{c2} \\ V_r^S &= V_r^{S\infty} & \alpha \geq \alpha_{c2} \\ \alpha_S &= \frac{\alpha - \alpha_{c1}}{\alpha_{c2} - \alpha_{c1}} \end{aligned}$$

Johnson, A (1997), "An Integrated Model of the Development of Process-Induced Deformation in Autoclave Processing of Composite Structures" P.H.D. Thesis, University of British Columbia.

Modulus Development

- All parameters are determined from combination of rheology and previously determined TGA+DSC measurements
- Isothermals (C): 120, 140, 160, 180, 200
- Dynamics (C/min): 1, 2, 3, 4, 5

$$E_r' = \begin{cases} E_r^0 + \frac{E_r^0}{(T_{C2}^* - T_{C1}^*)} (E_r^\infty - E_r^0) & T^* < T_{C1}^* \\ E_r^\infty & T_{C1}^* < T^* < T_{C2}^* \\ E_r^\infty & T^* > T_{C2}^* \end{cases}$$

$$E_r = E_r' [1 + a_{Er} (T - T_0)]$$

$$T^* = (T_{ga} + T_{gb} x) - T$$

$$T_{C1}^* = T_{C1a}^* + T_{C1b}^* T$$

Symbol	SI Units
E_r^0	Pa
E_r^∞	Pa
T_{C1a}^*	K
T_{C1b}^*	None
T_{C2}^*	K
T_{ga}	K
T_{gb}	K
T_0	Pa
a_{Er}	1/C

Strain Sweep

- Performed at 80 C (uncured, but viscous)
- Ramp strain, hold strain rate constant
- Select strain at which Viscosity vs strain slope is constant

Strain Rate Sweep

- Performed at 80 C (uncured, but viscous)
- Ramp strain rate, hold strain constant
- Select strain rate at which Viscosity vs Angular Freq. slope is constant

Isothermal Rheology

- Use strain and strain rate values determined above
- Constant temperature in curing range
- Hold for long time so resin will at least reach gel point

Dynamic Rheology

- Use strain and strain rate values determined above
- Ramp from 60 C to just before degradation temperature (from TGA)
- Perform at different heating rates

Johnston, Andrew, (1997), "An integrated Model of the Development of Process-Induced deformation in Autoclave Processing of Composite Structures", PhD Thesis, The University of British Columbia

Aim 1. Determination of the dimensional stability of thin-ply composites during manufacturing

Aim 1.1 – Thermo-Chemical Model Development

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Governing Equations

Thermo-chemical analysis

$$\frac{\partial}{\partial t}(\rho C_p T) = \frac{\partial}{\partial x} \left(k_{xx} \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k_{yy} \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(k_{zz} \frac{\partial T}{\partial z} \right) + \dot{Q}$$

$$\dot{Q} = \frac{d\alpha}{dt} (1 - V_f) \rho_r H_R$$

ρ_c, ρ_r - Density of composite and resin
 C_p - Specific heat capacity
 k_{ii} - Thermal conductivity
 $\dot{Q}$ - Resin heat generation
 α - Resin degree of cure
 H_R - Resin heat of reaction

Flow Compaction

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

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

P - Fluid pressure
 μ - Viscosity of fluid
 S - Permeability of the solid porous structure
 σ' - Effective stress tensor of the solid porous structure

Stress Deformation

$$\Pi_p = U + \Omega$$

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

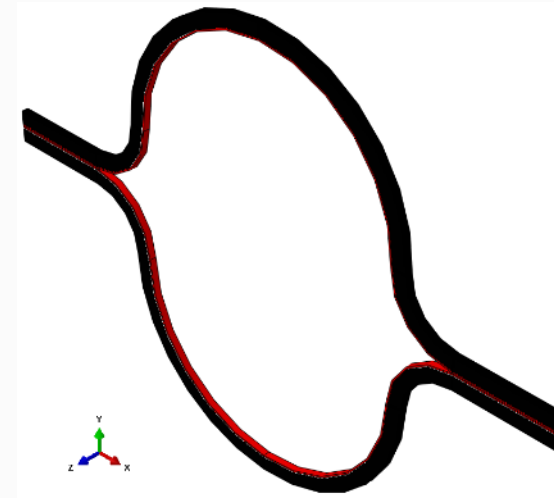
U - Internal work
 Ω - Work done by external forces
 ε - Strain tensor
 σ - Stress tensor
 ε_0 - Free/thermal strain tensor
 σ_0 - Initial stress tensor
 u - Displacement vector
 X - Body forces
 q_S - Surface forces

Abaqus+COMPRO

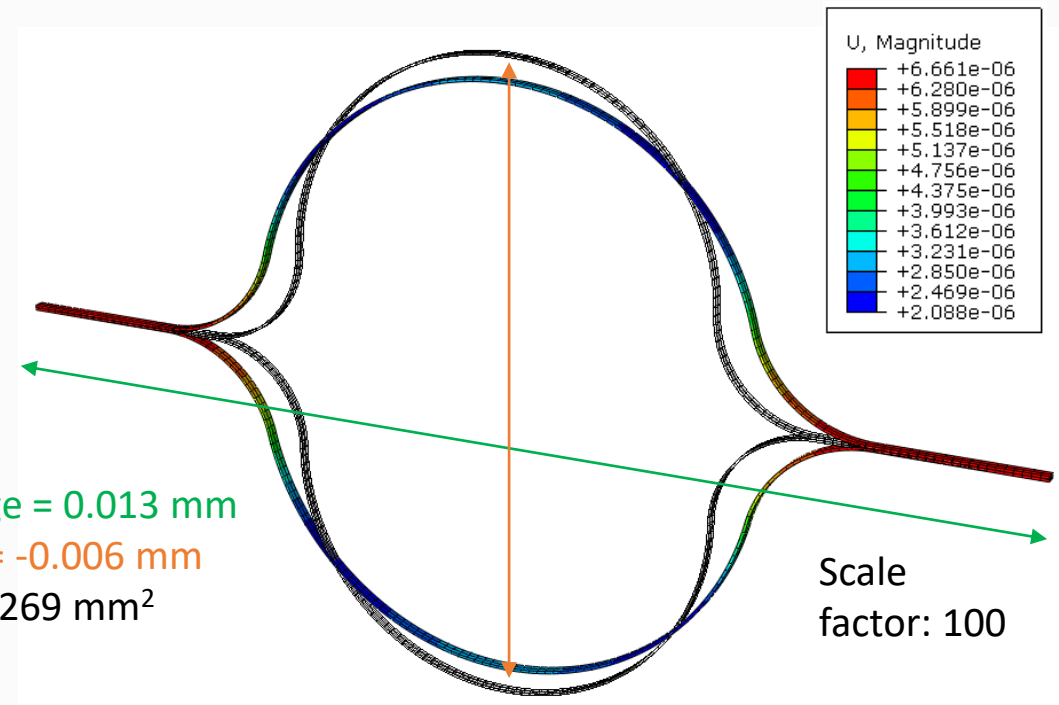
- Simplified model for initial computation
- Cross section 2D analysis
 - Tooling simplified (not entire mold is shown)
 - One ply thick (samples will be made accordingly)
- Part thickness = 0.27 mm (red in figure)
- Tooling thickness = 2.7 mm

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 mm²



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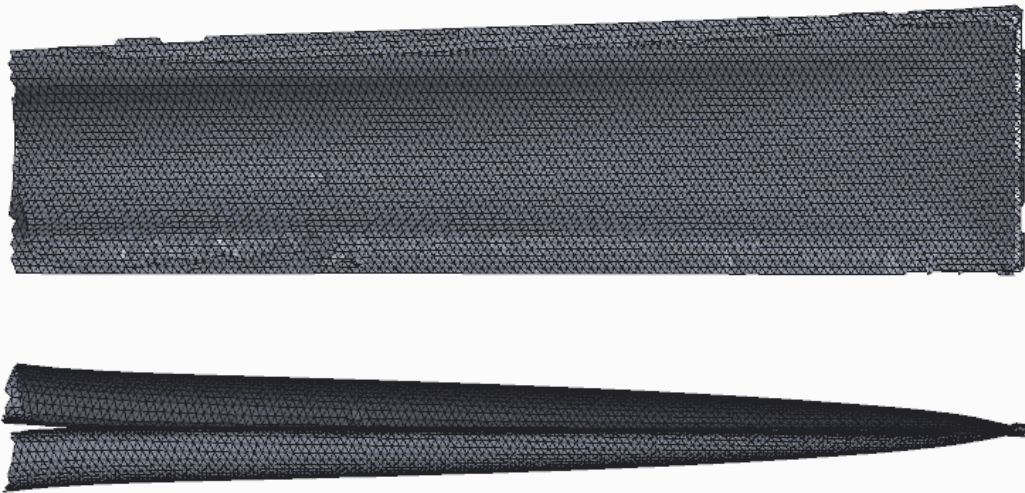
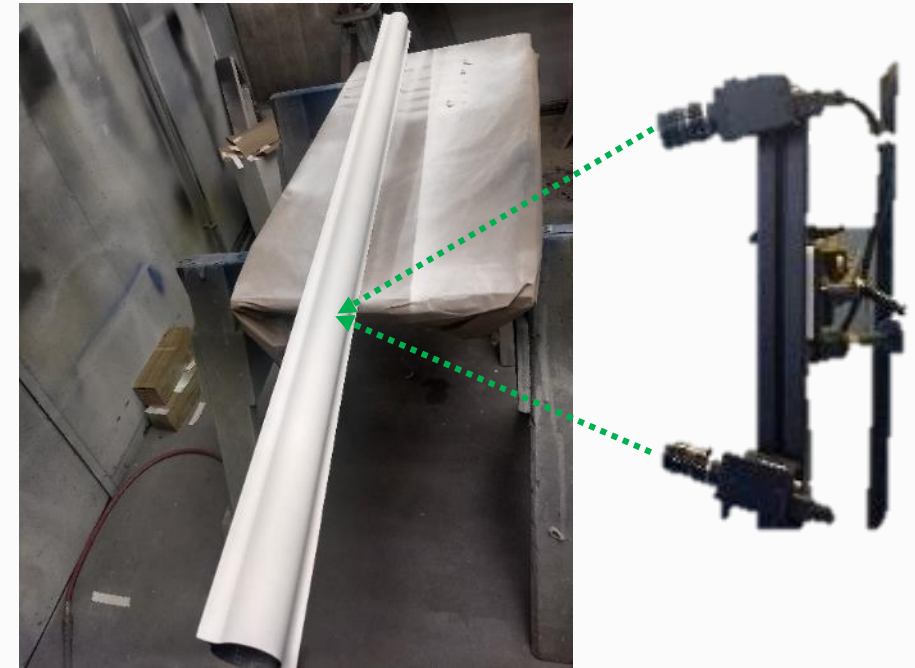
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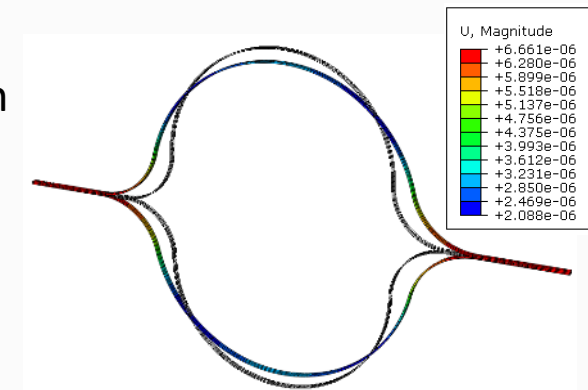
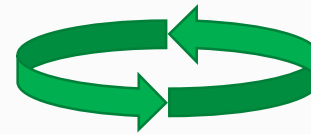
Aim 1.5 – Stress Deformation Analysis Verification

Boom 3D Mapping

- Used ARAMIS Digital Image Correlation software to map the surface of a boom
- Generates a mesh of the mapped structure
- Can be used to measure and compare manufactured dimensions against designed dimensions



FEA Model Verification



Aim 1 Summary

Large number of polymer test 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

Thermo-Chemical

$$\dot{x} = \frac{Kx^m(1-x)^n}{1 + e^{C(x-x_{C0}-x_{CT}T)}}$$
$$K = Ae^{-\Delta E/RT}$$

Flow Compaction

$$E_{11} = E_{22} = E_{33} = E$$
$$\nu_{12} = \nu_{23} = \nu_{13} = \nu$$
$$k = \frac{E(1-\nu)}{(1+\nu)(1-2\nu)}$$
$$G_{12} = G_{23} = G_{13} = k \frac{(1-2\nu)}{2(1-\nu)}$$

Stress Deformation

$$E_r' = \begin{cases} E_r^0 & T^* < T_{C1}^* \\ E_r^0 + \frac{(T^* - T_{C1}^*)}{(T_{C2}^* - T_{C1}^*)} (E_r^\infty - E_r^0) & T_{C1}^* < T^* < T_{C2}^* \\ E_r^\infty & T^* > T_{C2}^* \end{cases}$$
$$E_r = E_r' [1 + a_{Er}(T - T_0)]$$
$$T^* = (T_{ga} + T_{gb}x) - T$$
$$T_{C1}^* = T_{C1a}^* + T_{C1b}^* T$$

Finite Element Analysis ABAQUS + COMPRO

$$\Pi_p = U + \Omega$$

$$\Pi_p = \int_V \frac{1}{2} \varepsilon^T D \varepsilon dV - \int_V \varepsilon^T D \varepsilon_0 dV - \int_V \varepsilon^T \sigma_0 dV - \int_V u^T X dV - \int_S u_s^T q_s dS$$

Introduction

Research objectives – Aim 1

Discussion

Research Objectives

Aim 1. Determination of the dimensional stability of thin-ply composites during manufacturing

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

Collaborative Research Effort



University of Central Florida (UCF)

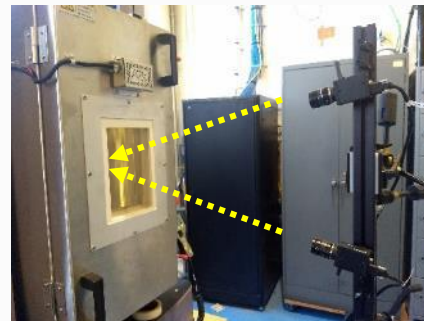
Dr. Kawai Kwok

- Abaqus + Ugens
- Viscoelastic material modeling
- Boom bending viscoelastic modeling and characterization



NASA Langley Research Center (LaRC)

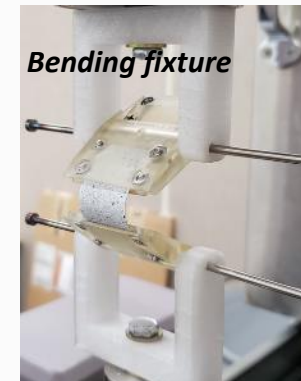
- Polymer Matrix Viscoelastic Characterization
 - Flat coupon large deformation bending relaxation
 - Boom adhesive viscoelastic characterization
 - Bending test method development for booms
- DIC system for full-field strain measurements*



Purdue University

Dr. Wenbin Yu

- Abaqus + Swiftcomp
- Viscoelastic / viscoplastic material modeling
- Full scale boom stowage modeling

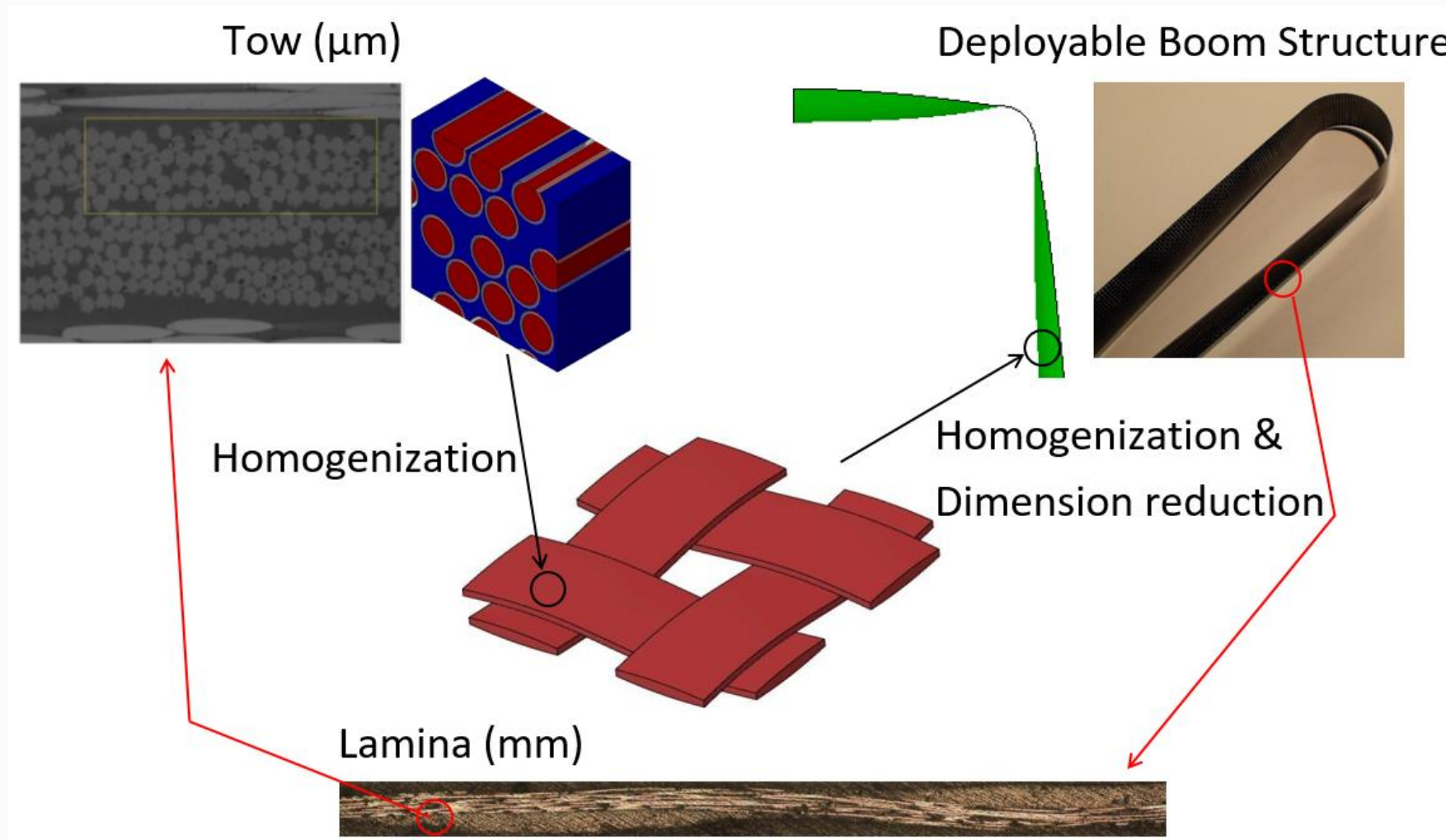


Introduction

Research objectives – Aim 2 Stowage

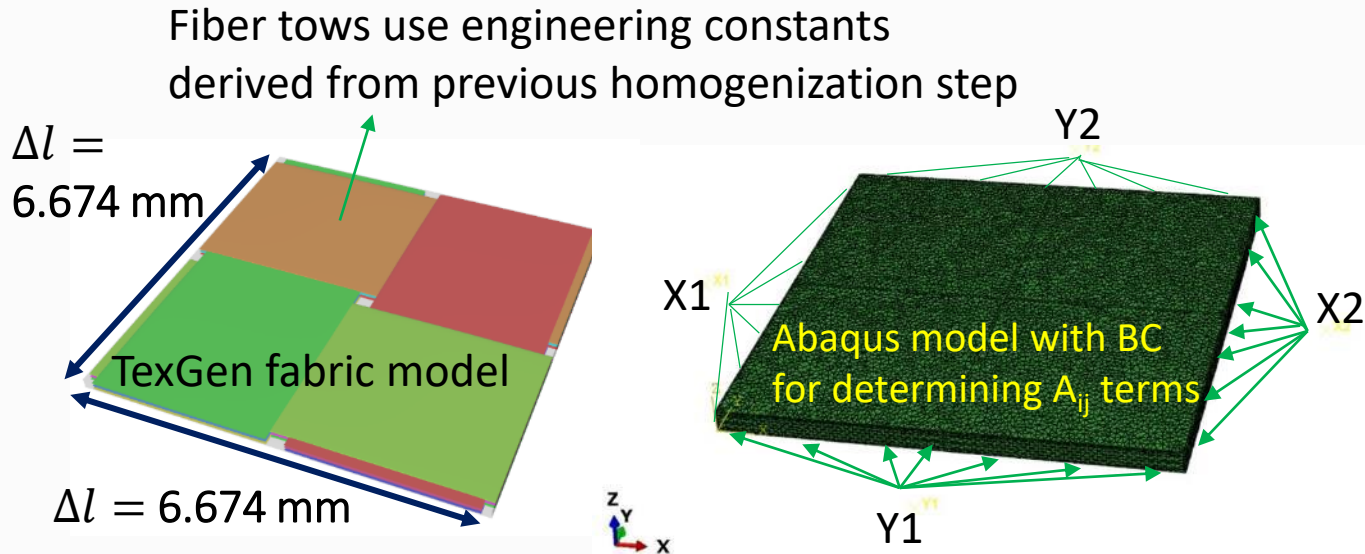
Discussion

Micromechanics Modeling Method Overview



Laminate Time-Dependent Analysis

Unit cell model for a 4-ply plain-weave laminate



Kirchhoff viscoelastic plate equations:

$$N_i(t) = \int_0^t A_{ij}(t - \tau) \frac{d\epsilon_j}{d\tau} d\tau + \int_0^t B_{ij}(t - \tau) \frac{d\kappa_j}{d\tau} d\tau$$

$$M_i(t) = \int_0^t B_{ij}(t - \tau) \frac{d\epsilon_j}{d\tau} d\tau + \int_0^t D_{ij}(t - \tau) \frac{d\kappa_j}{d\tau} d\tau$$

Relaxation ABD stiffness matrix

All entries represented with Prony series of the form:

$$A_{ij} = A_{ij,\infty} + \sum_{k=1}^n A_{ij,k} e^{-t/\rho_k}$$

$$\begin{Bmatrix} N_1 \\ N_2 \\ N_6 \\ M_1 \\ M_2 \\ M_6 \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} & B_{11} & B_{12} & B_{13} \\ A_{21} & A_{22} & A_{26} & B_{21} & B_{22} & B_{26} \\ A_{61} & A_{62} & A_{66} & B_{61} & B_{62} & B_{66} \\ B_{11} & B_{21} & B_{61} & D_{11} & D_{12} & D_{16} \\ B_{12} & B_{22} & B_{62} & D_{21} & D_{22} & D_{26} \\ B_{61} & B_{26} & B_{66} & D_{61} & D_{62} & D_{66} \end{bmatrix} \begin{Bmatrix} \epsilon_1 \\ \epsilon_2 \\ \gamma_6 \\ \kappa_1 \\ \kappa_2 \\ \kappa_6 \end{Bmatrix}$$

