Experimental Characterization of the Dimensional Stability of Deployable Composite Booms During Stowage

Joshua E. Salazar¹ and Juan M. Fernandez²

NASA Langley Research Center, Hampton, VA, 23681

Thin-ply carbon fiber reinforced polymer materials offer the opportunity to create long thin-shell booms with high strength to weight ratios. These booms can be rolled up and stowed in small volumes to be later deployed. These features make them ideal for use in gossamer solar sails as well as other deployable space structures. It has been observed that stowing the booms in rolled-up configurations can cause time dependent deformations. A comprehensive understanding of the detrimental effects of stowing the coiled booms is necessary to implement these structures in spaceflight missions. During stowage inside the spacecraft, the boom is subjected to a constant deformation/strain that causes it to relax over time, measurable by a decrease in stress. Using large deformation bending tests the complete fold-stow-unfold-recover cycle of thin-laminate candidates for the rollable booms is characterized. Further bending and stowage testing is done at the boom level. The results from this test campaign will be used to evaluate the dimensional stability of deployable booms made from thin-ply composites that exhibit viscoelastic behavior and calibrate and validate numerical finite element models.

I. Nomenclature

\[ E_r = \] Relaxation Modulus
\[ \rho = \] Time constant
\[ E_1 = \] Young’s Modulus
\[ E_2 = \] Young’s Modulus
\[ v_{12} = \] Poison Ratio
\[ c_{12} = \] Shear Modulus
\[ D_{11} = \] Bending Stiffness
\[ D^*_{11} = \] Effective Bending Stiffness
\[ a_T = \] Shift Factor
\[ t_r = \] Thickness
\[ t = \] Time
\[ T = \] Temperature (°C)
\[ M = \] Moment
\[ P = \] Load
\[ s = \] Gauge Length
\[ l = \] Length
\[ r = \] Moment arm
\[ \phi = \] CBT angle
\[ \theta = \] Initial offset angle

II. Introduction

Spread-tow carbon fiber has allowed for the design of thin-ply carbon fiber reinforced polymer (CFRP) composites. With thinner plies a CFRP composite can be manufactured with multiple layers and fiber orientations, taking advantage of the benefits of combining different weave patterns, while still having an overall thin gauge needed for compact

¹ PhD Student, University of Texas at Dallas, Pathways Student Trainee, Structural Dynamics, NASA LaRC, 2 West Bush Road MS 497.
² Research Aerospace Engineer, Structural Dynamics, NASA LaRC, 4 West Taylor St, MS 230. AIAA Member.
stowage. This gives access to much thinner and more flexible composite structures that have a higher strength-to-weight ratio than their thicker counterparts [1]. These thinner composite structures have proven useful for deployable structures, which have many applications in space structures. Thin-ply deployable composites are currently being used for boom structures in solar sails and drag sails [1, 2]. They also have many more applications including deployable antennas, deployable panels/surfaces as well as thin parabolic reflectors [3]. These thin structures have advantages over other materials like metals, because of their low thermal expansion and thermal conductive properties. In-space thermal fluctuations can be detrimental to thin structures due to their lower stiffness. This causes undesirable deformations in metals that would be alleviated by using CFRPs [4]. When stowed in a coiled configuration, the composite booms undergo time-dependent deformations due to the relaxation of the viscoelastic polymer matrix held at a constant deformation. An example of the deployable composite boom (DCB) partially rolled can be seen in Fig 1a. This is a Collapsible Tubular Mast (CTM) boom and is the focus of this work. The CTM closed cross section is formed by bonding two omega shaped shells together with an epoxy adhesive. These booms have been observed to retain deformation after one month of stowage. This partially-recovered deformation can be seen in Fig. 1b and 1c. for a previous boom laminate architecture no longer in use and prone to creep. The flattening of the boom shown is caused by prolonged stowage that can lead to a decrease in the buckling load of the boom by 50 percent. It reflects how important an adequate laminate design is to the long-term viability of thin-shell rollable booms. The loss of strain energy during storage may also impair the self-deployment capability of the boom and stall extension [5]. These slender deployable booms can pack into very small volumes as shown in figure 1d and 1e, but their dimensional stability during stowage should be understood to use them effectively in the applications considered [6]. Considerations of the viscoelastic effects in thin-shell composites have been conducted previously on structures in the form of tape springs [7,8]. These studies present viscoelastic micromechanics models of plain weave (PW) composites in order to determine the macroscopic relaxation effects in tape springs. A similar approach can be applied to the more complicated geometries of deployable composite booms like the CTM. In order to develop these models, the material and structural properties of the composite booms need to be determined using viscoelastic characterization testing methods. In this work, viscoelastic testing will be performed on the polymer matrix used in the composite as well as the polymer adhesive that bonds together the two omega-shaped thin-shells of the booms. Viscoelastic testing will also be conducted on the composite laminates of interest at the coupon/material level. Finally, testing for viscoelastic properties will be carried out at the structural level by testing sections of composite booms as well as full-scale boom structures.
III. Polymer Viscoelastic Testing

