Design and Testing of Bi-Stable Booms for Space Applications

Mark Pankow\(^1\), Charlie White

\(^1\) Assistant Professor
Department of Mechanical and Aerospace Engineering
North Carolina State University
911 Oval Dr, Raleigh, NC, 27695
Email: mpanyo@ncsu.edu webpage: http://www.mae.ncsu.edu/pankow

Keywords: Composite Booms, Deployable Structures, Bi-Stable, Satellite, Testing

ABSTRACT

CubeSats have tremendous potential to facilitate low-cost astrophysics and orbital science experimentation, but are limited by the proximity of sensors to interference from the satellite itself. In order to facilitate reliable data collection from sensitive instruments, deployable booms provide a means of separation from the spacecraft. In this work, a deployable carbon fiber boom was designed and tested to show feasibility at this small scale. Prototype booms with a lenticular cross section were developed in conjunction with a computational model. Mechanical testing has shown the ability to reliably flatten the booms in a bi-stable configuration so that it can be stored on a reel.

1. Introduction

Spacecraft often require that sensitive instruments be mounted as far away as possible to avoid interaction with the electronics and fields produced from the spacecraft. For CubeSats this poses a large problem as everything has been tightly packed inside the small cube not allowing for any isolation. On larger spacecraft this is accomplished through using deployable structures enabling the structure to footprint to grow after launch. These types of structures have a significant amount of flight heritage on larger satellites, but have limited use on CubeSats as often the technology does not scale down properly.

To date about 272 CubeSat missions have flown. All of them have the basic configuration of a cube in varying configurations [4]. Often the only deployable structure will be simple solar panels or antennas that deploy after launch. These elements are tape measures that have been mounted on the structure and pop out after deployment. The scientific capabilities of CubeSats could be enhanced by the development of a deployable instrument boom providing a new, quick test bed for instrument development. In order to foster this development we will examine deployable structures to enable separation of the instrument relative to the CubeSat.

Deployable carbon fiber booms have been used previously on larger spacecraft structures. The German Aerospace Center (DLR) has developed large scale deployable booms. For a full scale solar-sail demonstration, DLR has fabricated booms as long as 28m (Ref. [1]). Additionally, deployment tests in a simulated microgravity environment (aboard an Airbus A300 executing parabolic dives) have been conducted on a 14m test article (Ref. [2]). While these large scale test indicate that a reeled, CFRP boom is feasible, they do so on a much larger scale than required for a CubeSat application. CubeSat-based solar sail missions have been proposed (Ref. [3]) but utilize metal tape-spring booms to deploy the sail.

The DLR boom design is comprised of two lenticular cross sections that are glued together. Their boom was 14 m long with a material thickness of 0.2 mm and a width of 209 mm yielding a flattened thickness to width ratio of 0.00096 (Ref. [3]). The major challenge in scaling down the boom is that the thickness cannot simply be scaled down. To preserve the same ratio, a CubeSat scale boom with a 40 mm flattened width would need to have a total thickness of 38 μm or a laminate thickness of 19 μm. For context, consider that graphite fibers range from 5-10 μm in diameter. The ideal laminate thickness of 19 μm is equivalent to the thickness of 2-3 single graphite fibers. Achieving the ideal laminate thickness is clearly impractical.

In this report we will outline the design and fabrication of a deployable boom system capable of fitting inside of a 1U CubeSat. First an overview of existing deployable booms was examined and how they would scale to CubeSat level. Initial designs were manufactured and tested to understand performance-limiting characteristics. Preliminary computational models were developed to explore the design space and aid in future development. Final thoughts on
the next steps moving forward will be presented. Ultimately, CubeSat deployable booms will expand the range of scientific investigations that can be conducted from the CubeSat platform.

2. Geometry, Material and Fabrication

The lenticular cross section was modeled and modified from existing geometries to try and minimize the strain during flattening while maintaining a large cross section to resist bending. In order to achieve this equal radii of curvature were built into the geometry of the lamina. The final geometry is shown Fig. 1 where the flattened width will be 4cm wide to preserve some of the CubeSat volume.

![B) Lenticular Cross Section of Boom a) Equal moments of inertia b) Unequal moments of inertia](image)

The boom will be made out of carbon fiber as compared to other fibers and its high strength to weight ratio make it an ideal candidate for weight savings. Multiple different carbon fiber fabrics were evaluated and special attention was paid to keeping the material as thin as possible see Table 1. Therefore, the VectorPly C-BBX 0300 and the ACP 2.9 oz. are the main materials in consideration, as they will provide the thinnest materials.