Prony series fitting

- A prony series is fit to the uniaxial relaxation modulus and the relaxation bending stiffness data using method of least squares:
- Relaxation modulus fitting:
 - $E_r = E_{r,\infty} + \sum_{k=1}^n E_{r,k} * e^{-\frac{t}{\rho_k}}$
- Relaxation bending stiffness fitting:
 - $D_{11} = D_{11,\infty} + \sum_{k=1}^n D_{11,k} * e^{-\frac{t}{\rho_k}}$

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

Aim 2.1 – Polymer Matrix Viscoelastic Characterization

Aim 2.2– Polymer Adhesive Viscoelastic Characterization

Aim 2.3 – Composite Coupon Viscoelastic Bending Characterization

Aim 2.4 – Composite Structure Viscoelastic Bending Characterization

Aim 2.5 – Full structure stowage testing

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

Aim 2.1 – Polymer Matrix Viscoelastic Characterization

Aim 2.2– Polymer Adhesive Viscoelastic Characterization

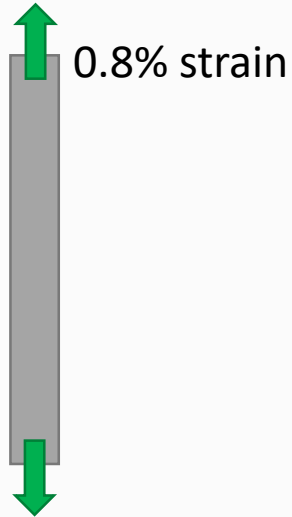
Aim 2.3 – Composite Coupon Viscoelastic Bending Characterization

Aim 2.4 – Composite Structure Viscoelastic Bending Characterization

Aim 2.5 – Full structure stowage testing

Relaxation modulus relative to 30°C for PMTF7 in Tension

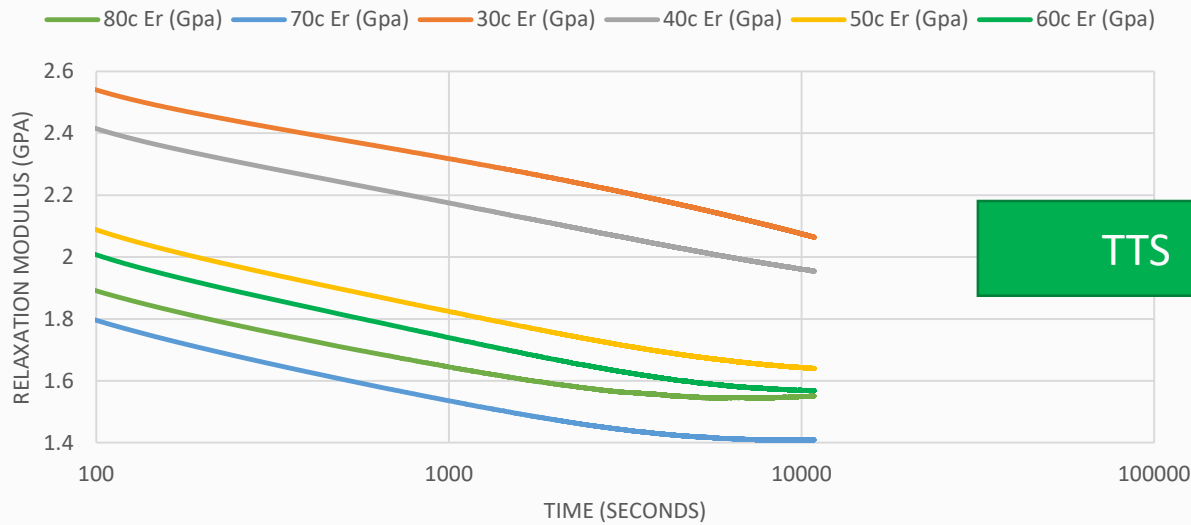
- A strain history is applied to a polymer sample
- Held for 3 hours
- Repeated at different temperatures



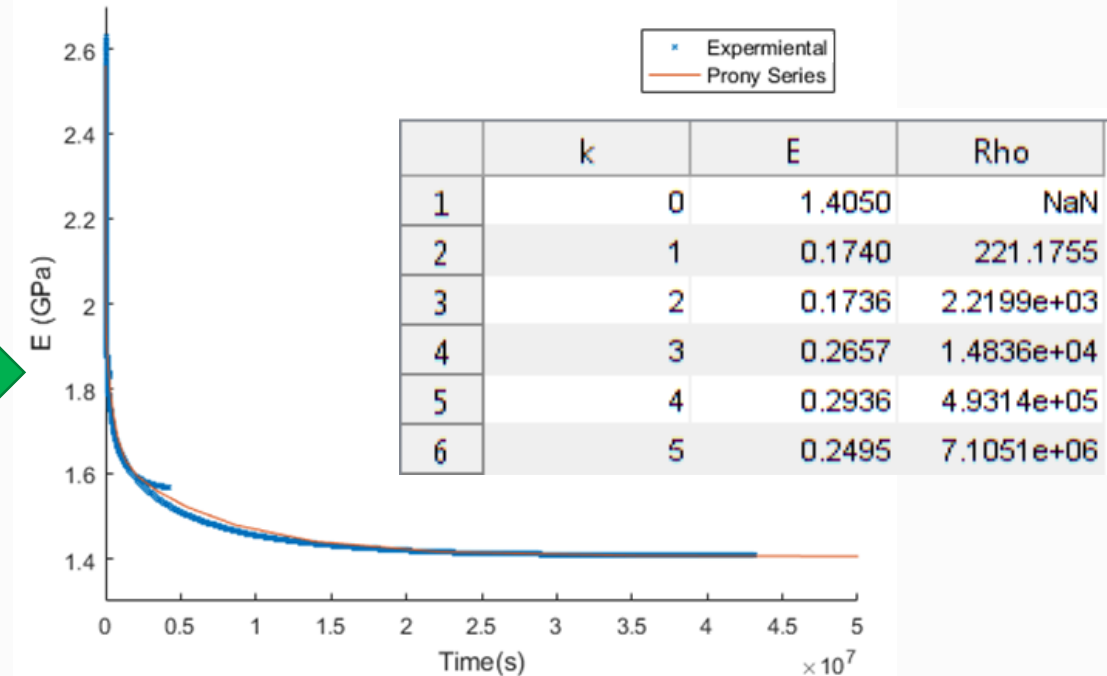
- *Pron series data fit*

$$E_r = E_{r,\infty} + \sum_{k=1}^n E_{r,k} * e^{-\frac{t}{\rho_k}}$$

RELAXATION MODULUS



TTS



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

Aim 2.1 – Polymer Matrix Viscoelastic Characterization

Aim 2.2– Polymer Adhesive Viscoelastic Characterization

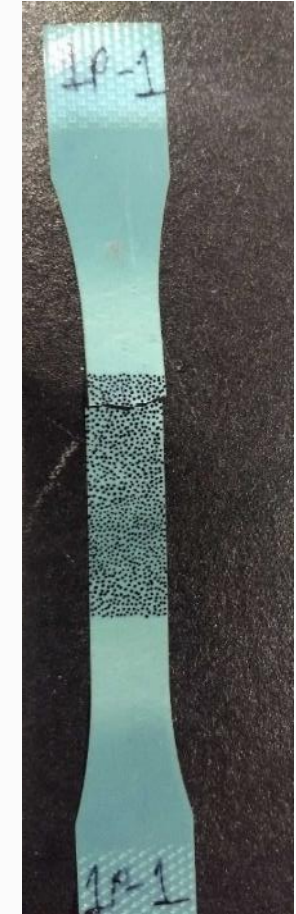
Aim 2.3 – Composite Coupon Viscoelastic Bending Characterization

Aim 2.4 – Composite Structure Viscoelastic Bending Characterization

Aim 2.5 – Full structure stowage testing

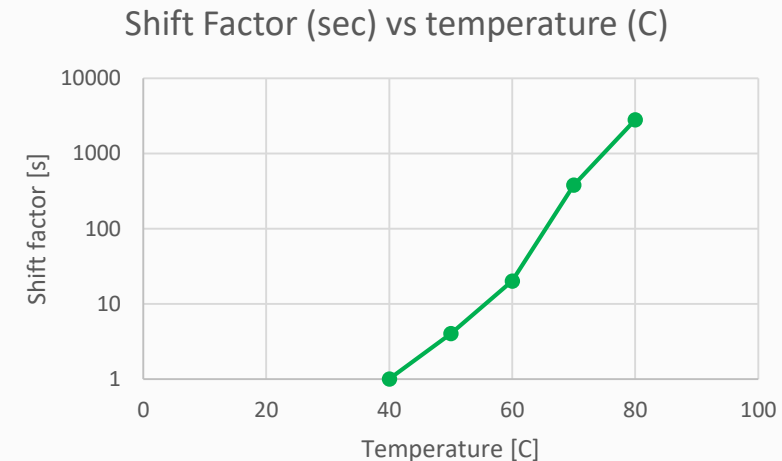
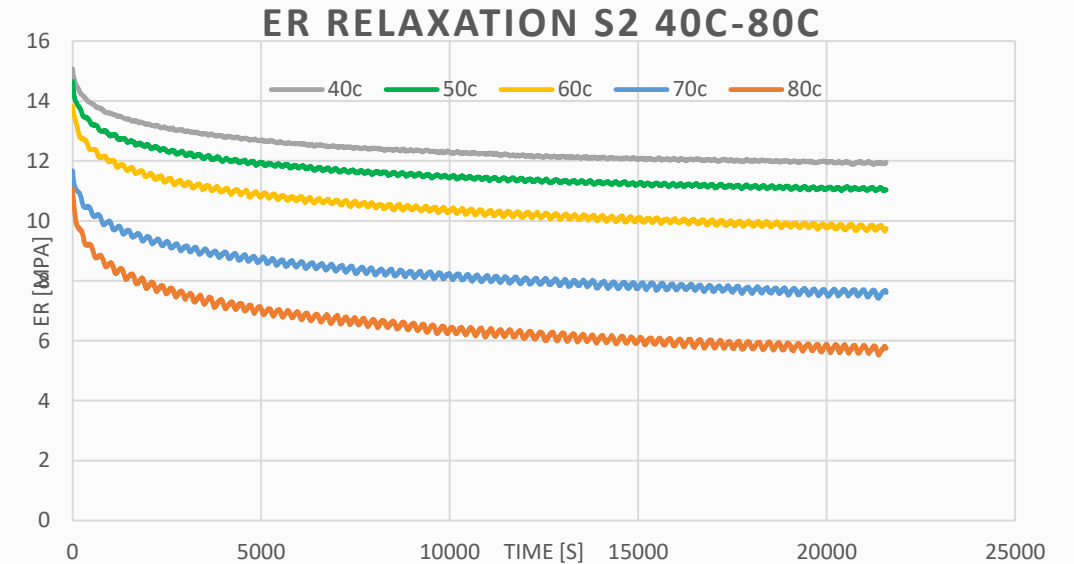
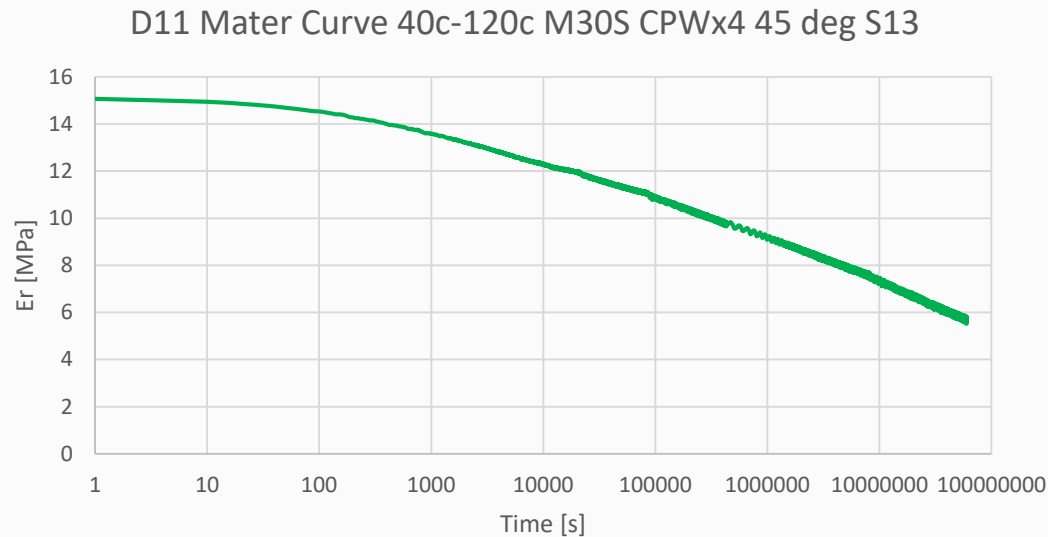
Polymer Adhesive testing

- Specimen was laser cut with a picosecond UV Laser into the shape of a dog bone
- A displacement of 0.04 inches was applied at rate of 0.04 in/min
- The displacement was held for 6 hours
- Creep recover at 0 load was then carried out for 2 hours
- This process was repeated, increasing the temperature by 10c each time up to 80c



Adhesive Tensile Relaxation Preliminary Results

- The relaxation curves for all 5 temperatures are plotted to the right
- For this preliminary test the dog bone may not have been aligned in the grips perfectly



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

Aim 2.1 – Polymer Matrix Viscoelastic Characterization

Aim 2.2– Polymer Adhesive Viscoelastic Characterization

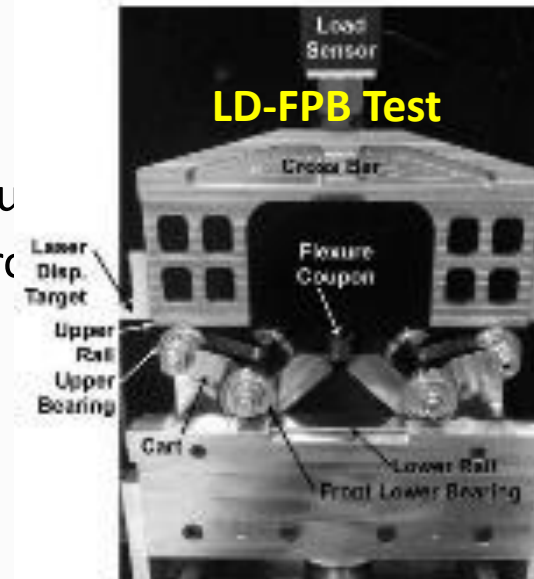
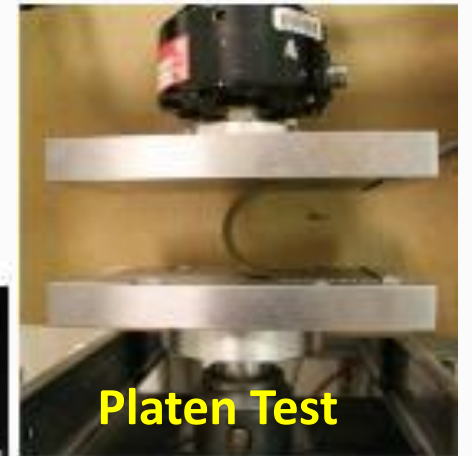
Aim 2.3 – Composite Coupon Viscoelastic Bending Characterization

Aim 2.4 – Composite Structure Viscoelastic Bending Characterization

Aim 2.5 – Full structure stowage testing

Current High Deformation Bending test

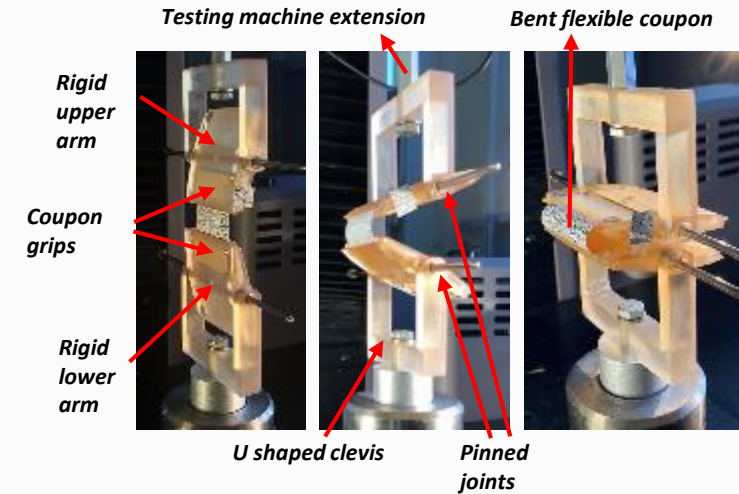
- Simple Vertical Test with tape hinges are prone to gravity-induced lateral loads and moments that tend to produce coupon/tape shear distortion at large rotation angles or induced curvatures.
- Platen Test generates a small localized region of high curvature in coupon apex, well away from coupon ends, that result in uncharacteristically high failure curvatures.
- Large Deformation Four-Point Bending (LD-FPB) subjects the coupon to a pure bending stress state, However, the abrupt transition from flat to curved causes premature failure at test grips (stress concentration).



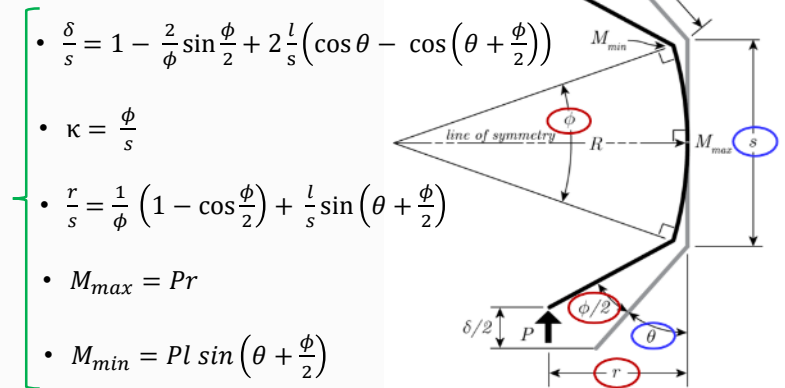
40

Column Bending Test (CBT)

- CBT method initially developed by Opterus R&D and LaRC: Fernandez, Murphey, AIAA 2018-0942.
- Test setup consists of double-symmetric weight-balanced rigid fixtures arms which firmly clamp the specimen.
- 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
 - 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).
 - 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.



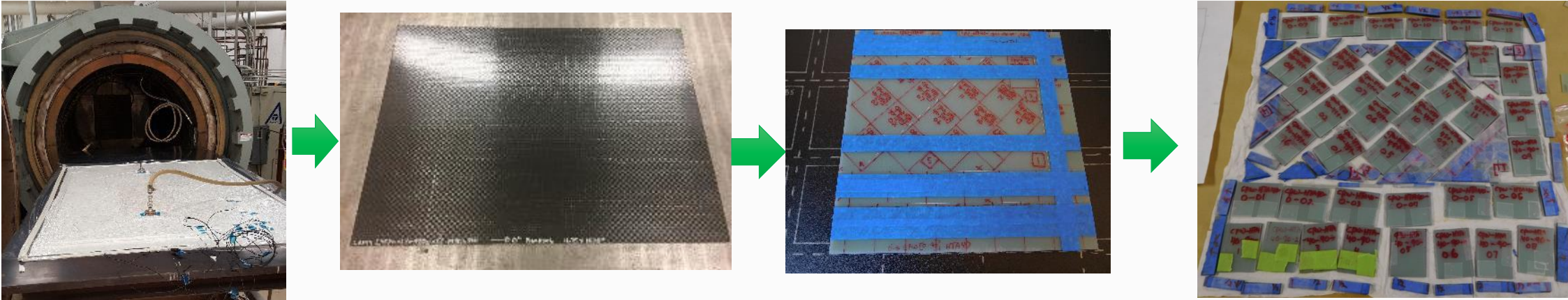
CBT Kinematics: numerically calculating r and ϕ



Output: Bending Stiffness $D_{11}^* = \frac{M_{max}}{\kappa}$

11

Composite Coupon Preparation



Test Coupon fabrication and painting

- Laminates laid by Kevin McLain in an autoclave at 14 psi and 350°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



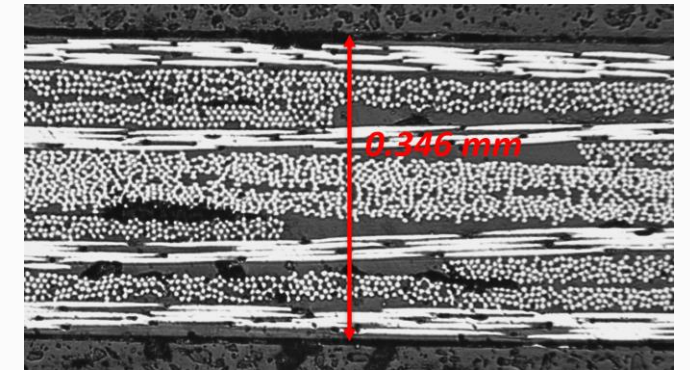
Composite Coupon Preparation

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	$[\pm 45\text{PW}]_4$	4	250 ± 10
M30S PW_0_x4	$[0-90\text{PW}]_4$	4	250 ± 10
LAM1_0_x6	$[\pm 45\text{PW}_2/0\text{UD}_2/\pm 45\text{PW}_2]$	5	330 ± 10
LAM1_90_x6	$[\pm 45\text{PW}_2/90\text{UD}_2/\pm 45\text{PW}_2]$	5	330 ± 10

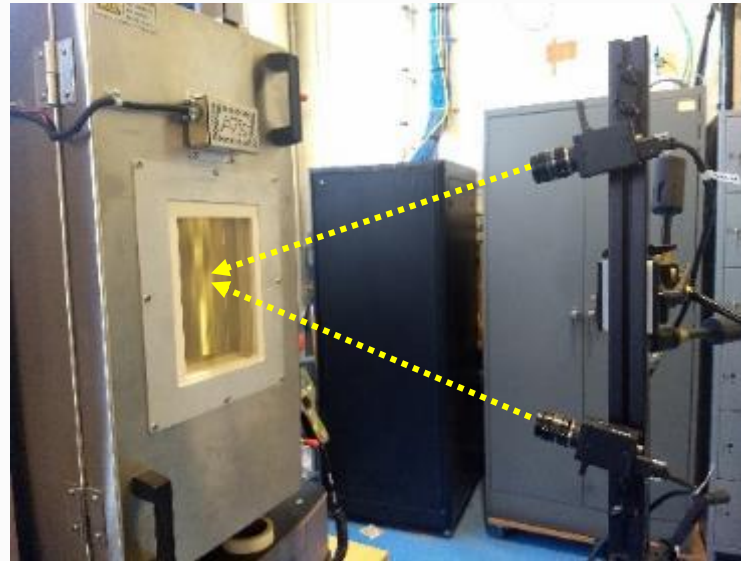


LAM1_0_x6

Material (fiber/resin)	Spread-tow Fabric Form	Width (mm)	FAW (g/m^2)	Ply AW (g/m^2)	FVF (%)	Cured Ply Thickness (μm)	E_1 (GPa)	E_2 (GPa)	ν_{12}	G_{12} (GPa)	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