A. Polymer Adhesive

One component of the DCBs is bonding the thin gauge sections together to achieve a closed cross-section geometry that has increased stiffness properties. The adhesives used are polymers that will relax over time when subjected to a constant strain. High shear stresses have been observed at the web (flat area at the edge of the boom cross section) where the shells are adhered together. Characterizing how this shear stress and the viscoelastic and viscoplastic properties of the adhesive affect each other can help evaluate the risks of using this technology. Table 1 shows the properties of the polymers of interest, Hysol EA 9696 film epoxy and PMT-F7 epoxy resin. Thin films of the EA9696 adhesive were cured in an autoclave and then laser cut into standard dog-bone shapes for tensile relaxation tests.

Table 1. Polymer material properties used in deployable composite booms in this study

<table>
<thead>
<tr>
<th>Material Description</th>
<th>Width (mm)</th>
<th>Thickness (mm)</th>
<th>E (GPa)</th>
<th>Vendor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hysol EA 9696</td>
<td>12.7</td>
<td>0.14</td>
<td>1.8</td>
<td>Henkel</td>
</tr>
<tr>
<td>PMT-F7</td>
<td>12.7</td>
<td>4</td>
<td>2.5</td>
<td>PatzM&amp;T</td>
</tr>
</tbody>
</table>

Fig. 2  Viscoelastic Polymer Testing.

After cut, the dog bones were speckled with black spray paint or a Sharpie®. The speckle pattern is necessary for digital image correlation (DIC). DIC will allow the measurement of large three-dimensional deformation fields. The sample is clamped by tensile grips to perform tensile relaxation test at temperatures increasing from 40 °C to 80 °C in 10 °C increments. The chamber was given 92 minutes to reach thermal equilibrium at each temperature. The dog bones were pulled to a displacement of 10.16 mm at 10.16 mm per minute. The displacement was held for 6 hours followed by a zero-load creep recovery step.
Figure 3 shows the relaxation modulus for the EA 9696 adhesive test. As expected, the modulus drops with increasing temperature and decreases with time. Assuming the material is thermorheologically simple the time temperature superposition (TTS) principle can be used to shift the relaxation modulus curves relative to the one at 40 °C to build a master curve and represent a much longer relaxation time frame at 40 °C. The shift factors used for the time shift are shown on the right plot.

![Fig. 3 EA 9696 Adhesive Relaxation Modulus Time Shift.](image)

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Fig. 4  EA 9696 Adhesive Relaxation Modulus Master Curve and Prony fit

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

(2)
After a master curve is created a Prony series is fitted to the experimental data using a least squares approach. Equation 2 shows the Prony series that is used. The coefficients $E_r$ and $\rho$ are determined for each respective $k^{th}$ term. A black dotted vertical line is marked on the graph at two years. Two years is assumed to be the upper limit stowage time for these deployable composites for current applications of interest to NASA. The experimental data and the fitted Prony series extend past this time frame.

B. Polymer Matrix

It is important to characterize the viscoelastic properties of the polymer matrix because the carbon fibers are highly elastic. The polymer matrix is the main cause for any time-dependent viscoelastic effects in the composite, though laminate architecture and fiber orientation can also have a significant effect [9]. The viscoelastic testing for the polymer matrix is done in a similar way to the adhesive. A set strain/displacement is applied to the polymer in a tensile test setup and held while the polymer relaxes over time. This is carried out at increasing temperatures starting at 40 °C and increasing to 70 °C in 10 °C increments with a relaxation time of 3 hours.