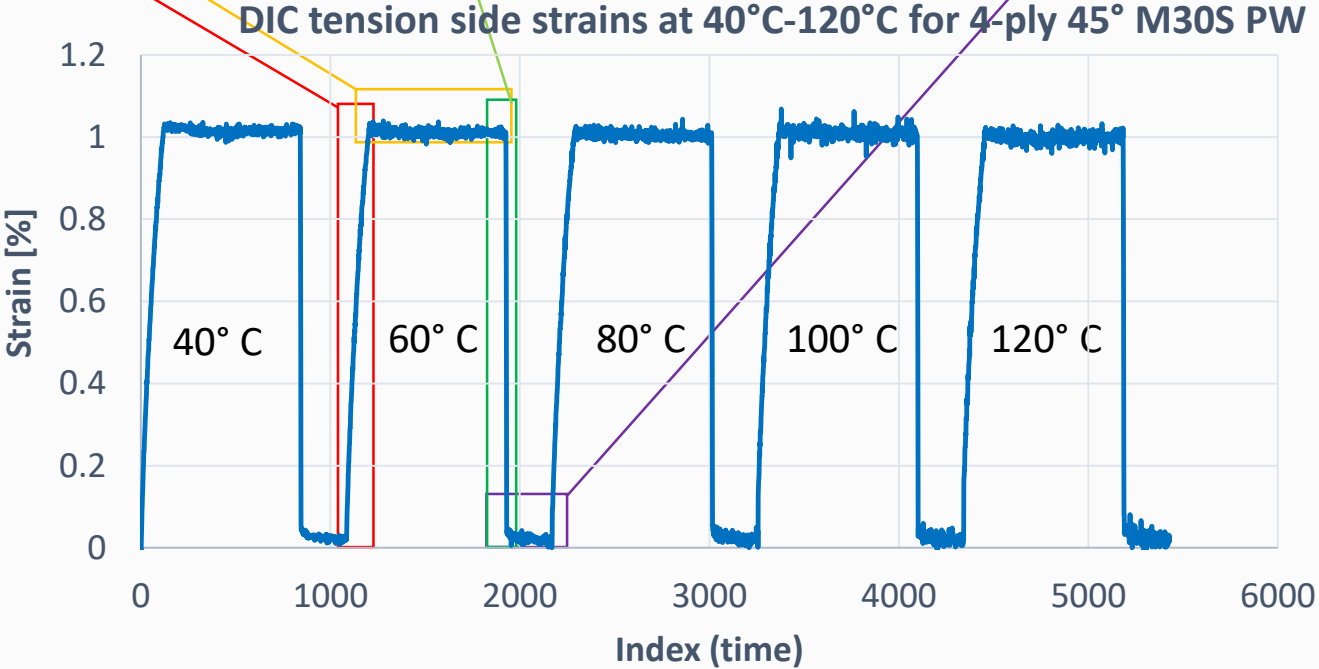
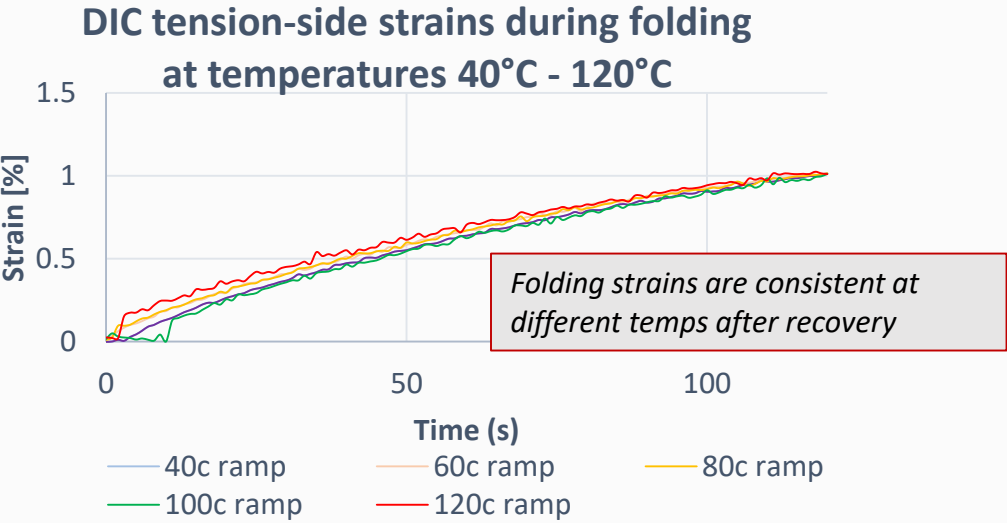
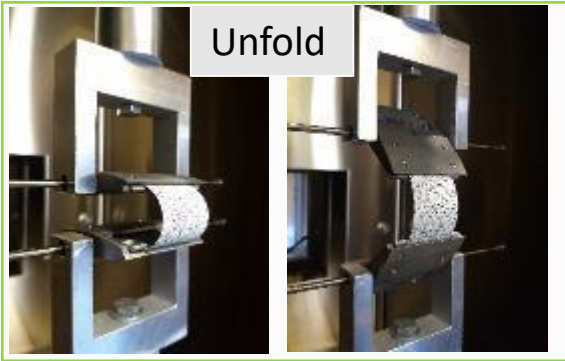
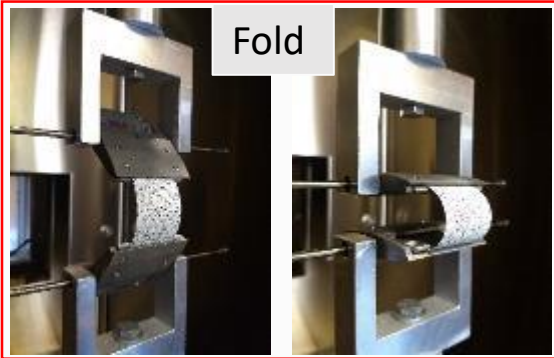
- Coupons were installed in CBT fixtures with pre determined gage lengths depend on material and laminate
- The CBT fixtures were then installed in the thermal chamber and it was set to testing temperature and allowed to equilibrate for 90 minutes
- MTS Load is zeroed at half the weight of the CBT clamps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



CBT Test Procedure for Viscoelastic Characterization

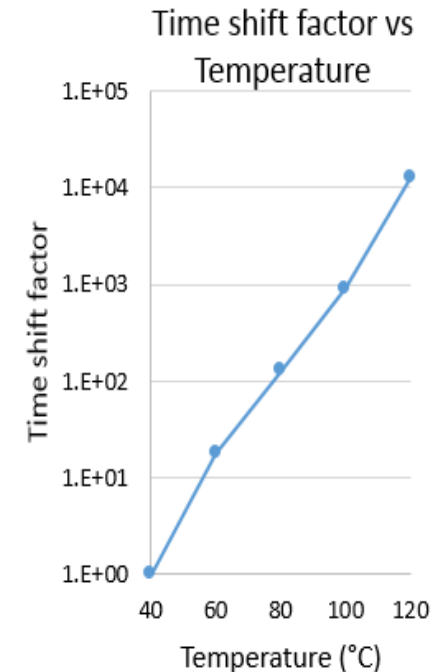
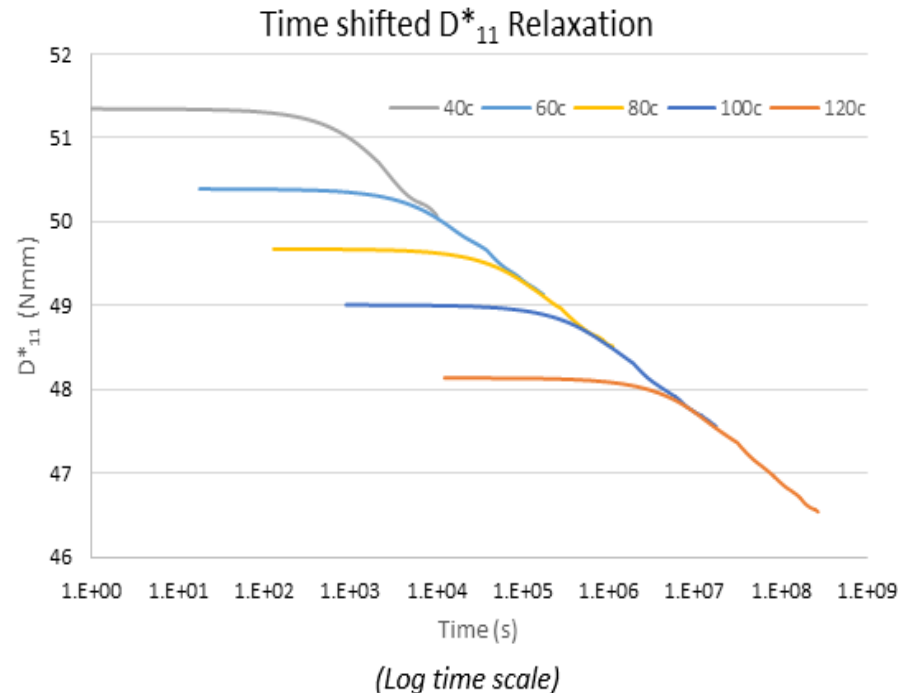
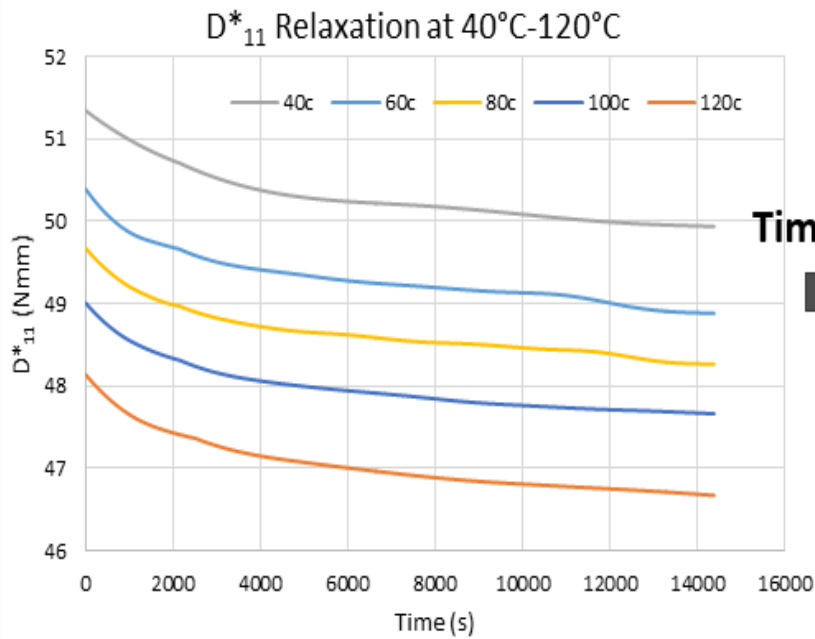
Test parameters adopted in this study

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



Bending Relaxation Characterization Method

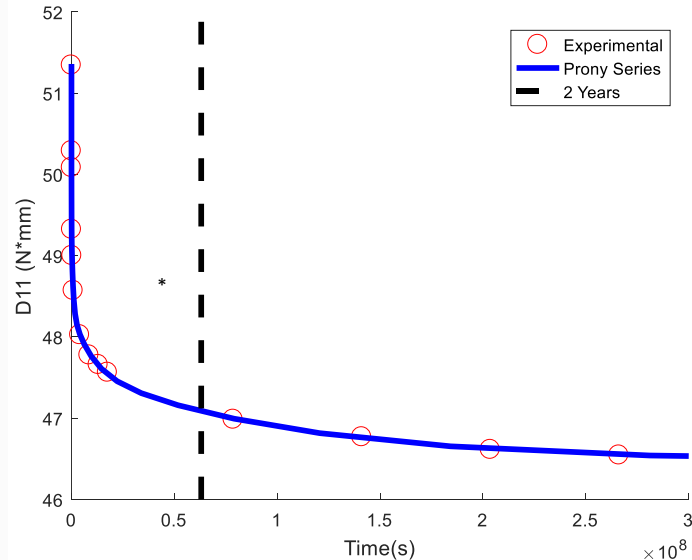
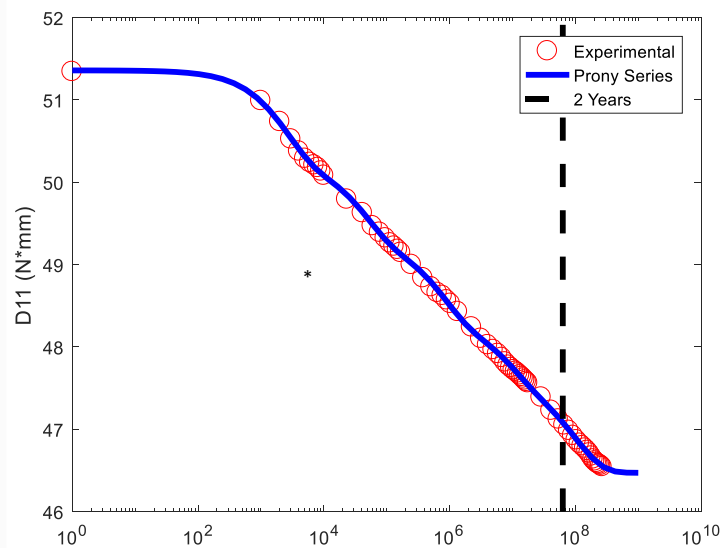
- CBT Bending relaxation tests of 4-ply $\pm 45^\circ$ PW (M30S/PMT-F7) laminate performed at 40 - 120 $^\circ\text{C}$ in 20 $^\circ\text{C}$ increments.
- Bending relaxation data shifted to form a master curve at 40 $^\circ\text{C}$ (expected max stowage temperature) using Time-Temperature-Superposition 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.



Bending Relaxation Characterization Method

- 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 ($D_{11}^*(t) = \frac{M_1(t)}{K_1 \Delta l}$) terms shown for one $\pm 45^\circ$ PW sample.
- The long-term coefficient ($D_{11,\infty}^*$) 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		
k	ρ_k (s)	$D_{11,k}^*$ (Nmm)	k	ρ_k (s)	$D_{11,k}^*$ (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

Introduction

Research objectives – Aim 2.3 Composite Coupon

Discussion

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

Aim 2.1 – Polymer Matrix Viscoelastic Characterization

Aim 2.2– Polymer Adhesive Viscoelastic Characterization

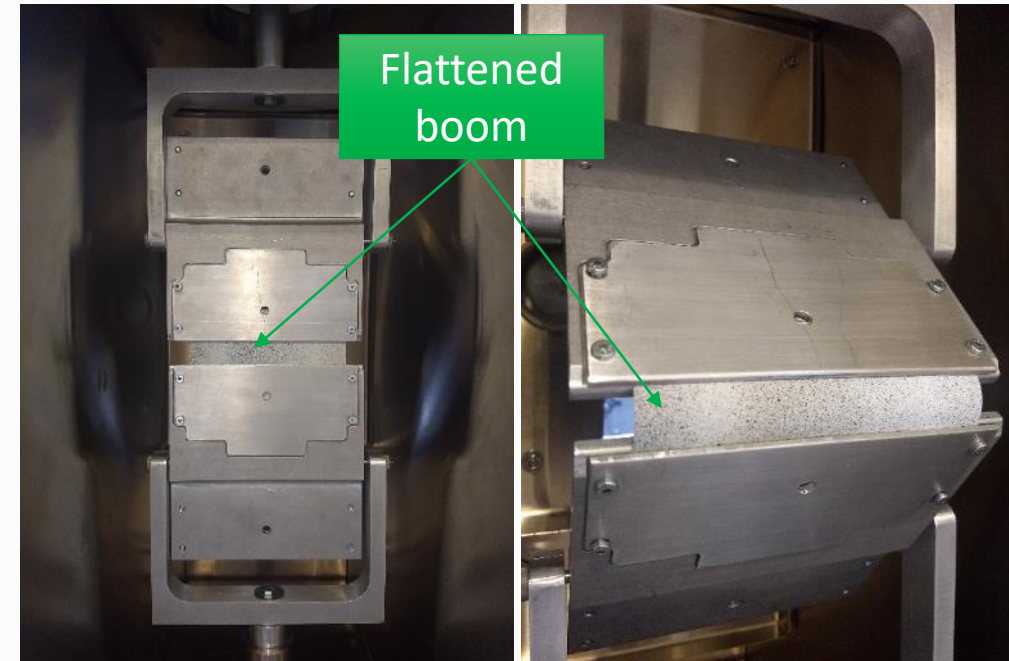
Aim 2.3 – Composite Coupon Viscoelastic Bending Characterization

Aim 2.4 – Composite Structure Viscoelastic Bending Characterization

Aim 2.5 – Full structure stowage testing

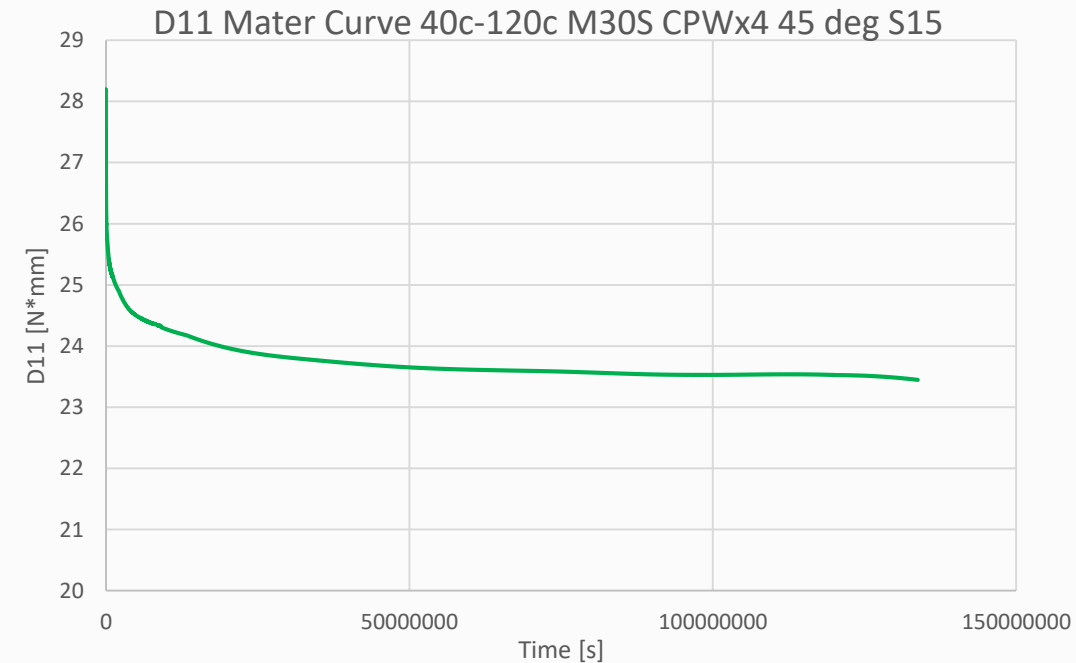
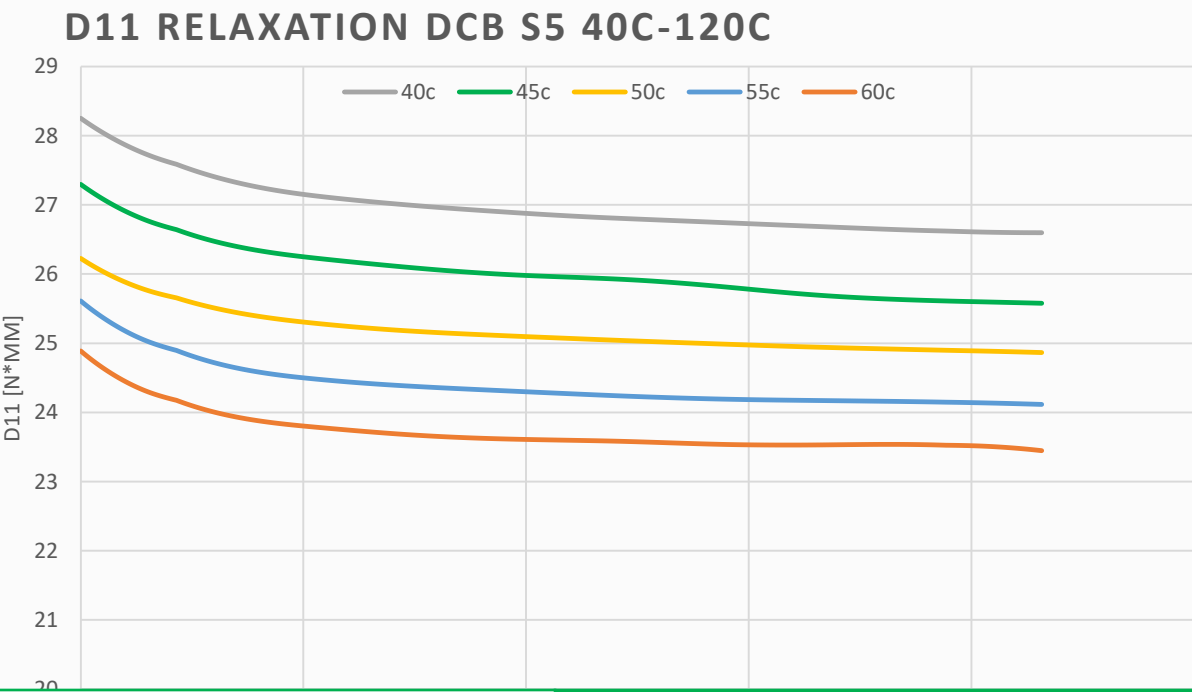
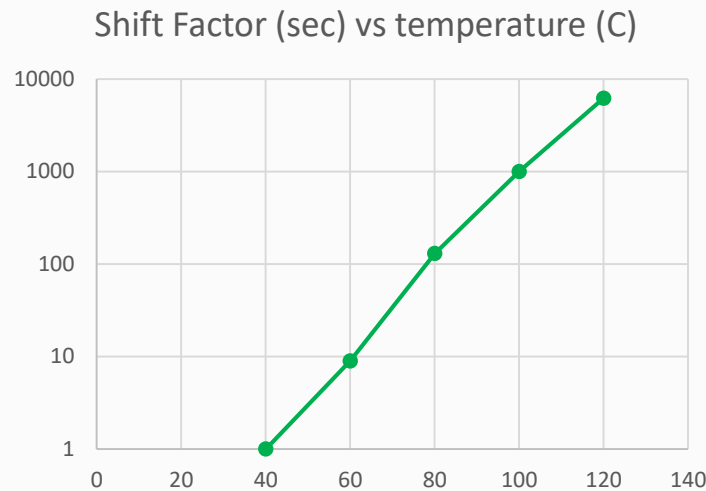
CBT test setup

- Boom is painted white and speckled with black paint then cut into 6 inch sections
- CBT clamps are secured for alignment
- 1 inch gage blocks used to separate the clamps while inserting and clamping a section of the boom
- CBT fixture with clamped Boom Inserted into top CBT clevis and the load is recorded
- The bottom CBT clamp is attached to the bottom clevis, everything is secured and the load is brought to $\frac{1}{2}$ the recorded load
- 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
- At the end of Recovery creep the temperature is increased and the steps are repeated
- The initial/reference temperature is 40c and is increased by 5c until 60c (5 times)



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 were 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