![PMT-F7 Relaxation Modulus](image1)

**Fig. 5** PMT-F7 Relaxation Modulus Time Shift.

Assuming the polymer is thermorheologically simple TTS is used to construct a relaxation modulus master curve at the reference temperature of 40 °C shown in Fig. 5. Further test will be carried out up to 120 °C to increase the time represented in the 40 °C master curve to beyond a few days shown in the graph. The data can then be fitted with a Prony series using Eq. 1. The viscoelastic response of the polymer matrix will be used to develop micromechanics models for the composites that will be applied to the booms to model the dimensional stability of the booms during stowage.
IV. Composite Viscoelastic Testing

The combination of carbon fiber with a polymer matrix creates a non-isotropic composite. This will cause the viscoelastic properties of polymer matrix to be lessened by the highly elastic carbon fibers. Understanding the viscoelastic effects of the thin-ply composites at a coupon/material level will help to validate micromechanical models being developed so the stowage of the boom can be modeled accurately [9, 10]. Thin-ply and thin-shell composites can sustain large bending deformations and strains. To study the composites at these large bending strain regimes, a test method suitable for large bending deformations was developed called the column bending test (CBT) [11]. This test method overcomes the limitations of previously developed test methods. Traditional testing methods including three-point and four-point bending are not designed to handle the high deformations that are required to study these thin composites effectively [11]. The other test methods for high deformation bending are the simple vertical test, bending platen test and the large deformation four-point bending (LD-FBD) test. The 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. The 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 are highly non-uniform requiring complex structural analyses to interpret test results. The platen test is used for determining upper limit on maximum coupon curvature or for computing strains and stresses at failure. Platen test are not used to assess bending stiffness as it does not represent a pure bending state well. 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 creates stress concentrations at the grips which cause premature failure at the grips and not in the test section. LD-FPB is not normally used for bending strength and strain to failure evaluation [11].

The CBT was developed at Opterus R&D and evaluated and improved at the NASA Langley Research Center (LaRC) [7]. Before other researchers have successfully used CBT to characterize the bending stiffness/strength of thin laminates [13]. The CBT has some of the benefits of the three tests mentioned earlier without having some of drawbacks for higher deformation bending test. This test method applies a moment across the test specimen that increases from the from the grips to the center of the test specimen, with the center having the highest moment and curvature. The moment gradient is known and is small across the specimen, but it insures the failure of the coupon at the center of the specimens and not at the grips. This gives the ability to test thin composites over a full range of curvatures up to failure. The Fixture is counterbalanced, meaning it is symmetric about the point it is pinned so that gravity has no effect on the test fixtures.

\[
\frac{\delta}{s} = 1 - \frac{2}{s} \sin \frac{\phi}{2} + 2 \frac{l}{s} \left( \cos \theta - \cos \left( \theta + \frac{\phi}{2} \right) \right) \]  
\[ \kappa = \frac{\phi}{s} \]  
\[ r = \frac{1}{s} \left( 1 - \cos \frac{\phi}{2} \right) + \frac{l}{s} \sin \left( \theta + \frac{\phi}{2} \right) \]  
\[ M_{max} = Pr \]  
\[ M_{min} = Pl \sin \left( \theta + \frac{\phi}{2} \right) \]

This test method has simple kinematics used to calculate the moment and bending stiffness of a coupon from the load and displacement data from a load frame. Equations 3-7 show the kinematic relationship and can be solved numerically for the moment. This test was originally made to study the failure of thin composites at high bending deformations [11]. The CBT will now be used to study the viscoelastic characteristics of various laminates under consideration for deployable booms. Previously the CBT fixtures were manufactured out of 3D printed plastic. The relaxation test fixture has been printed out of titanium to avoid viscoelastic effects observed on previous plastic fixtures.
Table 2. Lamina material properties of the thin-ply composites used in the study.

<table>
<thead>
<tr>
<th>Material (fiber/resin)</th>
<th>Spread-tow Fabric Form</th>
<th>Width (mm)</th>
<th>FAW (g/m²)</th>
<th>Ply AW (g/m²)</th>
<th>FVF (%)</th>
<th>Thickness (µm)</th>
<th>E₁ (GPa)</th>
<th>E₂ (GPa)</th>
<th>ν₁₂ (GPa)</th>
<th>G₁₂ (GPa)</th>
<th>Vendor (fiber / resin)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MR60H/PMT-F7</td>
<td>Unidirectional (UD)</td>
<td>50</td>
<td>38.0</td>
<td>63.4</td>
<td>56</td>
<td>40 ± 3</td>
<td>174.4</td>
<td>8.4</td>
<td>0.259</td>
<td>6.4</td>
<td>Sakai Ovex / Patz M&amp;T</td>
</tr>
<tr>
<td>M30S/PMT-F7</td>
<td>Plain Weave (PW)</td>
<td>1000</td>
<td>61.0</td>
<td>89.7</td>
<td>54</td>
<td>58 ± 3</td>
<td>94.2</td>
<td>94.2</td>
<td>0.026</td>
<td>3.9</td>
<td>Sakai Ovex / Patz M&amp;T</td>
</tr>
</tbody>
</table>

Table 3. Lamina material properties of the thin-ply composites and adhesive used in the study.