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

Aim 2.1 – Polymer Matrix Viscoelastic Characterization

Aim 2.2– Polymer Adhesive Viscoelastic Characterization

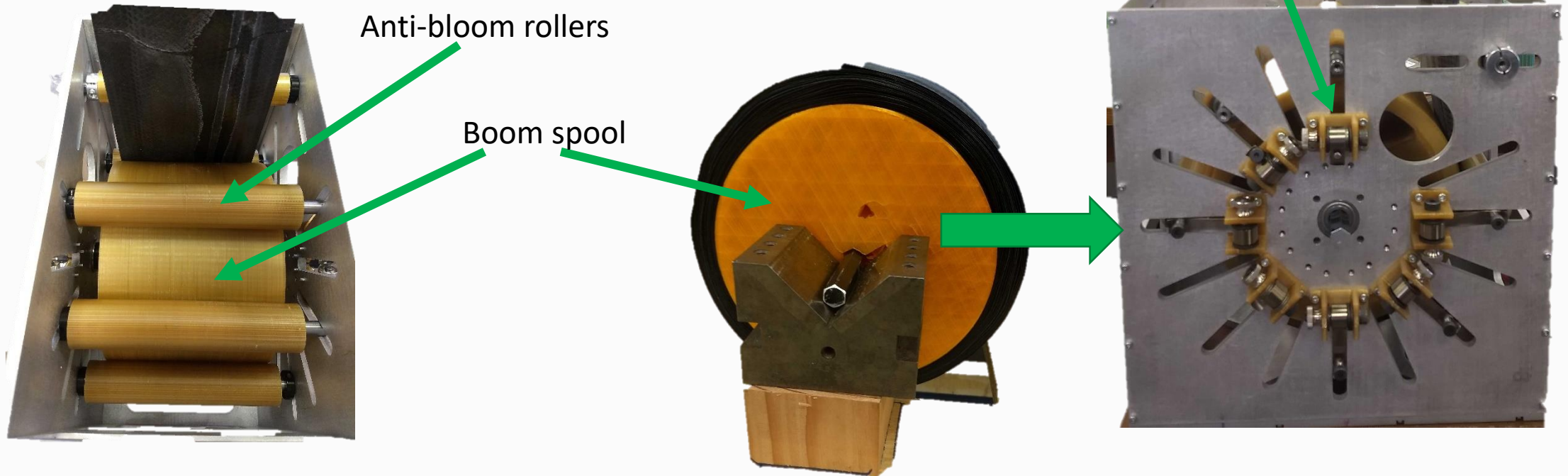
Aim 2.3 – Composite Coupon Viscoelastic Bending Characterization

Aim 2.4 – Composite Structure Viscoelastic Bending Characterization

Aim 2.5 – Full structure stowage testing

Full scale boom stowage test

- Measure time-dependent deploying force
- Calculate Full boom bending stiffness based on curvature
- Determine bending stiffness relaxation
- Compare results with CBT testing



Aim 2 Summary

Deployable Composite Stowage testing

Polymer Matrix Testing

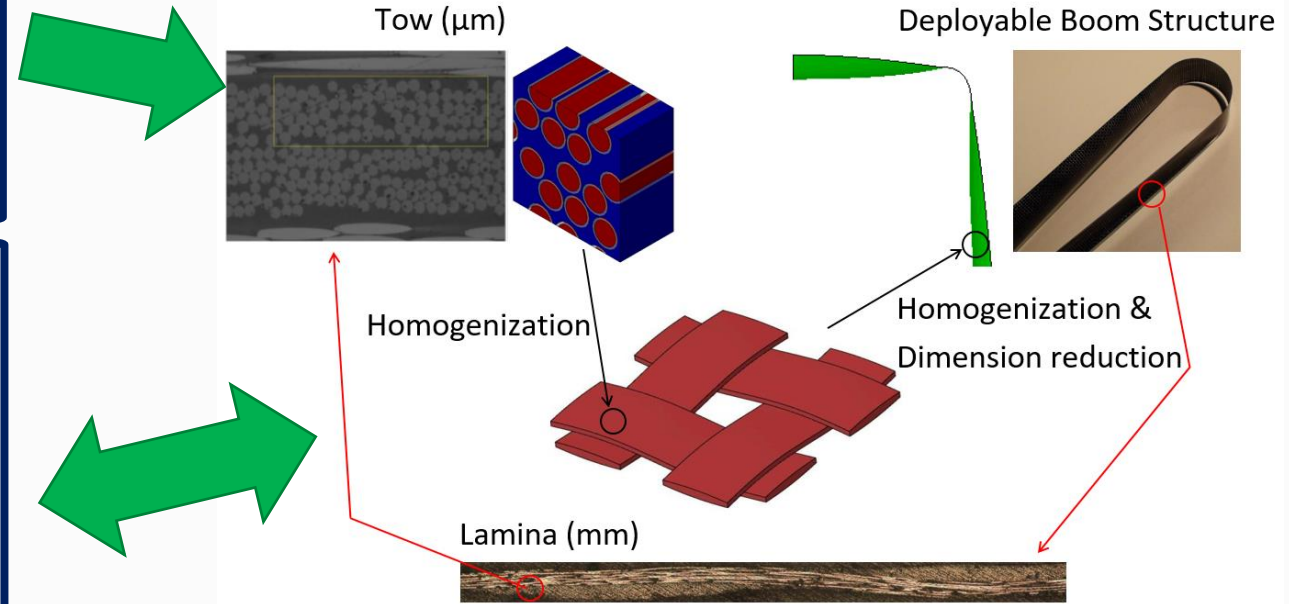
Polymer Adhesive Testing

Composite coupon bending

Composite Boom bending

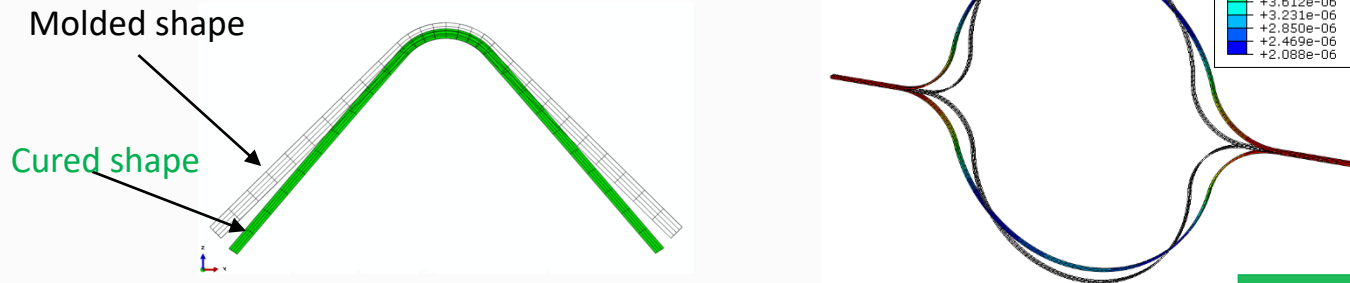
Full boom stowage Test

Micromechanical Modeling

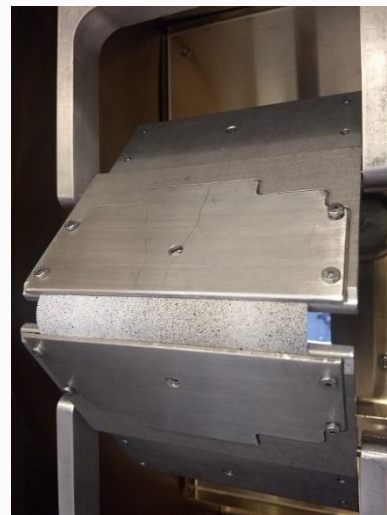


Summary

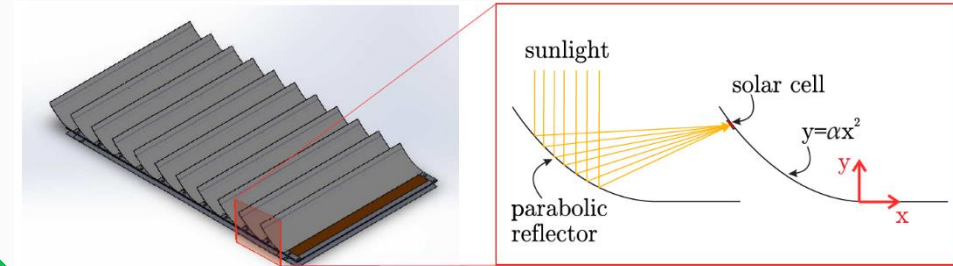
Dimensional stability of thin-ply composites post curing



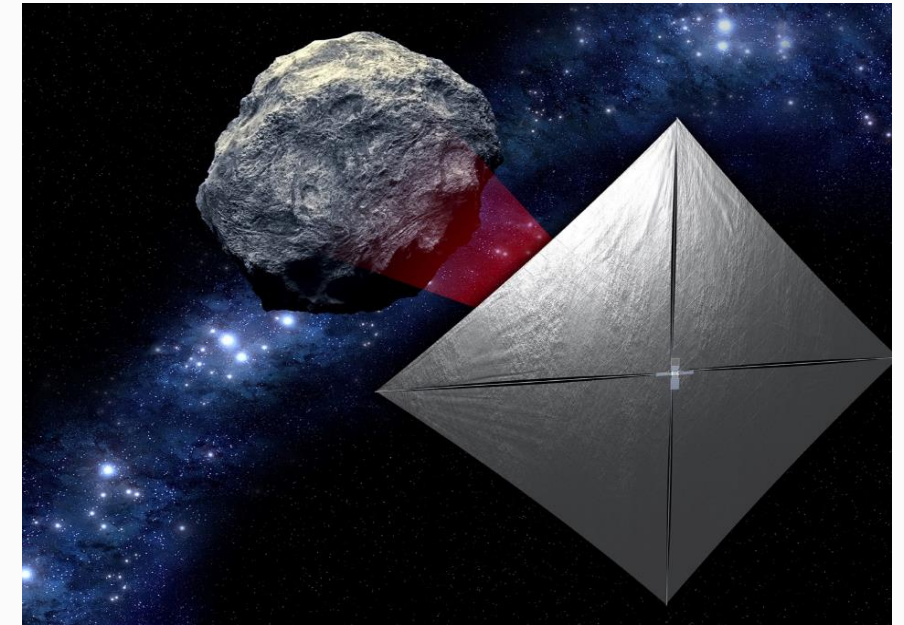
Dimensional stability of thin-ply composites post stowage



Improved thin ply deployable composite structures



Bosi, F., Et al, Cure-induced deformation of ultra-thin composite laminates, AIAA SciTech Forum, 8-12 (2018)



Introduction

Research objectives

Discussion

Timeline

Task	Fall 2018	Spring 2019	Summer 2019	Fall 2019	Spring 2020	Summer 2020	Fall 2020
Aim 1 Dimensional Stability During Manufacturing							
Thermo-Chemical Model							
Flow Compaction Model							
Stress Deformation Model							
Cure deformation FEA							
Cure Deformation FEA Verification							
Paper writing							
Aim 2 Dimensional Stability During Stowage							
Polymer Matrix Characterization							
Composite Coupon Characterization							
Composite Strucutre Characterization							
Adhesive Characterization							
Stowage Testing							
Paper writing							
Dissertation							
Writing							
Defense							

Introduction

Research objectives

Discussion

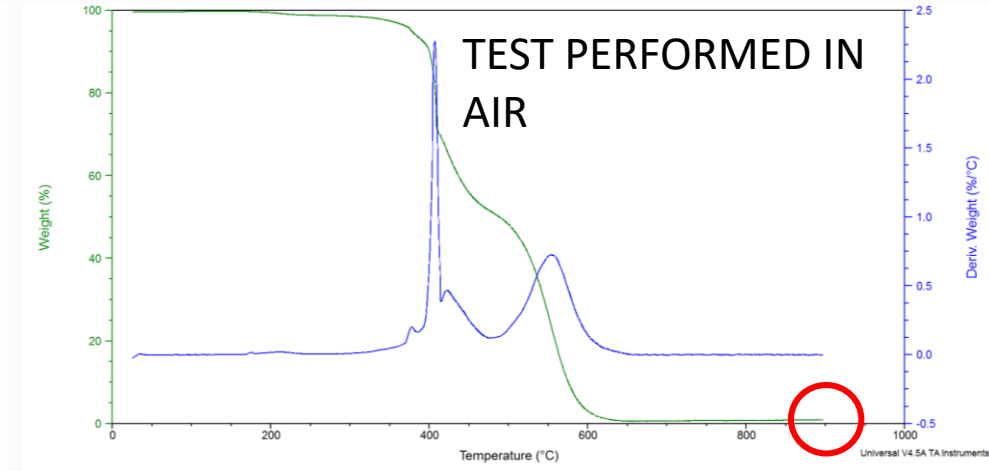
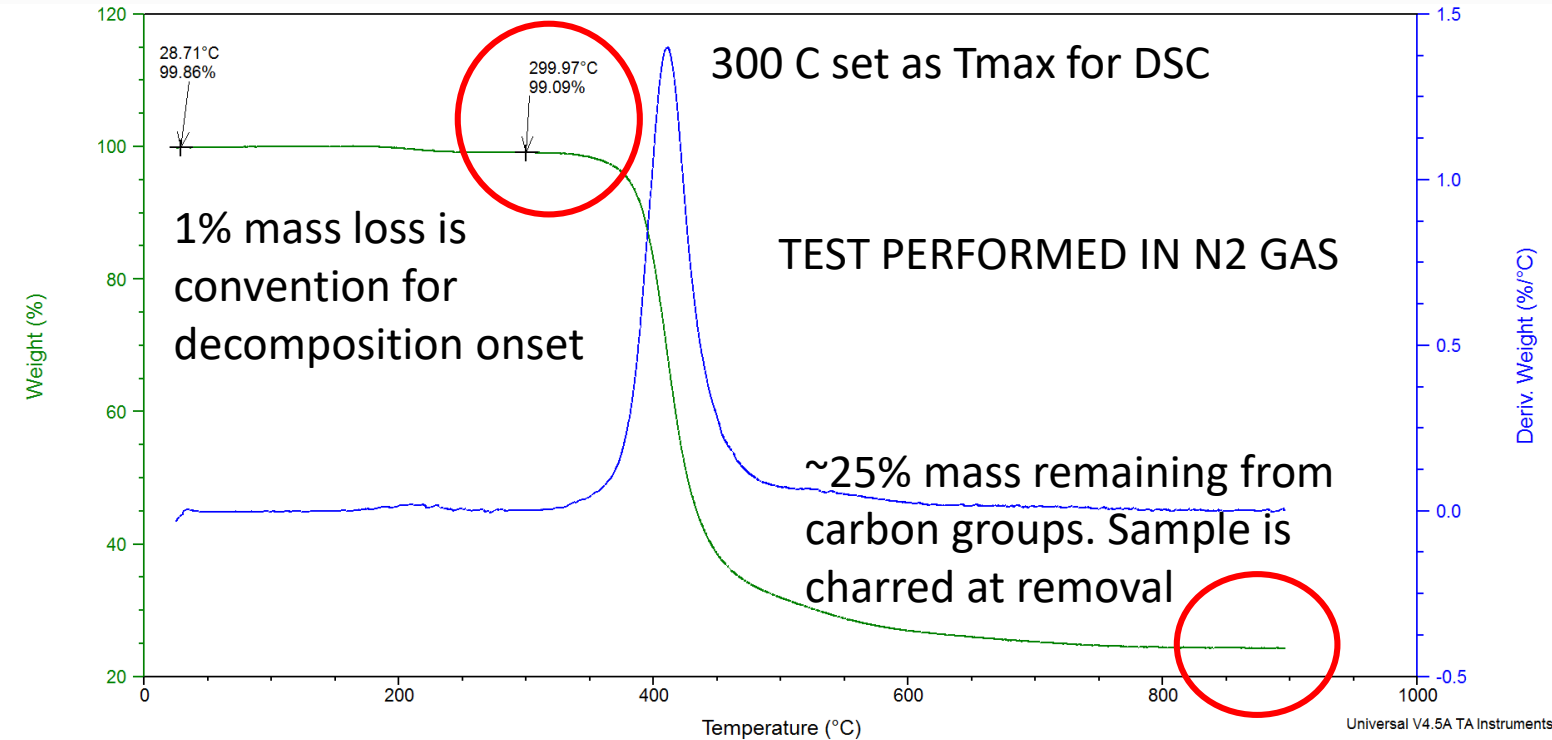
Thank you!

Questions?



Back-up Slides

Thermogravimetric Analysis (TGA) on PMTF7

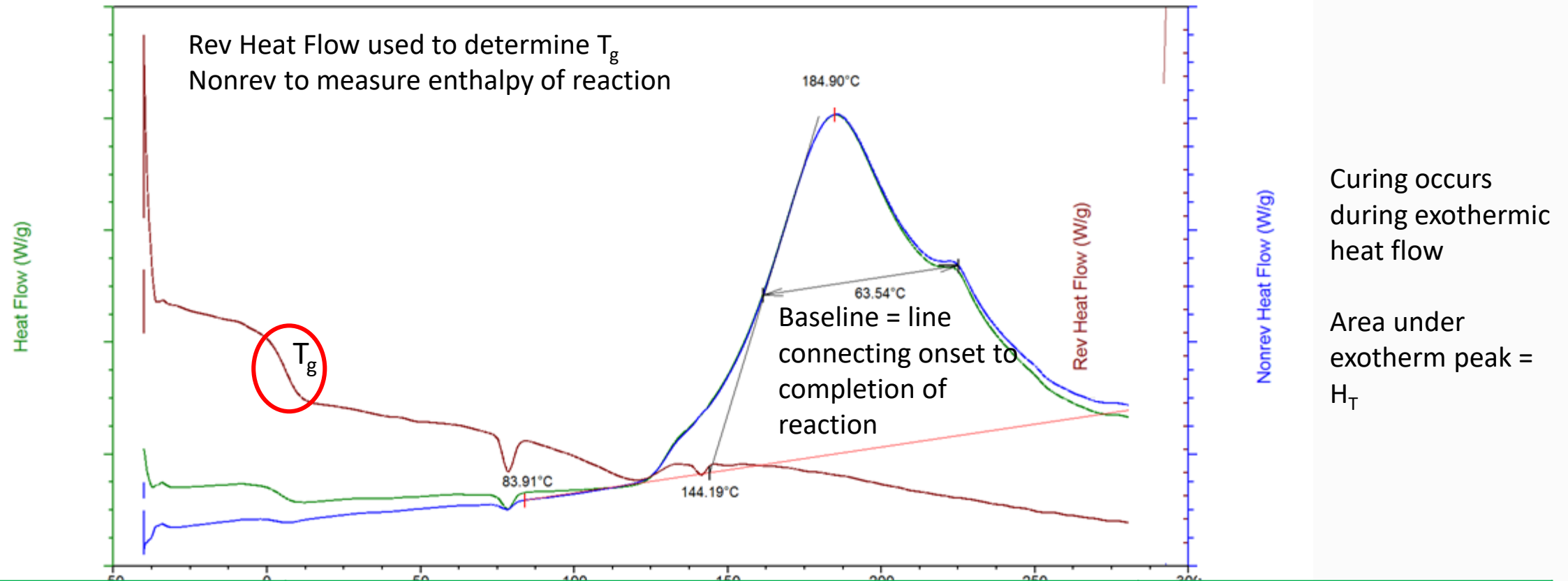


<1% mass remaining indicates no inorganics present in sample (i.e. silica). No remains of sample at removal

Differential Scanning Calorimetry (DSC)

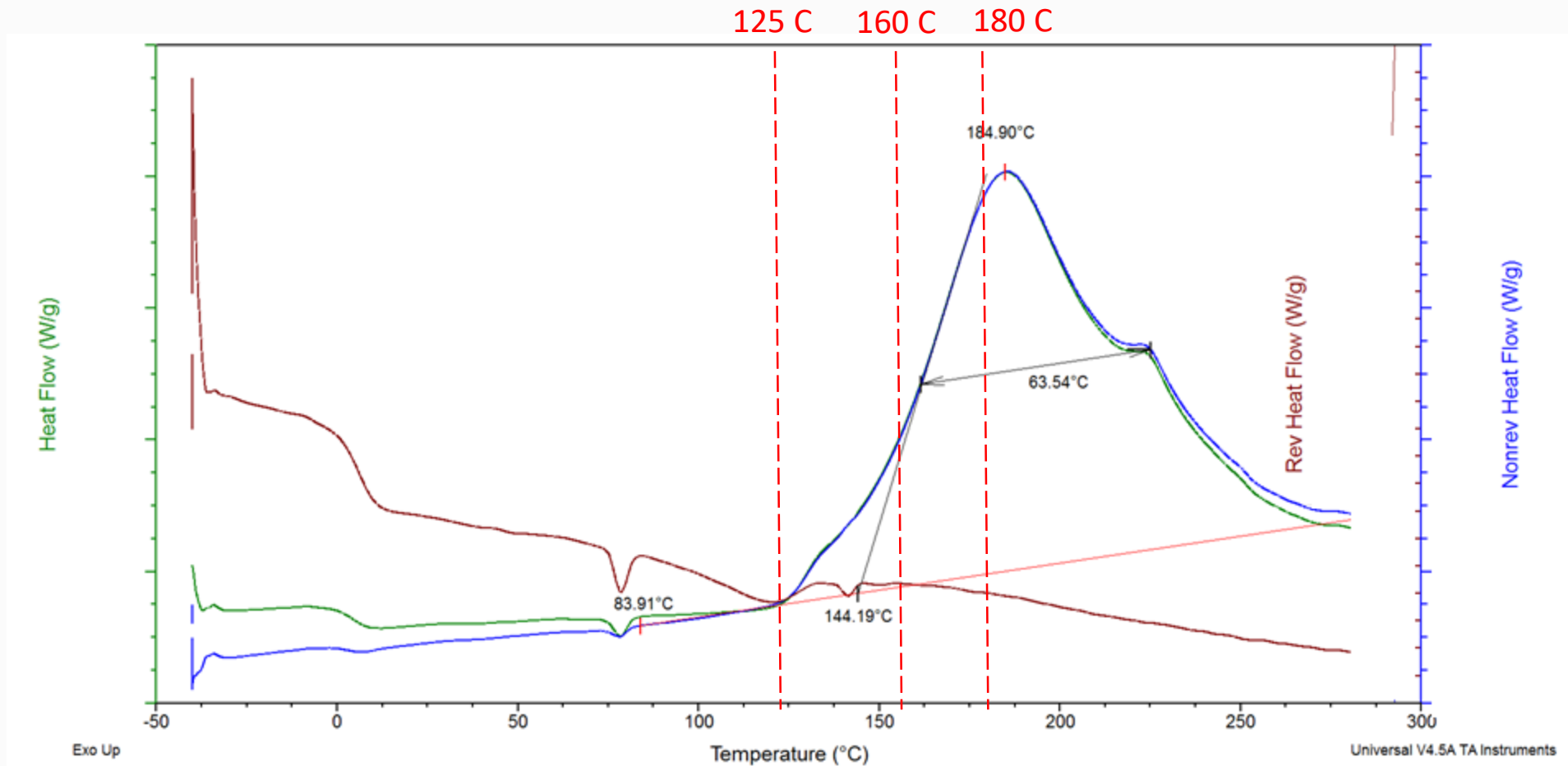
Sweep Test

3 C/min, -40 C → 295 C



Differential Scanning Calorimetry (DSC)

Isothermal Temperature Selection

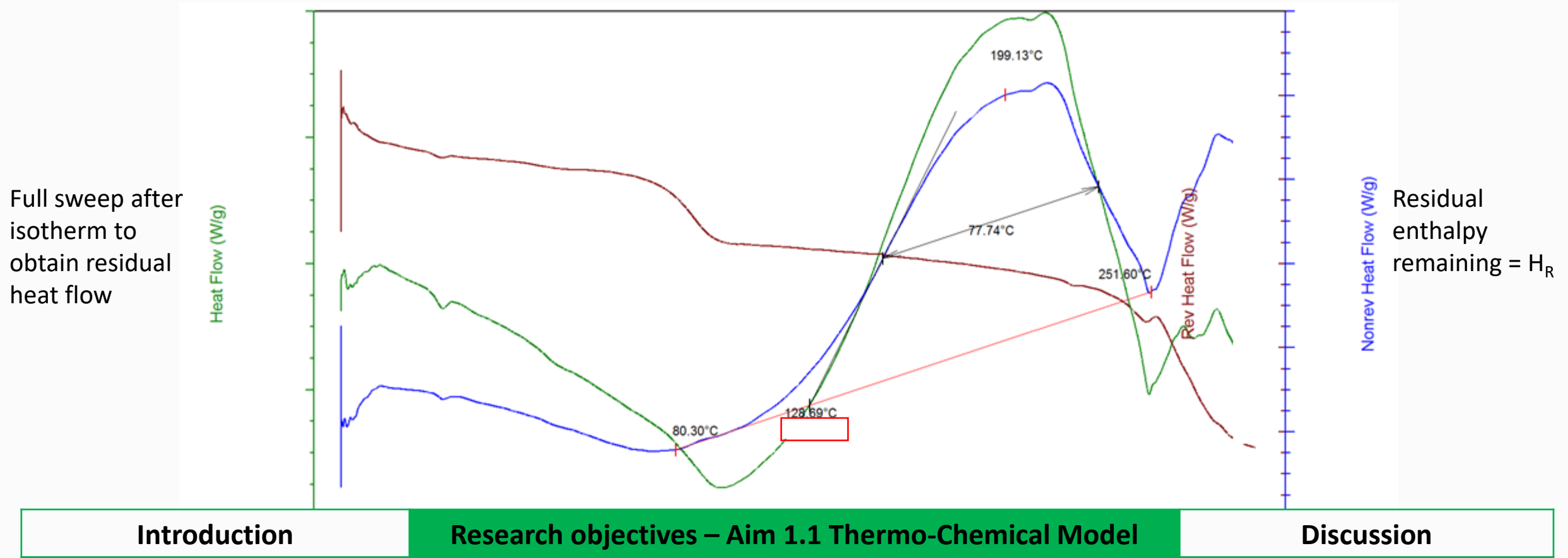


Differential Scanning Calorimetry (DSC)

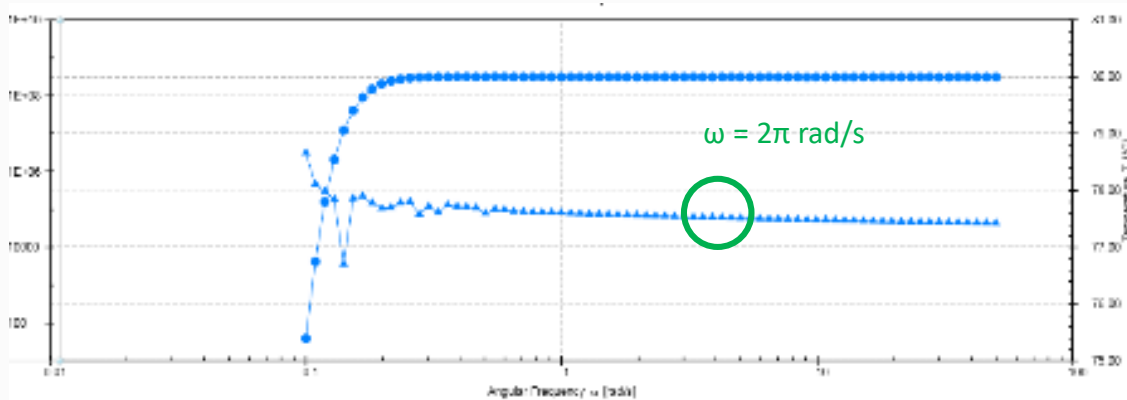
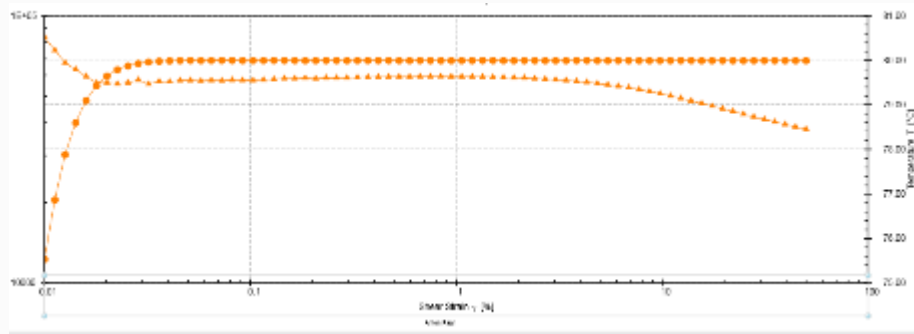
$$\text{Degree of cure} = x = \frac{H_T - (H_T - H_{ISO})}{H_T} = \frac{H_T - H_R}{H_T}$$

H_T = Total Enthalpy of reaction H_{ISO} = Enthalpy of isothermal curing reaction H_R = Residual enthalpy

Example: 160 C Isotherm for 60 min



Modulus Development (Rheology)

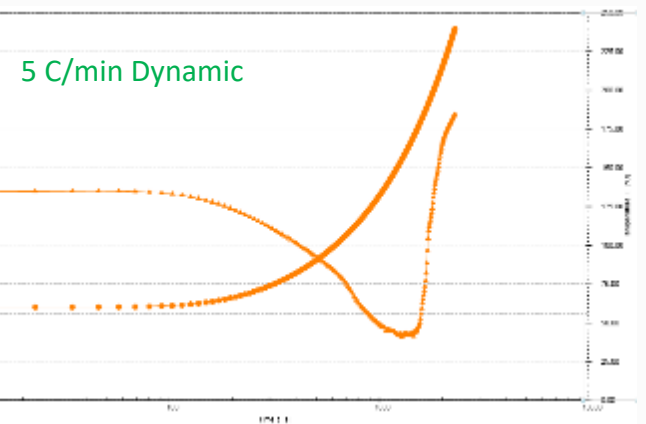
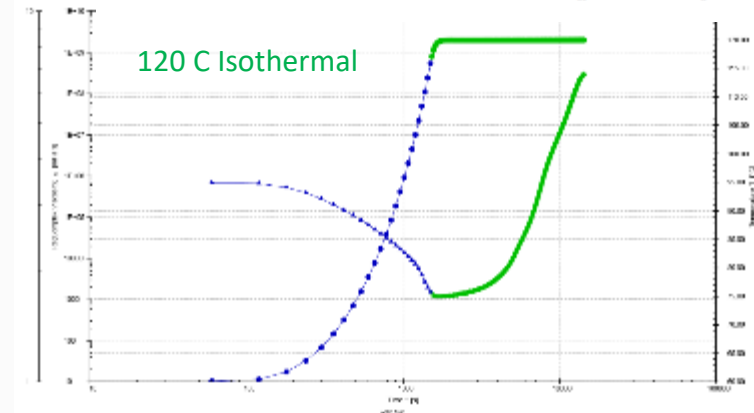


$$E_r' = \begin{cases} E_r^0 & T^* < T_{C1}^* \\ E_r^0 + \frac{(T^* - T_{C1}^*)}{(T_{C2}^* - T_{C1}^*)} (E_r^\infty - E_r^0) & T_{C1}^* < T^* < T_{C2}^* \\ E_r^\infty & T^* > T_{C2}^* \end{cases}$$

$$E_r = E_r' [1 + a_{Er} (T - T_0)]$$

$$T^* = (T_{ga} + T_{gb}x) - T$$

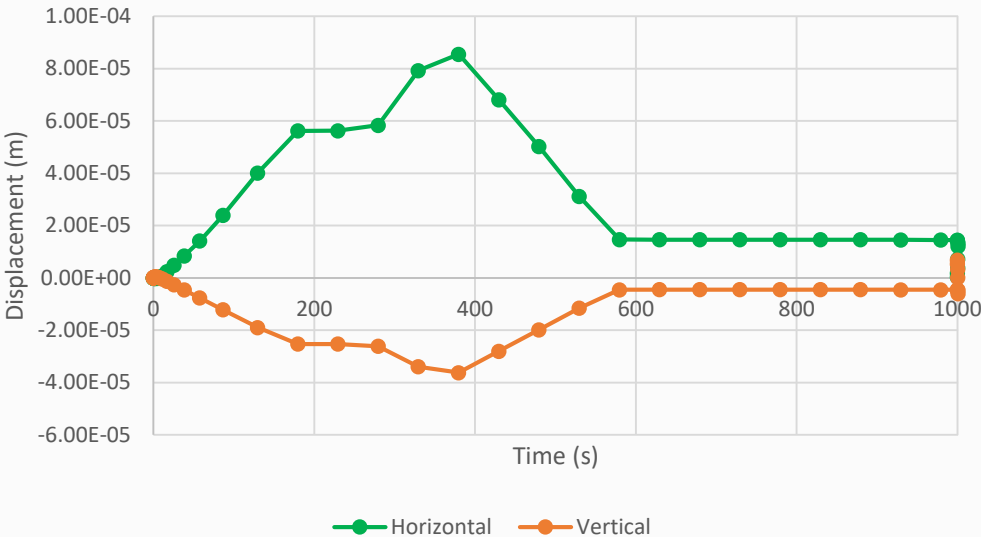
$$T_{C1}^* = T_{C1a}^* + T_{C1b}^* T$$



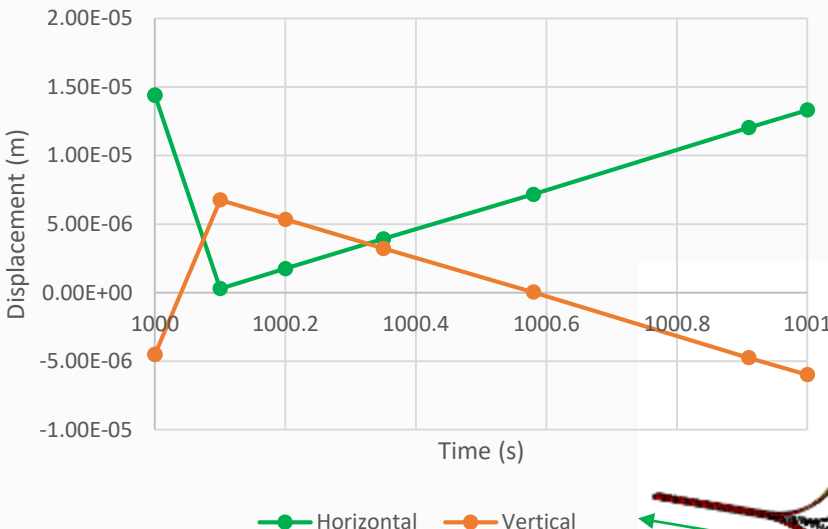
Isothermals (C):
120, 140, 160, 180, 200
Dynamics (C/min):
1, 2, 3, 4, 5

Abaqus+COMPRO Results

Change in Length

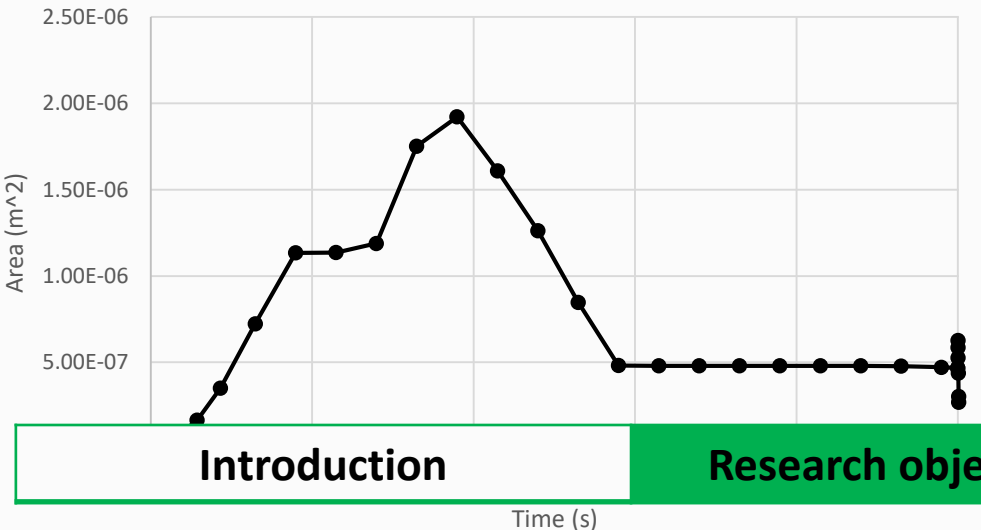


Change in Length

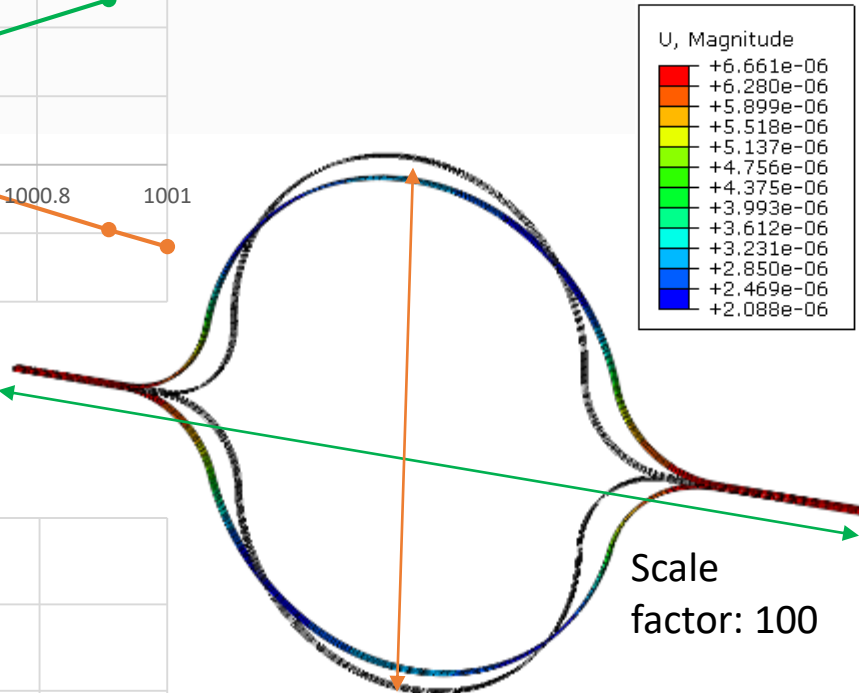
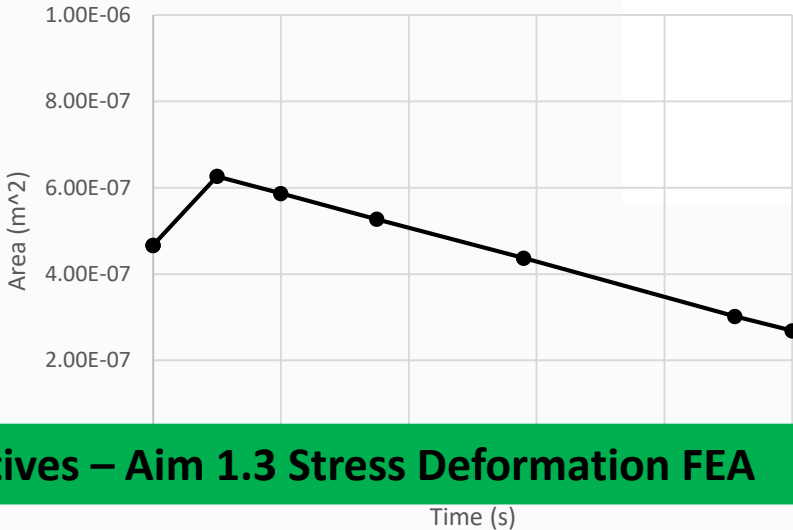


Horizontal Change = 0.013 mm
Vertical Change = -0.006 mm
Area Change = 0.269 mm²

Change in Area



Change in Area



Introduction

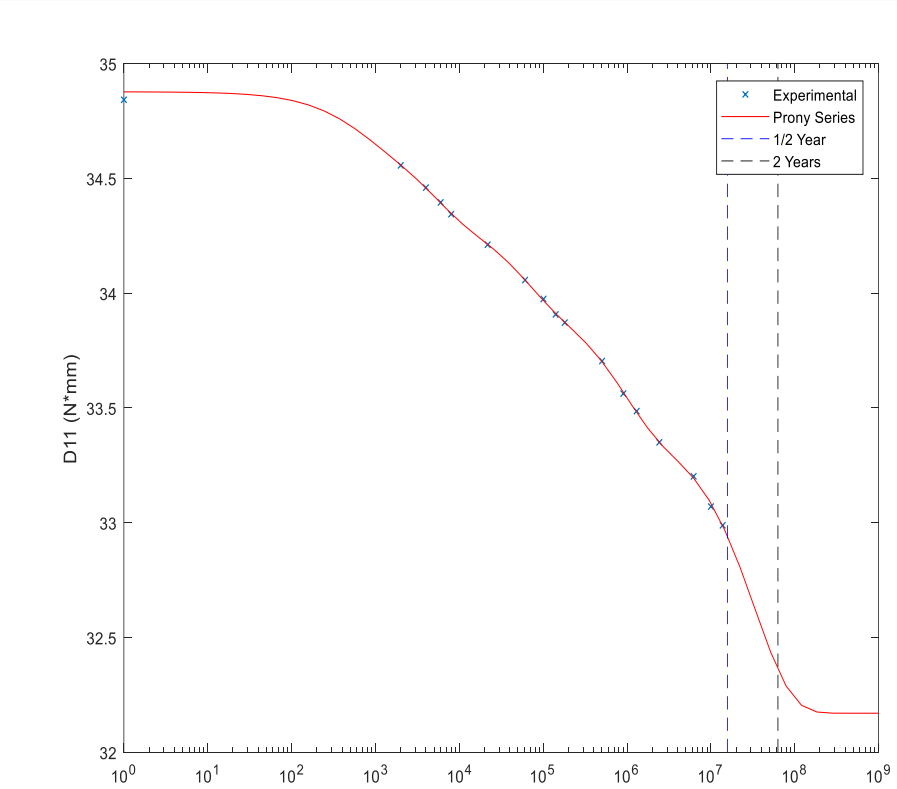
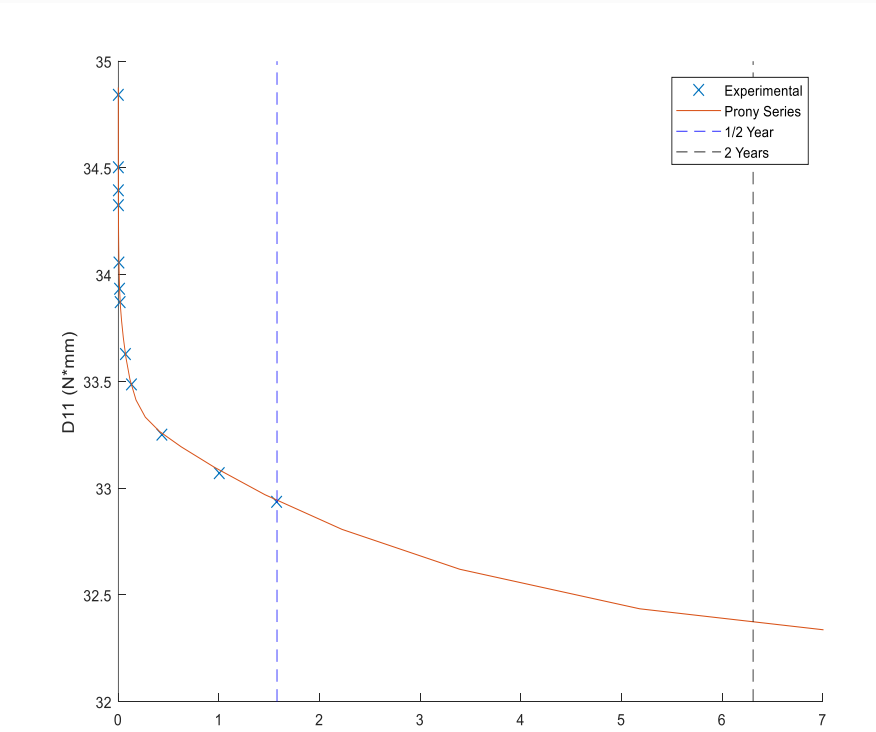
Research objectives – Aim 1.3 Stress Deformation FEA

Discussion

Coupon CBT Relaxation Bending Stiffness

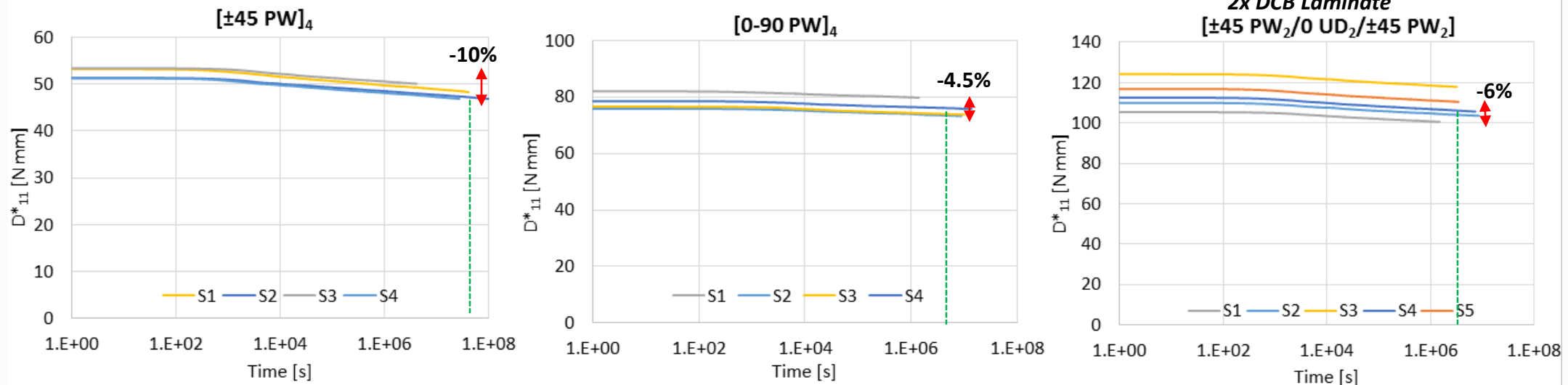
- $D_{11} = D_{11,\infty} + \sum_{k=1}^n D_{11,k} * e^{-\frac{t}{\rho_k}}$
- Relative to 40°C for 45 deg M30S carbon plane weave 3-ply-thick
- Data is using temperatures 30-80 °C in 10 °C increments
- Five term prony fit of the

	k	D11(N*mm)	Rho(1/sec)
1	0	31.9896	NaN
2	1	0.2951	1.0067e+04
3	2	0.2880	1.0337e+06
4	3	0.3582	1.0394e+05
5	4	0.3394	6.9607e+06
6	5	1.7024	2.0533e+08