<table>
<thead>
<tr>
<th>Label</th>
<th>Laminate</th>
<th># Coupons tested</th>
<th>Avg thickness (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M30S PW_0_x4</td>
<td>[0-90PW]ₜ</td>
<td>4</td>
<td>228±4</td>
</tr>
<tr>
<td>M30S PW_45_x4</td>
<td>[±45PW]ₜ</td>
<td>4</td>
<td>228±4</td>
</tr>
<tr>
<td>LAM1_0_x6</td>
<td>[±45PW]₀/0UD₂/±45PW₂</td>
<td>5</td>
<td>340±15</td>
</tr>
</tbody>
</table>

Table 2 and Table 3 show the lamina and laminate material properties. The polymer matrix is PMT-F7, the material described and tested in the previous section. Testing has been done on plain weave samples that are both oriented at ±45 degrees and 0-90 degrees as well as a laminate with ±45-degree-oriented weaves and a unidirectional axial 0-degree-ply in the middle. The samples were cured in an autoclave at 176.67 °C and 96.53 kPa. After curing, the laminate was sandwiched between G4 fiberglass plates for support and cut into coupons that are 5.08 cm in long and 2.54 cm wide using a diamond saw blades. They were painted white with black speckles for DIC strain measurements. The cross section of each sample was micro-graphed to get accurate thickness measurements of the laminates and paint because the paint thickness affects the strain measurements. The bending properties are proportional to the cube of the composite thickness so having an accurate thickness is necessary. The test methodology is shown in Figure 6. To represent loading history conditions similar to the stowage of a boom, the test has four steps. The initial folding step bends the coupon to a set strain/curvature that is representative of the boom during stowage. Once folded, the coupon is held at a constant strain while it relaxes for six hours. After relaxation, the coupon is unfolded to a zero-load condition where it is held for the creep recovery step. With 40°C being the desired stowage temperature, a temperature sweep can be done at higher temperatures. Using time temperature superposition, the 40 °C relaxation response can be represented for a desired 2-year time frame with much shorter six-hour relaxation testing times. The bending
moment can then be calculated from the load and displacement data gathered during the test. Ultimately, the coupon bending stiffness can be calculated from the dividing curvature from the moment.

![Fig. 7 Viscoelastic bending test.](image)

The strain from a test is shown in Fig. 7. The temperature is increased after each recovery step and held for 92 minutes so the chamber can reach thermal equilibrium. The strain returns to near zero during the 2-hour recovery stage and is subsequently folded back to the set strain after the temperature is increased and thermal equilibrium is achieved. Fig 6c shows the strains during folding for each temperature indicating that the folding deformation is consistent in this temperature regime, and that negligible permeant deformation is retained in the coupon.
An effective $D_{11}$ bending stiffness ($D^{*}_{11}$) term can be calculated from the kinematic Eq. (3-7) by dividing moment from curvature. This is an effective $D_{11}$, because there is not an unconstrained boundary condition on the test coupon due to constraints in the CBT fixture. In Fig. 8 the relaxation $D^{*}_{11}$ for the increasing temperatures is plotted. As expected the $D^{*}_{11}$ decreases over time and decreases as temperature is increased. Using TTS similarly to the polymer viscoelastic analysis a master curve can be generated at a relative temperature of 40 °C to represent the relaxation bending stiffness $D^{*}_{11}$ for a longer time at this temperature.