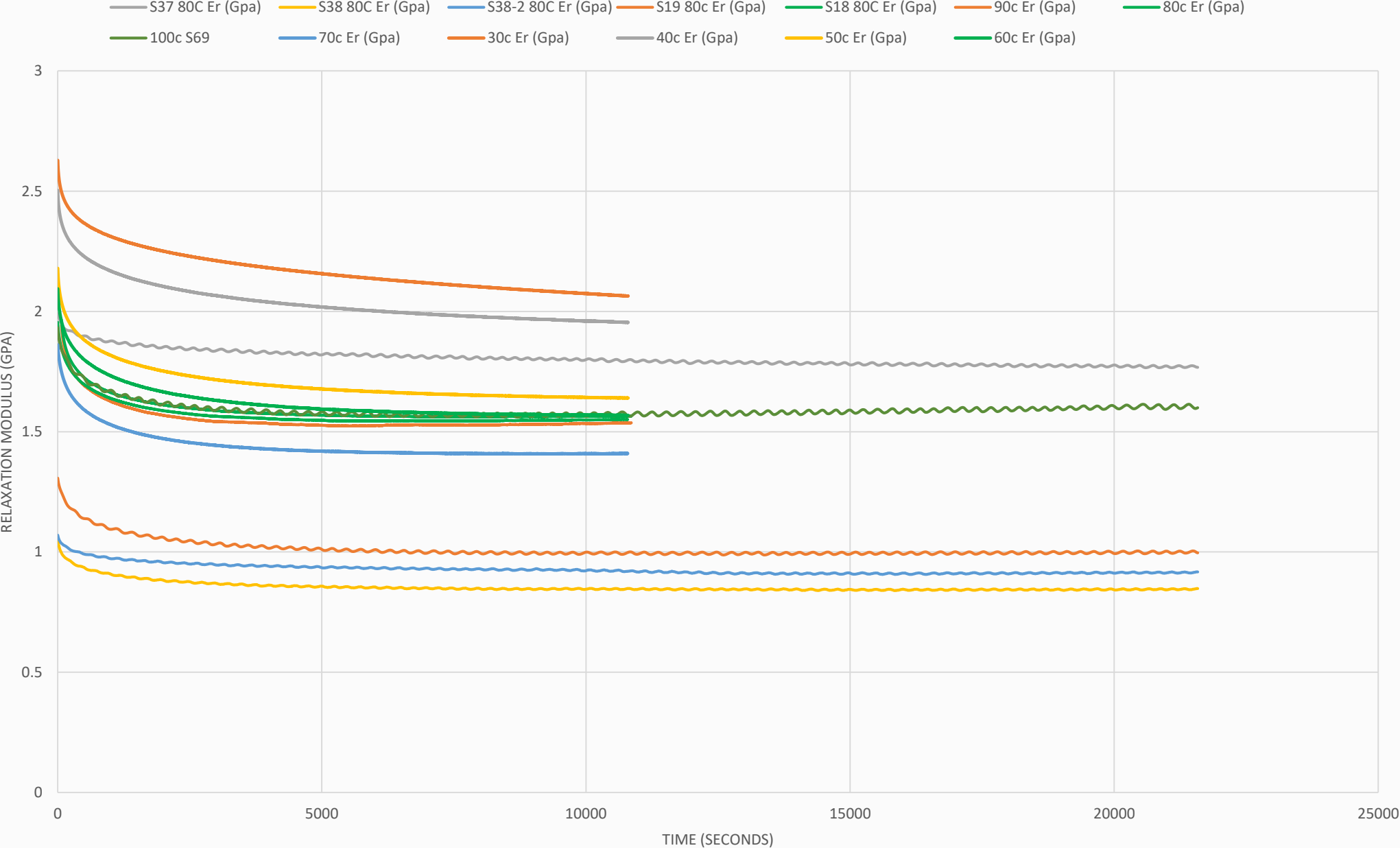


Composite coupon Viscoelastic Characterization: Test Data Summary

- 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 $[\pm 45 \text{PW}/0/\pm 45 \text{PW}]$ 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 $\pm 45^\circ$ PW laminate (10%), followed by $[\pm 45 \text{PW}/0/\pm 45 \text{PW}]$ laminate (6%) due to the viscoelastic matrix of the surface plies being highly loaded in shear as coupon gets bent axially.
- $0-90^\circ$ PW relaxes the least (4.5%) due to elastic fibers oriented in the principal loading 1-direction.
- The $\pm 45^\circ$ PW laminate showed the largest shift factors resulting in higher relaxation times, while the others had similar time



F7 RELAXATION MODULUS



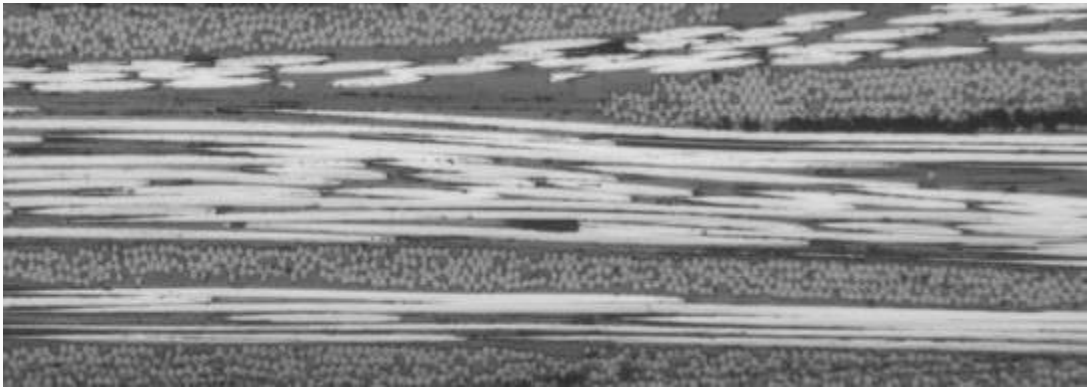
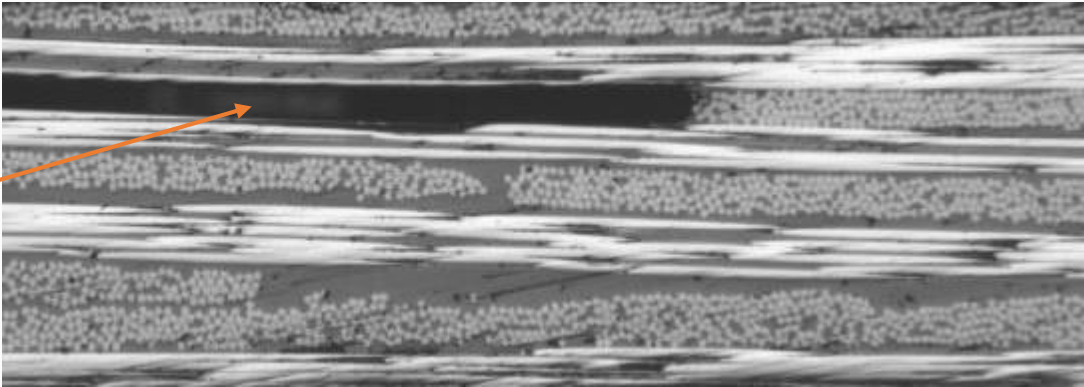
Composite Variance

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



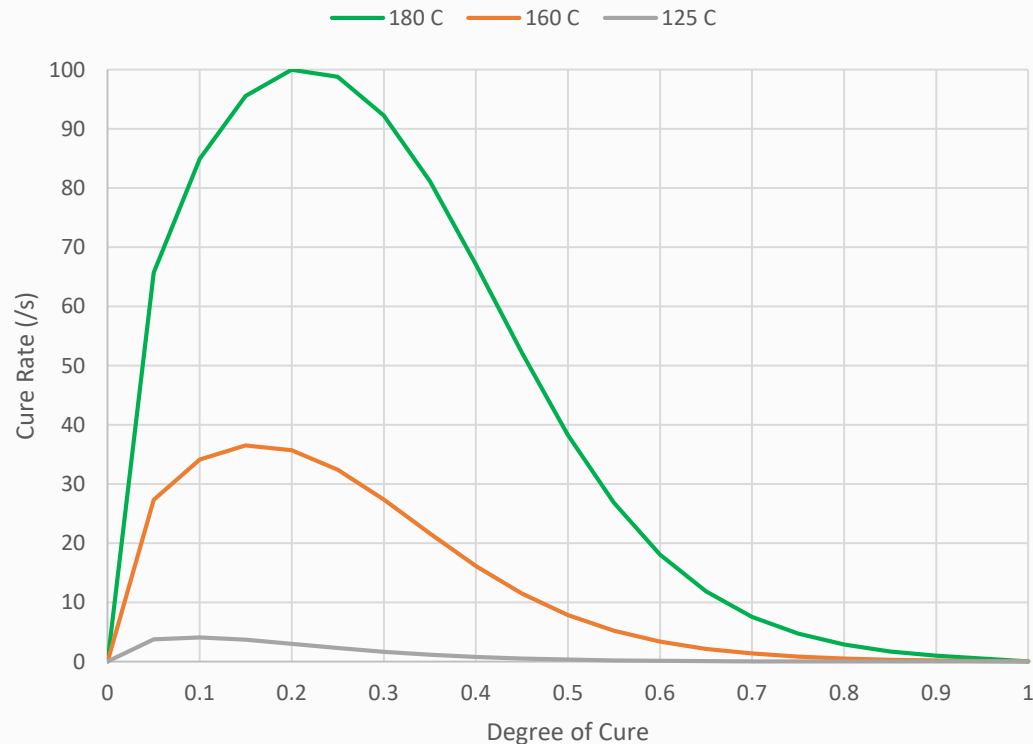
	Sample 1		Sample 2	
D11	82 N*mm	↑	76 N*mm	↓
Thickness	0.241 mm	↑	0.234 mm	↓
FVF	60.4%	↓	62.4%	↑
RVF	38.4%		38.5%	
Voids	1.2%	↑	-0.9%	↓

More voids and increased thickness moves fibers away from neutral axis

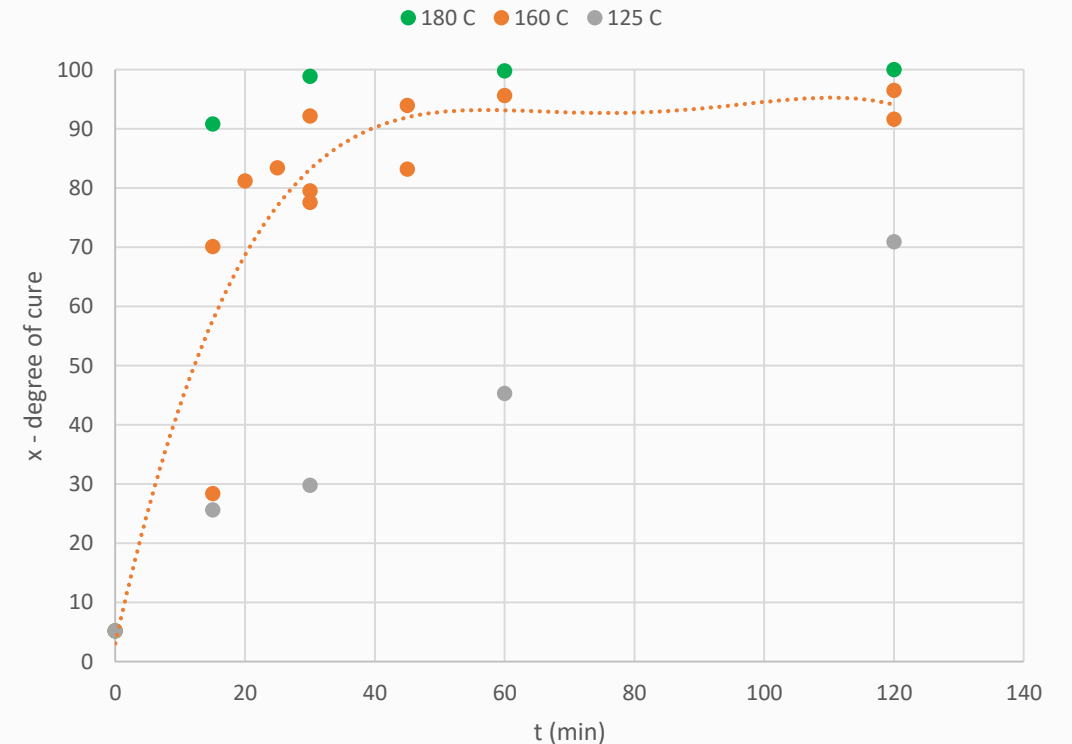


DSC Results

- Cure kinetics model according to least squares analysis derived parameters.
- Model shape as predicted, according to COMPRO references



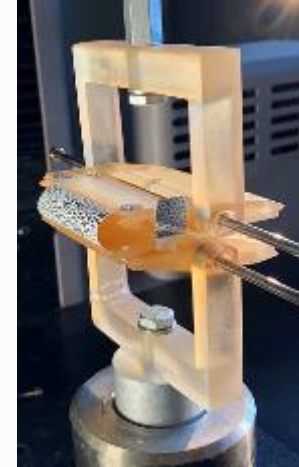
- Experimental Data follows predicted trend
- INCOMPLETE: Some sort of integration of cure kinetics model should give equation for x vs t



CBT Fixture: 3D Printed Plastic vs Titanium

- The same 0.3-mm-thick isotropic stainless steel sample was CBT tested at low strains at increasing temperature to assess time-dependent response of two additive manufactured fixtures made from SLA and Ti.
- Test data with high temperature SLA fixture showed relaxation at temperatures $\geq 50^\circ\text{C}$ well below the heat deflection temperature of the plastic material.
- Since load data with Ti fixture did show relaxation it was determined that the difference was due to the viscoelastic behavior of the plastic fixture at high temperatures. Conclusion: SLA not valid for accelerated relaxation/creep tests.

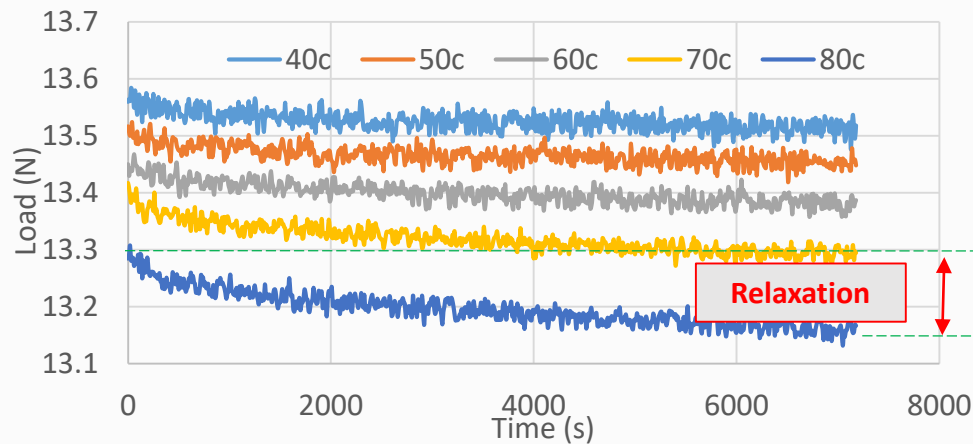
3D printed SLA fixture



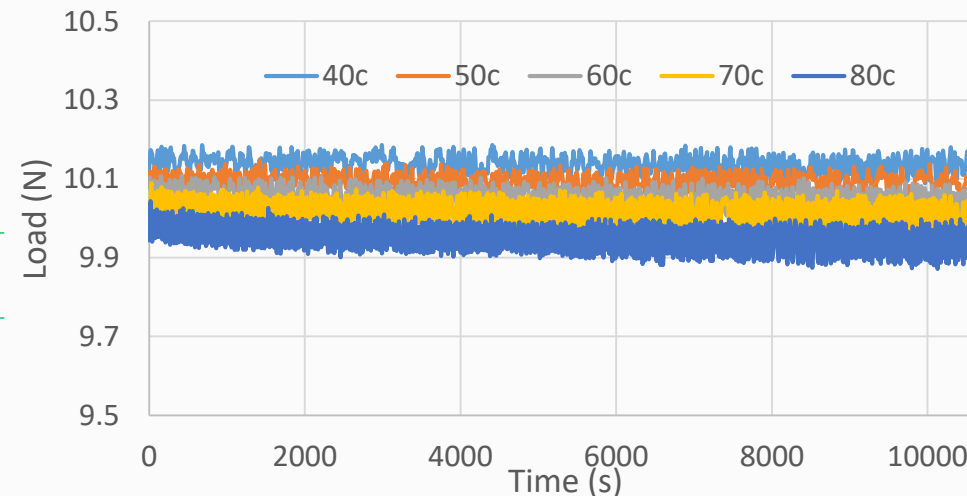
3D printed Titanium fixture



3D printed SLA fixture

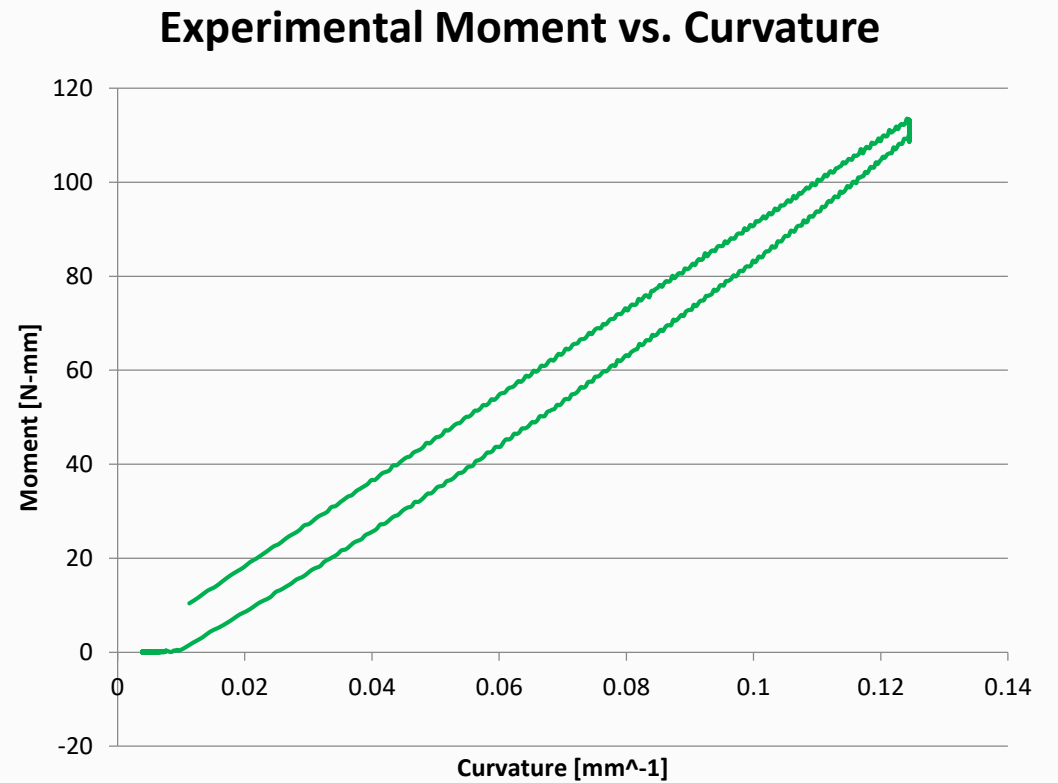
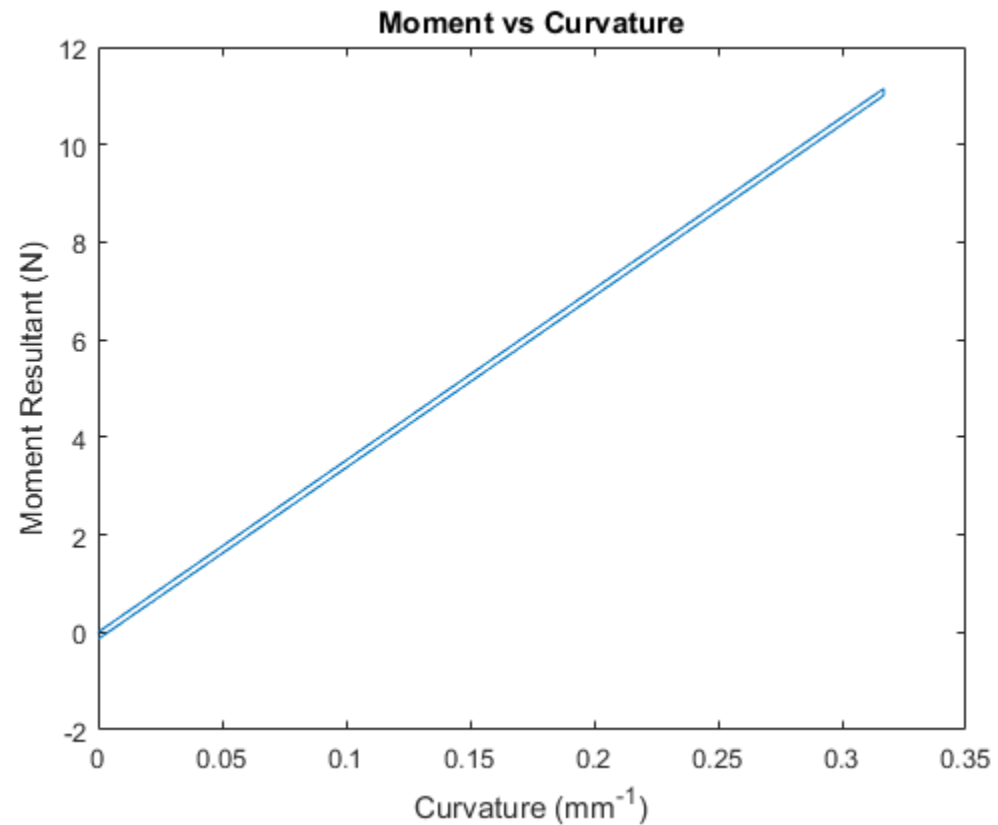


3D printed Titanium fixture



SS material softens with temperature (not relaxation)