Fig. 8  Coupon 4 ply 45 deg laminate D11 master curve.
Figure 9 presents an overview of all the bending stiffness relaxations for the test samples for the three different laminates presented in Table 3. There is some variance between samples most prominently in the Lam1_0_x6 [±45PW₂/0UD₂/±45PW₂] results. The variance is attributed to variation in the coupon thickness, fiber volume fraction and void content. M30S PW_45_x6 showed the most relaxation followed by Lam1_0_x6. During bending the surface strains (around 0.8-1%) are much higher and decrease as the neutral axis (0% strain) is approached. Therefore, laminates with 45-degree fibers on the surface will see a higher viscoelastic response. The M30S PW_0_x6 has fibers along the bending axis which lessens the viscoelastic effect of the polymer matrix, and thus they present the lowest relaxation.
V. Deployable Composite Boom Testing

A. Deployable Composite Boom Bending Test

A similar test method to the composite coupon viscoelastic bending testing can be applied to a section of a DCB. A scaled-up CBT test fixture was made from machined aluminum as shown in Fig 10. The same kinematic relationships apply to this fixture with some of the fixture dimensions increasing. CBT sections were cut and painted white with black speckle to capture strain with DIC. The DCB sections were flattened and secured on the CBT fixture, and then inserted into a load frame/thermal chamber to conduct bending viscoelastic test. A similar bending relaxation and temperature cycle to that of the laminate coupon testing was carried out on the DCB sections. A boom was cut into 15.24 cm sections to be placed into the CBT fixture. The test was run at an initial reference temperature of 40 °C and increased by 5 °C after 6 hours of relaxation and 2 hours of recovery until 60 °C. The deformations of the boom section can be split into two separate parts, flattening and bending. The strain energy can also be decomposed into these two deformations steps [13]. Figure 10c and 10d shows there is some cross-sectional loss after the bending relaxation test. For the CBT test on the DCB, the calculated bending stiffness does not represent the $D_{11}$ of the material, so for these tests it is simply referred to as bending stiffness.

![Fig. 10 Relaxation CBT for Boom section.](image-url)
Figure 11 shows the bending stiffness relaxation results from the CBT test of the DCB section. The individual relaxation curves at each test temperature are shown in the top plot for boom sample DCB-S2. The curves were shifted in the time domain to form a master curve at 40 °C. The bending stiffness master curve of the seven DCB sections are shown in the bottom of Fig. 11. There is a 15% variation in the bending stiffness across the seven samples. The bending stiffness is related to the strain energy stored in the DCB section and can be determined and compared to the finite element model-based analysis framework under development that includes the composite material viscoelastic properties [14], as well as a full-scale DCB stowage test with the inclusion of the strain energy from previous flattening step of the boom.

**B. Full-Scale Deployable Composite Boom Stowage Test**

The full-scale boom can be tested in the stowed configuration using the testing fixture shown in Fig 12. As the boom is stowed, the strain energy stored in the boom will cause it to self-deploy and/or unravel/bloom. This test fixture has seven radial rollers with constant force springs on each roller to keep the boom from blooming. The radial force that each spring exerts was chosen to achieve a uniform near-constant force around the boom under gravity.
The boom is coiled around a lightweight 180 mm diameter cylindrical spool. This spool connects to a central shaft that rests on roller bearings to minimize friction. While the boom is stored, the strain energy from the flattened and rolled boom generates a torque on the shaft of the spool. A torque sensor attached to the shaft of the spool measures this torque. As the boom relaxes, the torque decreases over time in a similar fashion to the relaxation test done on the boom section and composite coupons. The strain energy can be determined from this torque. To accurately determine the deployment torque of the boom, the mechanical losses in the test fixture were determined. These losses come from friction and inertia in the test fixture and were determined by testing the fixture with a non-elastic material that does not store strain energy when coiled on the spool but presents a similar coefficient of friction to the boom. A dry carbon fiber fabric/cloth is used for this purpose. This material is tested with the fixture on a load frame. The torque resistance in the test fixture is determined from the load and the radius of the spool. By taking the torque resistance in the test fixture out of torque reading on the sensor that is connected to the spool, the torque generated from the strain energy of the stowed boom can be determined. The strain energy from the stowed boom can ultimately be compared to the strain energy of the CBT test done on the boom section and to the multi-scale finite element model under development [14] to ensure all forms of testing and analysis agree for predicting the dimensional stability of the boom during stowage.

Acknowledgments
This research was sponsored by NASA Space Technology Mission Directorate (STMD) under a Game Changing Development Program (GCDP) project to advance deployable thin-shell composite boom technology [15]. Assistance with boom specimen manufacturing from the Advanced Composites Fabrication Lab technicians at NASA LaRC, Kevin J. McLain and Mark Griffith, is gratefully acknowledged.
References