Stowage Simulation



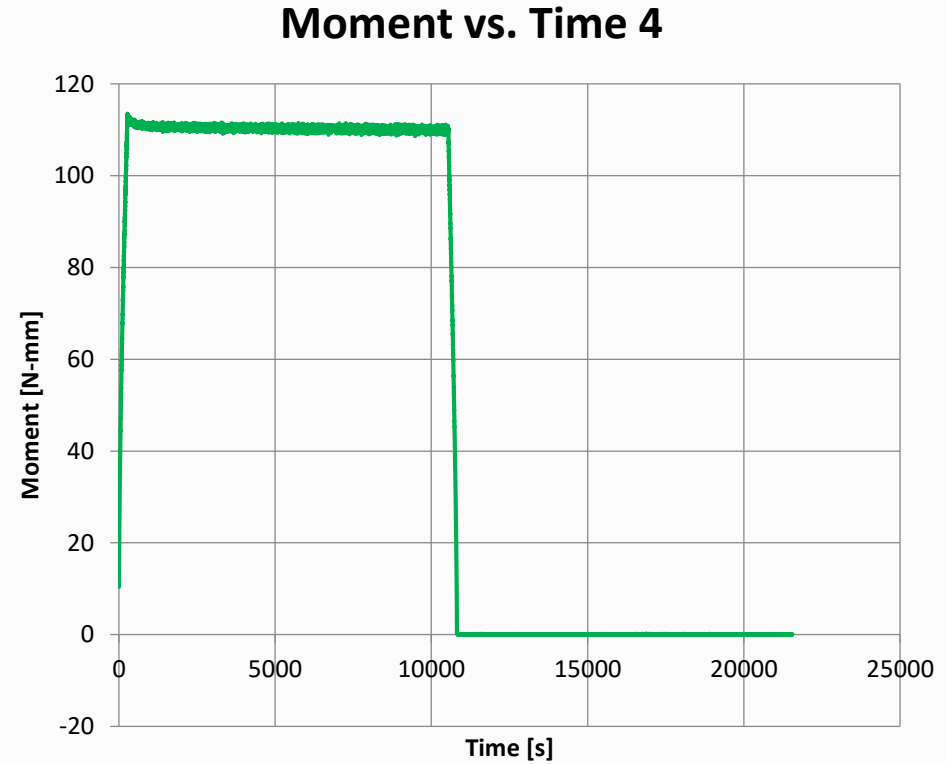
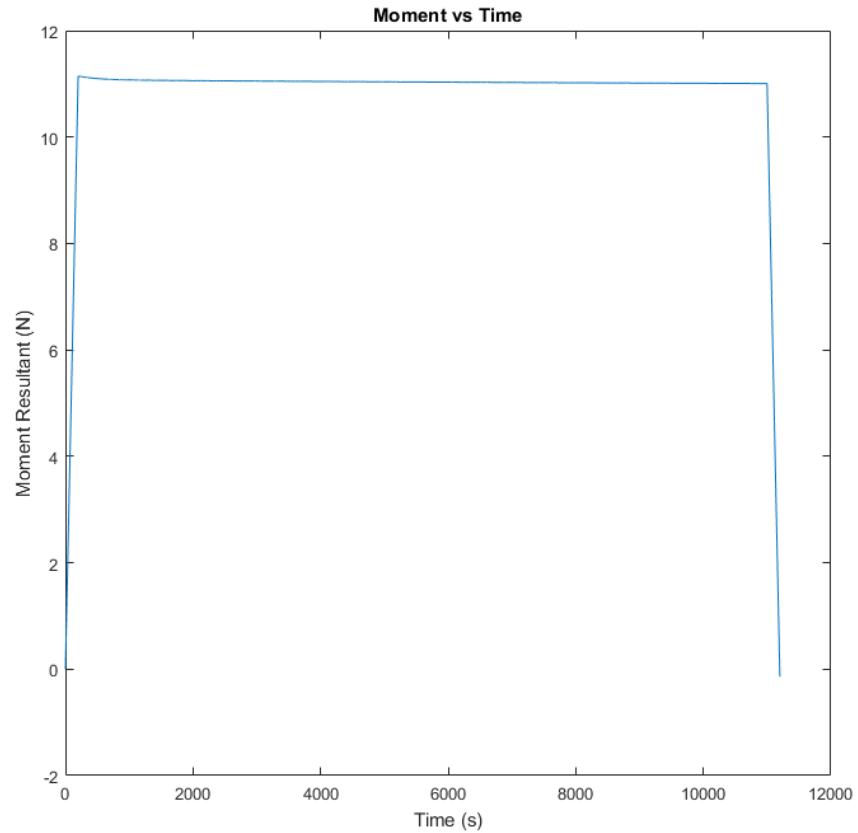
Introduction

Research objectives

Approach

Discussion

Stowage Simulation



Introduction

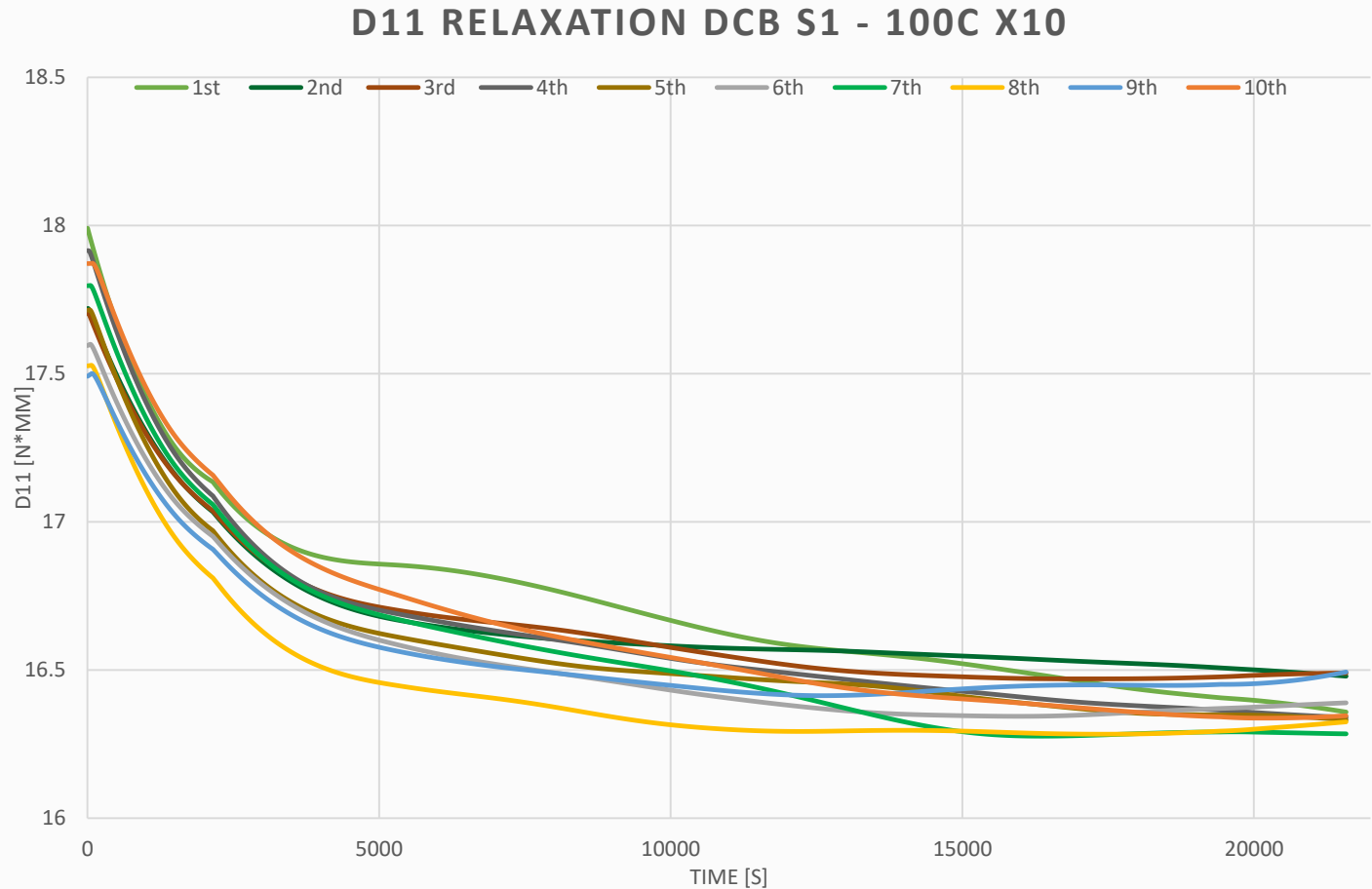
Research objectives

Approach

Discussion

Boom CBT D11 – Repeated test

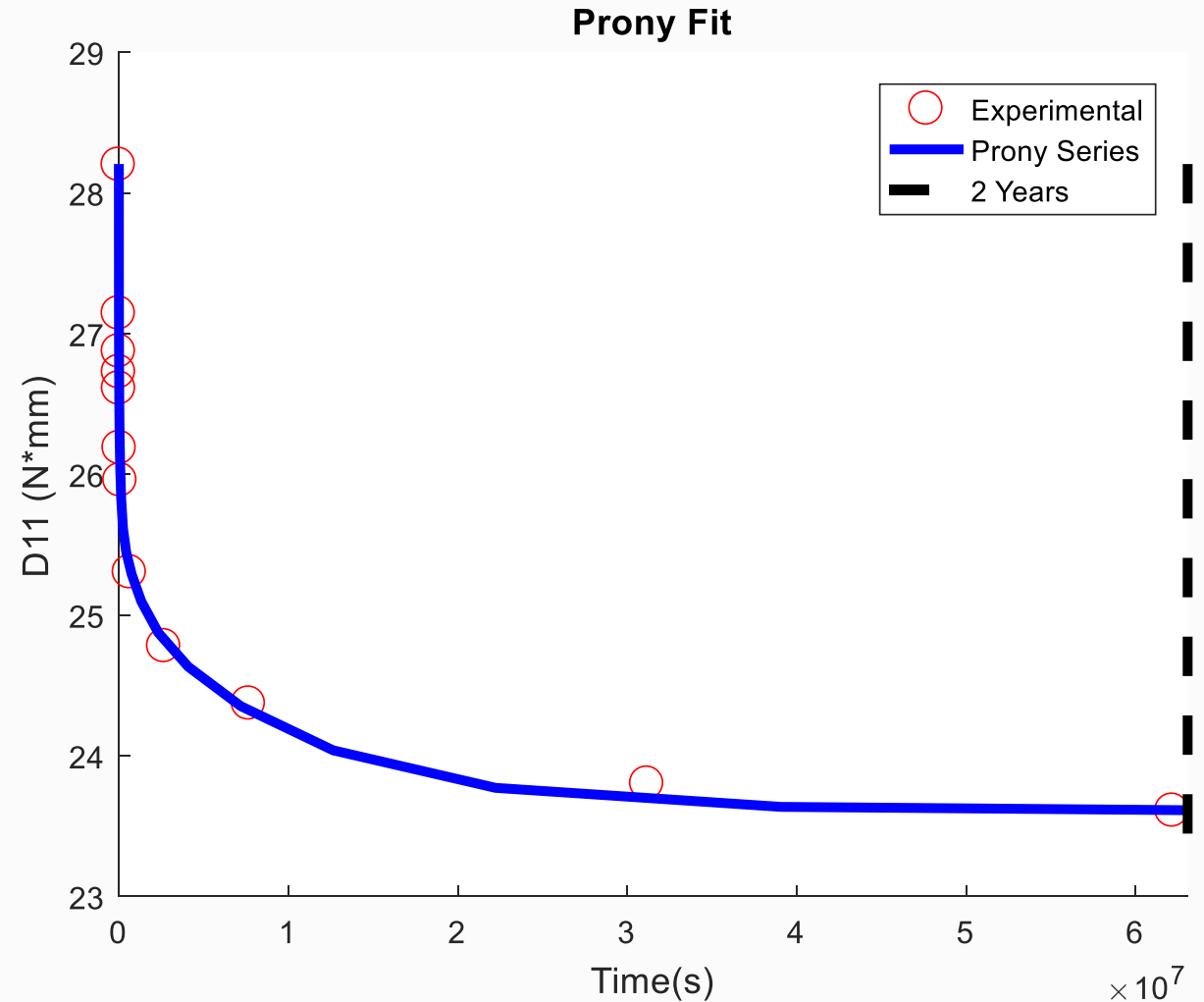
- A test was conducted repeatedly on the same sample to verify the test setup and see the variance in testing a single sample
- Boom was placed in the test fixture and temperature was set to 100c
- When the boom is in the test fixture a small amount of curvature remains (the boom is not completely flat)
- This is mostly eliminated after initially being bent and does not appear to have a significant affect upon repeated bending.
- The stiffness varies about 0.5 N*mm.



D11 Prony fit - Boom CBT

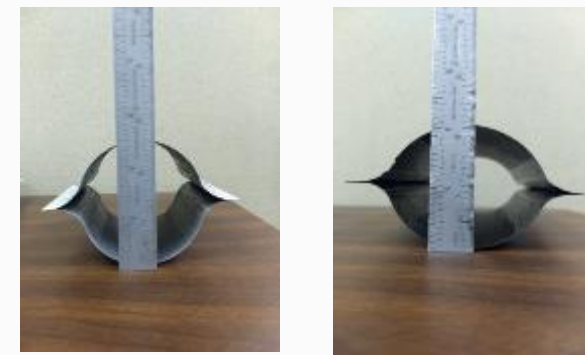
- A prony series was fit to the master curve using the method of least squares
- The prony series is fit to the data for up to 2 years at 40c
- The D11 prony coefficients and time constants are shown below

K	D11(N*mm)	Rho (sec)
0	23.6058	NaN
1	0.0221	0.0084
2	0.0368	2.22E-14
3	2.22E-14	99.4824
4	0.8822	2.24E+03
5	0.7445	1.48E+04
6	0.8831	9.98E+04
7	0.5579	1.00E+06
8	1.532	1.00E+07



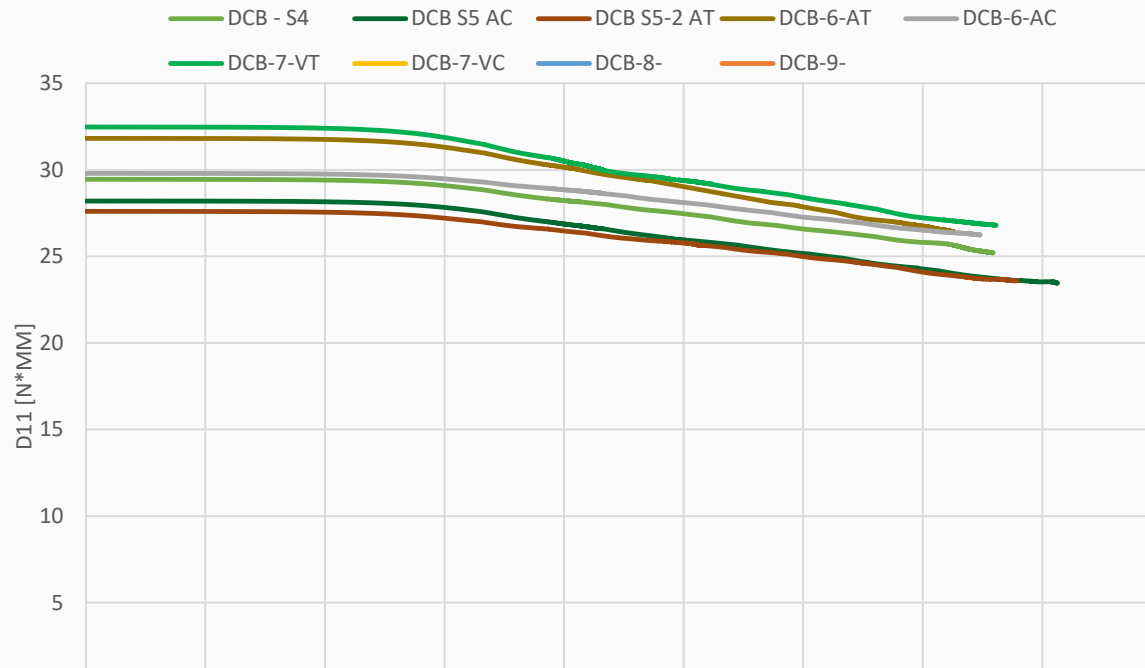
D11 Master Curves- Boom CBT

- A compilation of all the master curves from the relaxation test are shown below
- The strain recordings, captured by DIC is shown to the right
- The Estimated strain is greater than the measured strain and the curvature is slightly smaller.
- The discrepancy in strain could be from having two bonded laminates



Measured Strain and Curvatures					
		Ex [mm/mm]	Ey [mm/mm]	Cx [1/mm]	Cy [1/mm]
DCB	S5 Vic - Tension	0.042979	0.431899	-4.96E-07	0.039059
	S5-2 Vic - Compression	-0.01072	0.477101	0.000231	0.040758
	S6 - Vic - Compression	-0.00619	0.481745	0.000105	0.039031
	S6 - Vic - Tension	0.047176	0.281106	5.31E-05	0.032025
	S7 - Vic -Tension	0.096399	0.402866	1.56E-05	0.047913

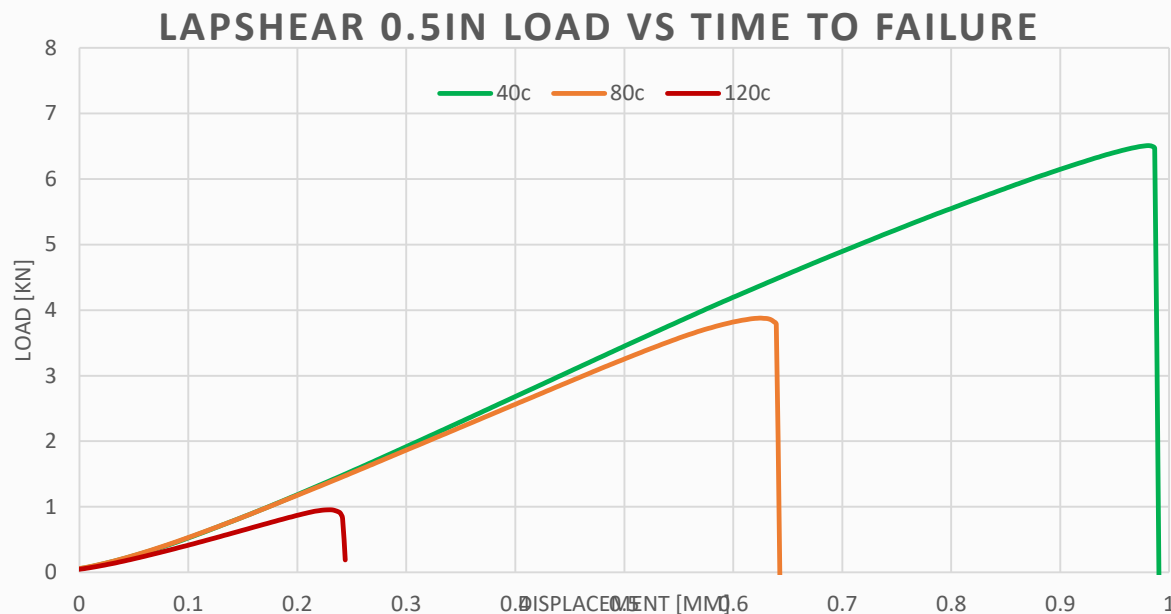
D11 RELAXATION 40C REFERENCE



Estimated strain	
CBT moment arm [in]	3.23
AVG Lam thickness [mm]	0.252644
total Average thickness [mm]	0.318196
Final Angle of Rotation deg	82
Final Angle of Rotation	1.430444
Gauge Length [in]	1.5
Expected radius of curvature [mm]	26.63508
Expected Curvature [1/mm]	0.037544
offset [mm]	1.979341
Theta [rad]	0.071541
Expected Strain with paint [%]	0.597324
Expected Strain on coupon [%]	0.474269
crosshead displacement	2.006459

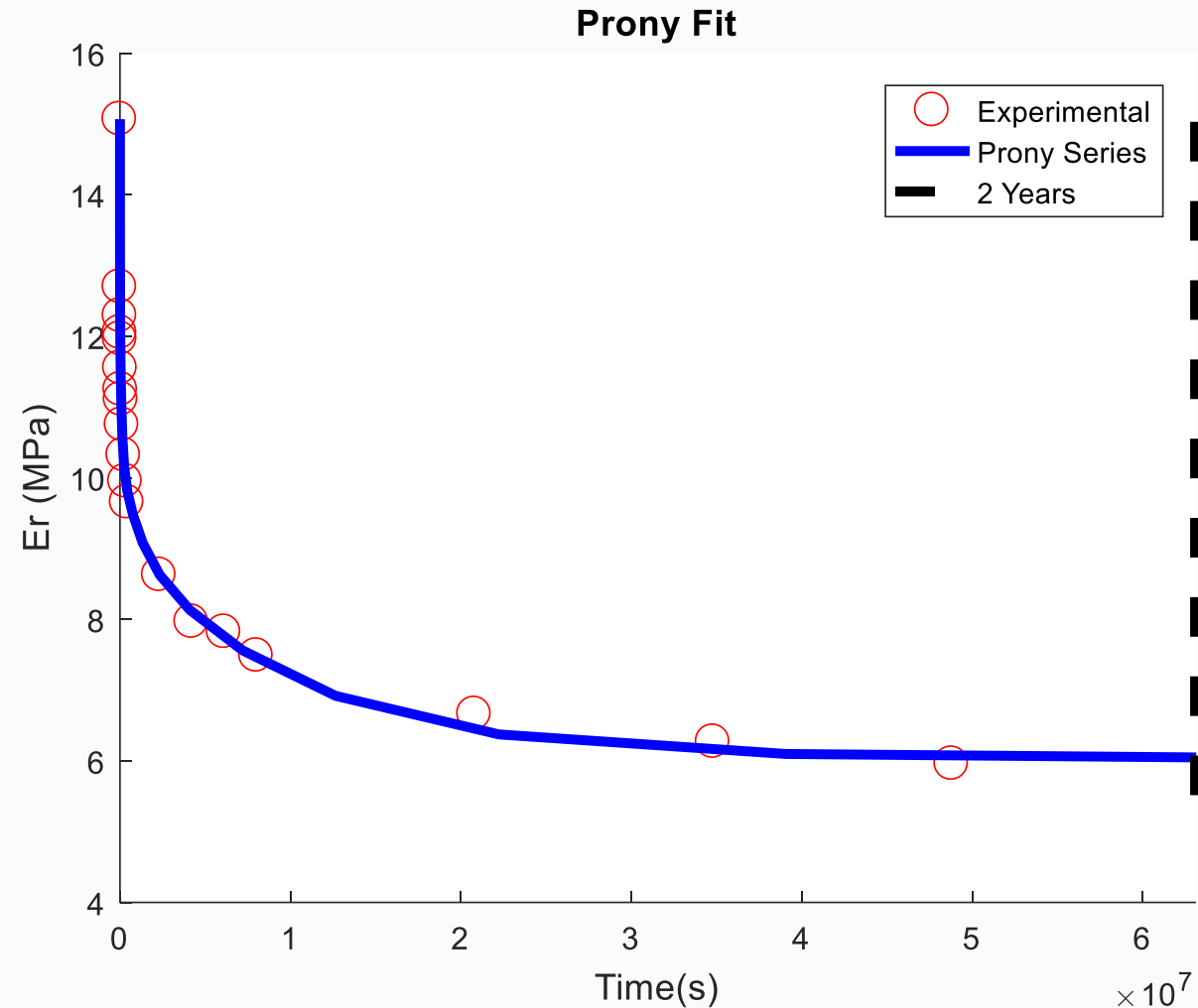
Adhesive Lapshear Test Method Establishment

- Lapshear test method in the process of being established for the Adhesive (LOCTITE EA 9696 .03NW AERO) used on the Omega Booms
- Ti Lapshear specimens joined with a 1in by 0.5in patch of adhesive
- Lapshear test fixtures had too much slack for recovery test (zero load creep)
- Tension grips with spare Ti Specimens bolted to the test specimen is currently being explored



Master Curve Prony fit

k	Er [Mpa]	Rho [s]
0	6.0348	NaN
1	0.3571	0.3434
2	0.2538	26.2756
3	0.7293	260.6837
4	1.0609	2.07E+03
5	0.8549	9.85E+03
6	1.8399	1.00E+05
7	1.1564	1.00E+06
8	3.132	1.00E+07



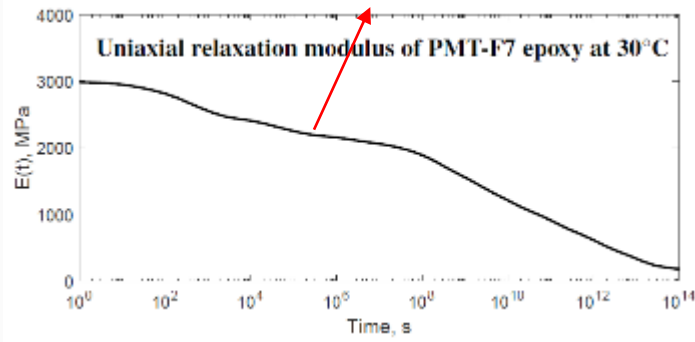
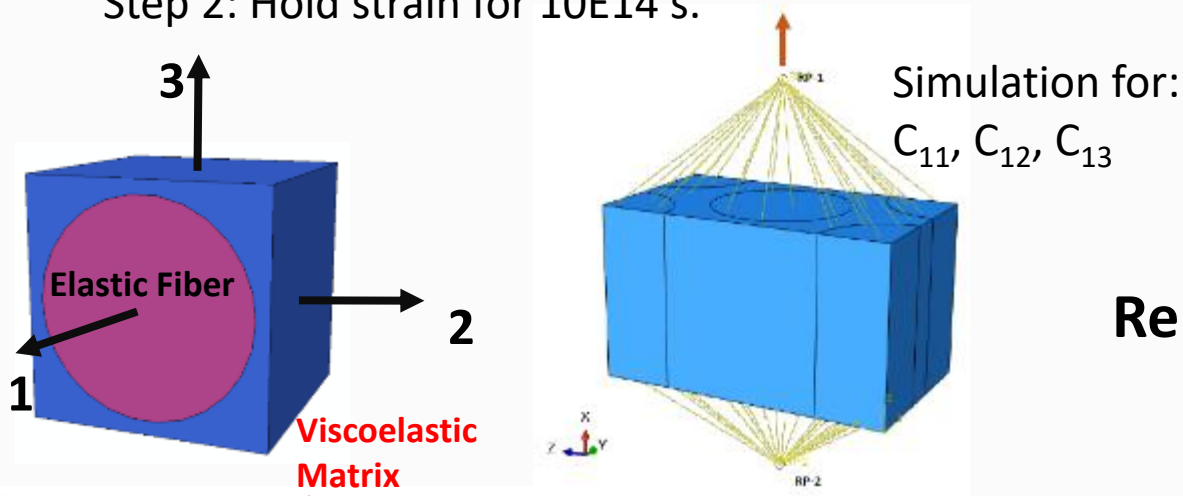
Unidirectional Tow/Ply Analysis

Unit cell model for a unidirectional tow/ply

Simulation carried in two steps:

Step 1: Apply axial strain of 0.1%

Step 2: Hold strain for 10E14 s.



Kirchhoff viscoelastic plate stress-strain relation:

$$\bar{\sigma}_i(t) = \int_0^t C_{ij}(t - \tau) \frac{d\bar{\epsilon}_j(\tau)}{d\tau} d\tau$$

Relaxation stiffness matrix (transversely isotropic)

All entries modeled with Prony series of the form:

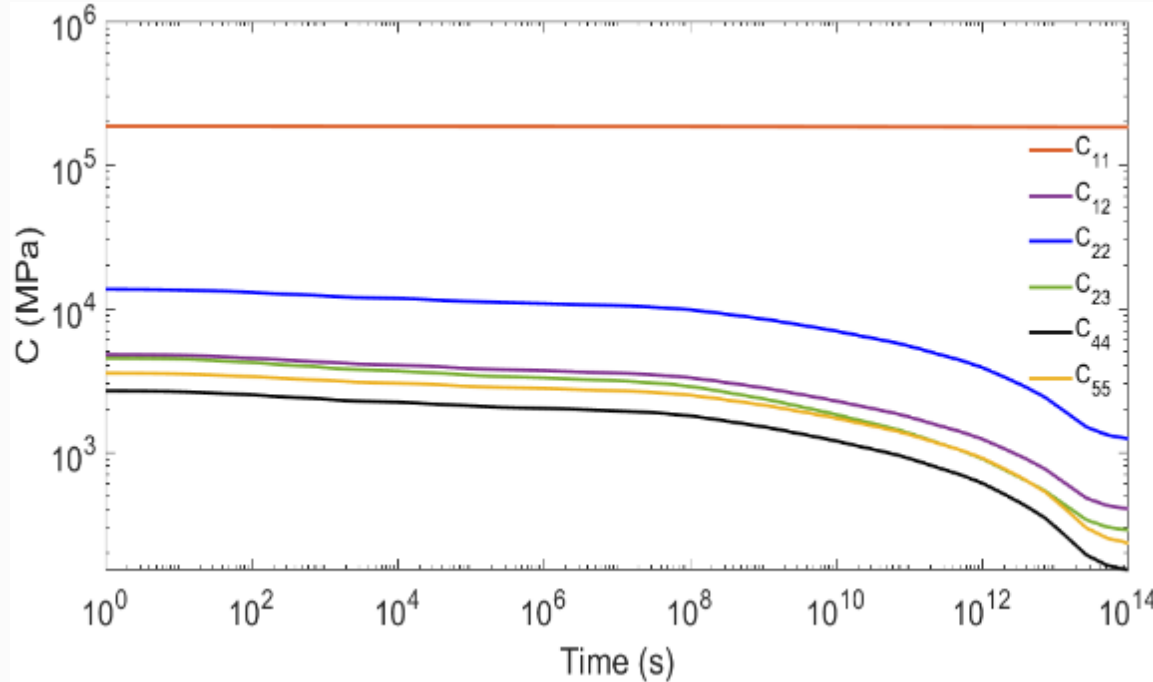
$$C_{ij} = C_{ij,\infty} + \sum_{k=1}^n C_{ij,k} e^{-t/\rho_k}$$

$$C = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{12} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{13} & C_{23} & C_{22} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{55} \end{bmatrix}$$

Unidirectional Tow/Ply Analysis

- Time dependence of C_{11} term is insignificant due to elastic fibers are dominant in the 1-direction.
- The rest of the tensor modulus terms show a similar time-dependence behavior due to the viscoelastic matrix response.
- Non-linear curve fitting using the least square method of the relaxation data from the numerical analysis was employed to obtain the Prony series coefficients.

M30S fiber tow relaxation moduli

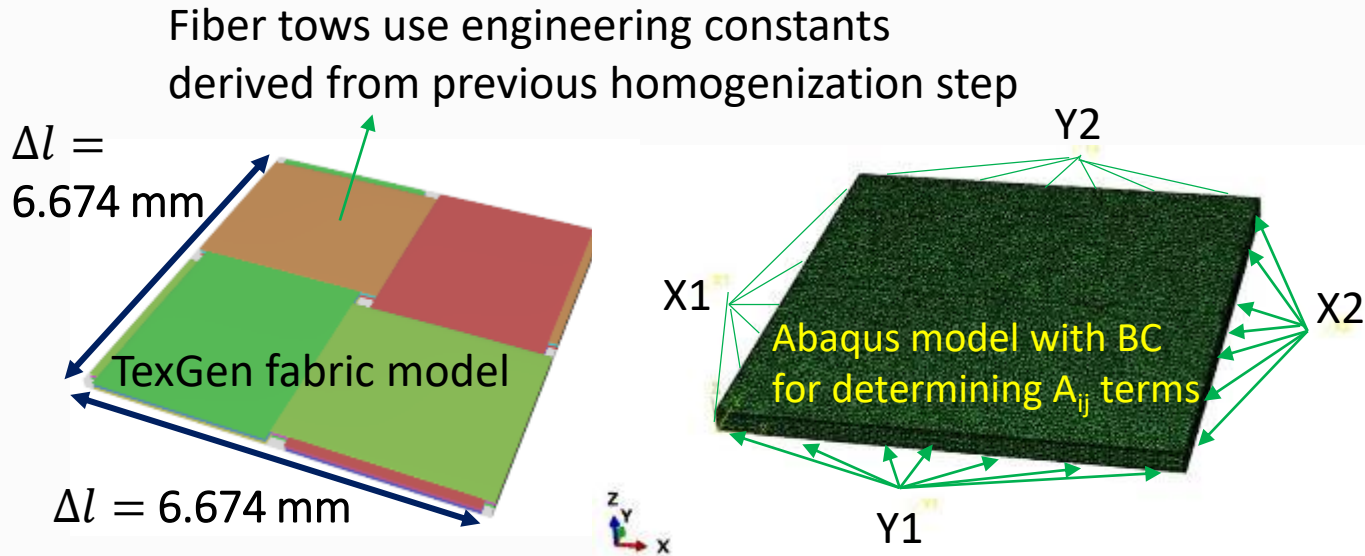


Prony coefficients and relaxation time of tow fiber model

k	ρ_k	$C_{11,k}$	$C_{21,k}$	$C_{22,k}$	$C_{23,k}$	$C_{44,k}$	$C_{55,k}$
∞	—	183114.7	374.9	1131.8	269.4	135.3	207.2
1	1.89E+01	142.3	163.8	406.8	188.8	98.6	113.5
2	1.00E+02	209.0	241.5	600.8	277.2	140.0	161.8
3	1.00E+03	232.7	274.8	705.6	306.9	163.8	195.6
4	2.00E+04	138.0	163.2	414.1	180.5	95.6	114.0
5	1.00E+05	173.1	206.2	544.7	228.4	122.2	148.9
6	1.95E+06	113.9	137.1	356.5	146.2	79.7	97.9
7	1.77E+07	80.2	95.9	248.6	105.3	56.5	68.6
8	1.74E+08	355.8	429.8	1143.9	460.2	251.4	312.4
9	1.38E+09	373.0	461.3	1262.1	469.5	266.9	343.0
10	1.00E+10	383.6	482.0	1370.9	471.0	276.7	368.8
11	1.00E+11	412.3	527.2	1533.9	474.6	297.9	407.9
12	1.00E+12	398.0	515.1	1586.2	452.2	291.9	415.8
13	1.00E+13	495.3	657.6	2084.7	462.9	358.8	532.0
14	1.00E+14	56.1	76.7	290.8	48.1	42.6	69.6

Laminate Time-Dependent Analysis

Unit cell model for a 4-ply plain-weave laminate



Kirchhoff viscoelastic plate equations:

$$N_i(t) = \int_0^t A_{ij}(t - \tau) \frac{d\epsilon_j}{d\tau} d\tau + \int_0^t B_{ij}(t - \tau) \frac{d\kappa_j}{d\tau} d\tau$$

$$M_i(t) = \int_0^t B_{ij}(t - \tau) \frac{d\epsilon_j}{d\tau} d\tau + \int_0^t D_{ij}(t - \tau) \frac{d\kappa_j}{d\tau} d\tau$$

Relaxation ABD stiffness matrix

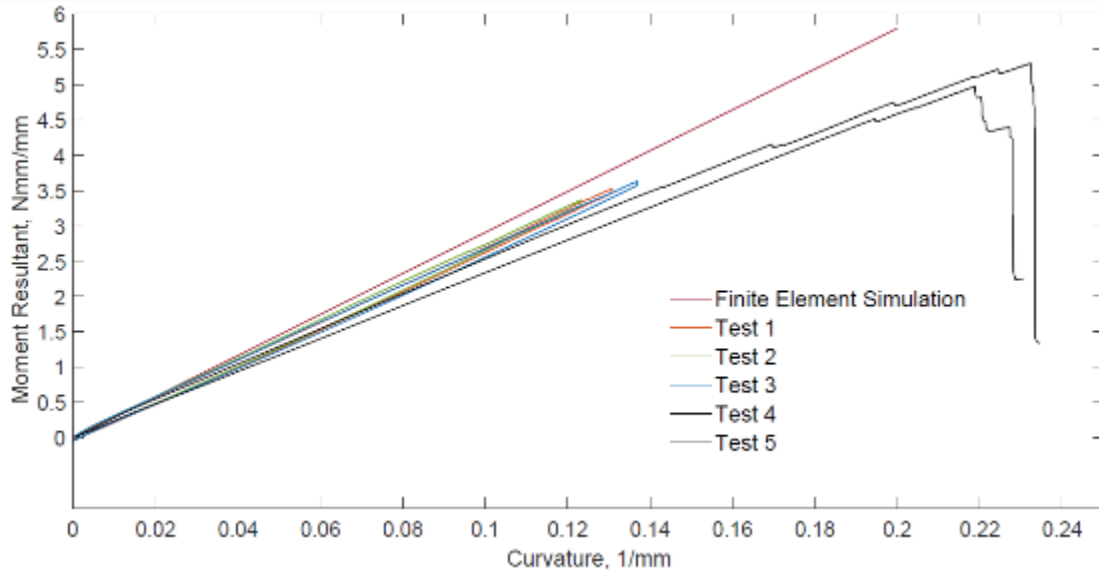
All entries represented with Prony series of the form:

$$A_{ij} = A_{ij,\infty} + \sum_{k=1}^n A_{ij,k} e^{-t/\rho_k}$$

$$\begin{Bmatrix} N_1 \\ N_2 \\ N_6 \\ M_1 \\ M_2 \\ M_6 \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} & B_{11} & B_{12} & B_{13} \\ A_{21} & A_{22} & A_{26} & B_{21} & B_{22} & B_{26} \\ A_{61} & A_{62} & A_{66} & B_{61} & B_{62} & B_{66} \\ B_{11} & B_{21} & B_{61} & D_{11} & D_{12} & D_{16} \\ B_{12} & B_{22} & B_{62} & D_{21} & D_{22} & D_{26} \\ B_{61} & B_{26} & B_{66} & D_{61} & D_{62} & D_{66} \end{bmatrix} \begin{Bmatrix} \epsilon_1 \\ \epsilon_2 \\ \gamma_6 \\ \kappa_1 \\ \kappa_2 \\ \kappa_6 \end{Bmatrix}$$

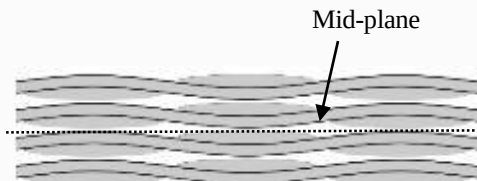
Elastic Properties of M30S PW material

Moment-curvature response for the 3-ply 0° PW coupon

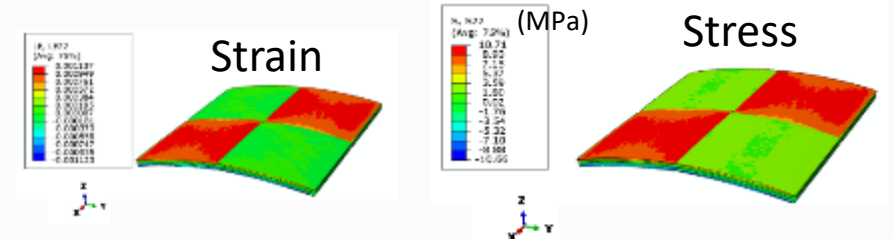
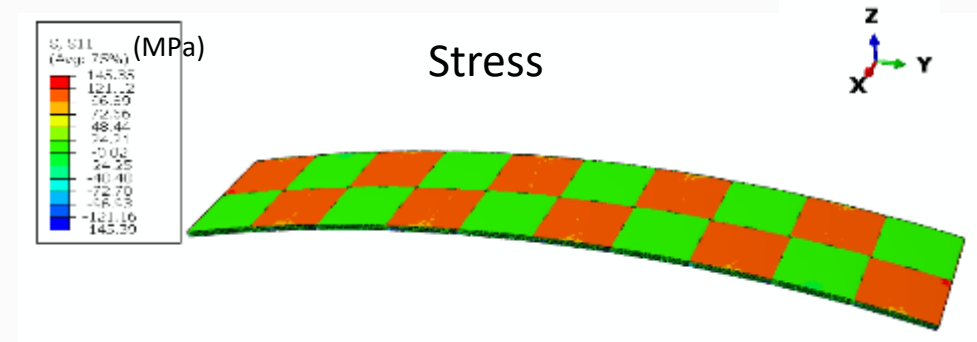
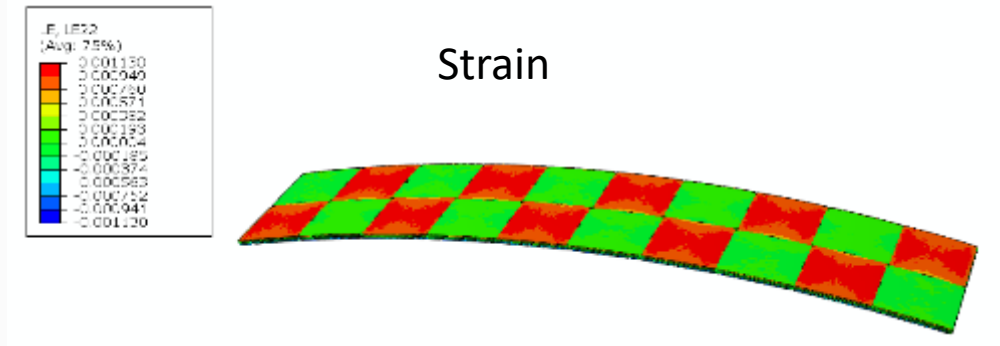


ABD matrix for the constitutive PW ply

$$ABD = \begin{bmatrix} 11900 & 467 & 0 & 0 & 2 & -1 \\ 467 & 11900 & 0 & 0 & 21 & 5 \\ 0 & 0 & 745 & -1 & 0 & 0 \\ -3 & 1 & 0 & 28 & 1 & -10 \\ 1 & 41 & 0 & 1 & 28 & -10 \\ 10 & -10 & 4 & 0 & 0 & 16 \end{bmatrix}$$



B matrix terms are non-zero due to chosen in-phase (asymmetric) arrangement of PW textile tows



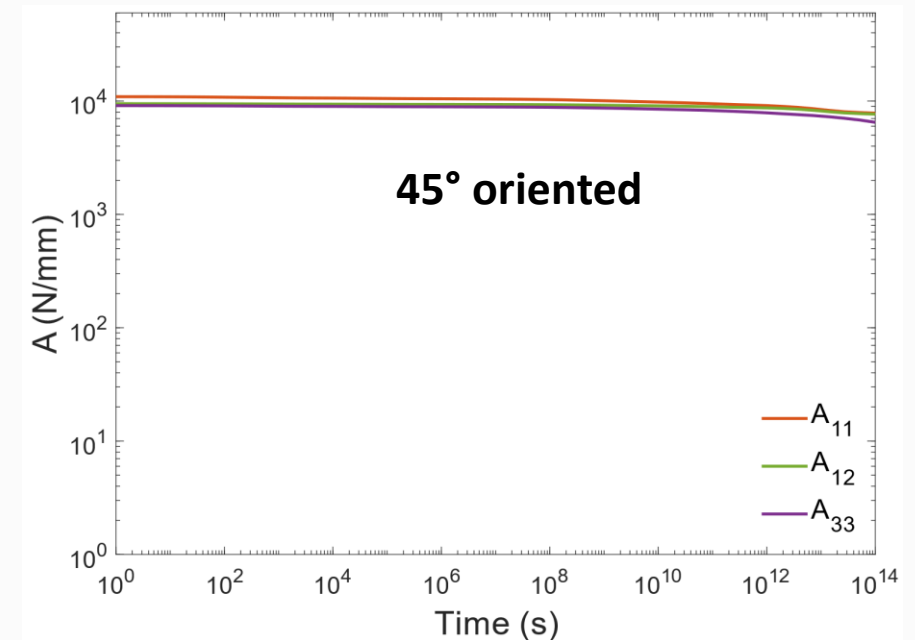
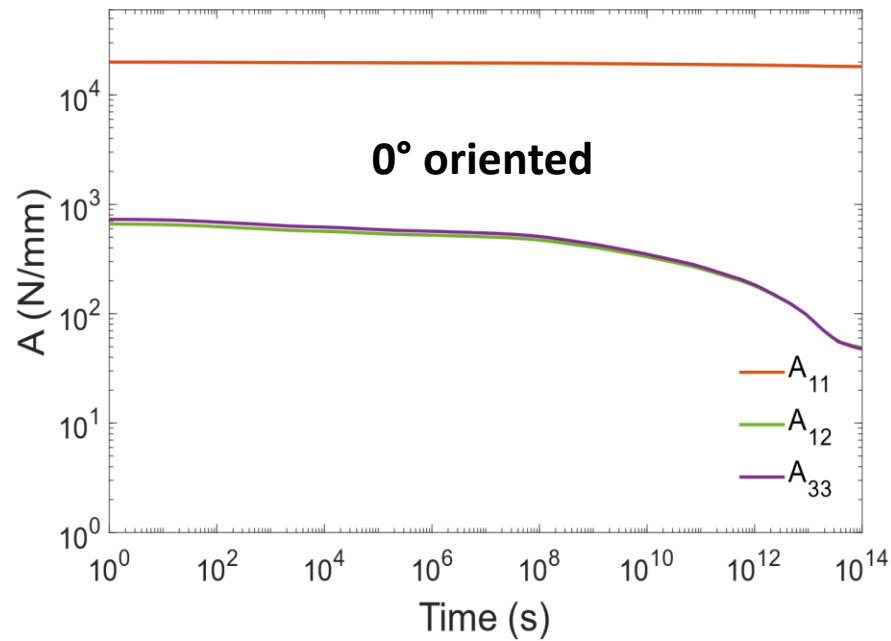
D_{11} [Nmm]	3-Ply Plain-weave M30S/PMT-F7
Single Unit Cell	28.0
Five Unit Cell	28.6

$$D_{11} = D_{22} = 28 \text{ Nmm}$$

Computed Axial Relaxation of 4-Ply M30S PW

Terms of the Extensional Stiffness Matrix, A

- Fiber-dominated directions (axial A_{11} , transverse A_{22}) are less prone to relaxation than resin-dominated directions (axial-transverse coupling A_{12} , shear A_{33}).
- All in-plane (A) relaxation moduli show small relaxation.



Computed Bending Relaxation of 4-Ply M30S PW

Terms of the Bending Stiffness Matrix, D

- Fiber-dominated bending directions (D_{11} , D_{22}) are more prone to relaxation/creep than bending coupling loading terms (D_{12}) or twist (D_{33}).
- All out-of-plane (D) relaxation moduli show slightly larger relaxation in 45° PW coupons but not as much as anticipated.