<table>
<thead>
<tr>
<th>Company</th>
<th>Fiber</th>
<th>Thickness [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>VectorPly C-BX 0300</td>
<td>Uni +/- 45°</td>
<td>~ 0.20</td>
</tr>
<tr>
<td>Textile Products</td>
<td>3K Plain Weave</td>
<td>~ 0.30</td>
</tr>
<tr>
<td>SAATI – CC201</td>
<td>3K Plain Weave</td>
<td>~ 0.30</td>
</tr>
<tr>
<td>ACP – 2.9oz</td>
<td>1K Plain Weave</td>
<td>~ 0.20</td>
</tr>
</tbody>
</table>

The matrix material also plays an important part in the performance of the composite system, choosing something that has a higher strain to failure will allow it to survive larger bending strains. Two matrix systems were investigated as shown in Table 2. The additional benefit of choosing a resin with larger elongation is that this typically produces a lower modulus composite with lower bending stiffness enabling the boom to be flattened out with less force.

<table>
<thead>
<tr>
<th>Company</th>
<th>Resin</th>
<th>Elongation</th>
</tr>
</thead>
<tbody>
<tr>
<td>West Systems</td>
<td>105 Epoxy Resin/205 Hardener</td>
<td>3.4%</td>
</tr>
<tr>
<td>Applied Poleramic</td>
<td>DR-7 Resin/EH-102 Hardener</td>
<td>5.6%</td>
</tr>
</tbody>
</table>

Out of autoclave manufacturing techniques were used in order to avoid excessive equipment requirements for boom manufacture. The major goal was to create a low cost tooling procedure that would make consistent booms. The use of a negative mold allowed for the fabrication of half sections of the boom in a standard wet-layup process. The vacuum driven matrix absorption by the breather material eliminated excess matrix from the final product. Figure 2 illustrates the wet layup fabrication process. Bonding of the two halves introduced a major issue of fabrication as the two halves must be bonded together and form a consistent width and thickness joint. In practice this becomes difficult over longer length booms.
To overcome the issues associated with fabrication a new one step method was created to eliminate potential fabrication issues that can be created with the glued joint. A silicone mold was fabricated using two negative molds, creating a removable plug. The new fabrication process uses the negative mold to help hold the shape and the silicone plug to produce proper spacing between the two halves. The boom was then laid up using a wet-layup process and creates an integral joint with consistent thickness and width. Figure 3 shows a whole boom manufactured with this technique and the silicone plug used for the process. The excess material on the side is trimmed to length after fabrication.

3. Experimental Results

Compression tests were performed on a load frame and load/deformation were recorded. Samples were loaded in the screw driven load frame at a rate of 0.02 mm/sec. Early tests revealed that the loads encountered were on the order of 4.45-44.5 N and deformations on the order of 0.254 – 2.54 mm. Samples were loaded with rollers to reduce stress concentration in the parts and eliminate premature failure. Testing was supplemented with the use of optical measurements to closely monitor the shape of the boom in the two main directions. The extensometers integrated with the load frames were capturing deformation in the test fixture in addition to the boom itself. Two cameras recorded boom deformation in the load frame (see figure 4). One looked side-on to the boom while one used a mirror to image the free end deformation. Deformation could be correlated with load at the first moment of test fixture contact with the boom and the first non-zero load indication.
Boom performance was examined by fabricating half-boom sections of four different fiber types and the Poleramic DR-7/EH-102 matrix. The load versus deflection curve for flattening half-boom sections can be seen in figure 5. The 1K and the Vector ply show the softest response characteristics to flattening, meaning they produce the least strain in the flattening process, this response was similar to the conclusions from Table 1.

Figure 5 shows a comparison between two different layup orientations for the woven composite system. It shows that for the same amount of deflection it takes roughly $\frac{1}{2}$ the force to flatten the boom out. The booms laid up at $\pm 45^\circ$ orientation make it easier to flatten out, while providing and increase in torsional rigidity, as the fibers are aligned with the principal torsional axes.

Buckling tests were performed on fully manufactured boom sections cut to 12 inch lengths. Each end was potted into a cube of resin to provide an effective load transfer mechanism. Samples were then loaded in compression until the onset of buckling. Figure 6 shows the load deflection curves along with the buckling shape from one of the booms in testing. The samples had an average buckling load of about 70 lbs. After buckling displacement was controlled until the boom came to 10 lbs of load after buckling and was then completely unloaded, the boom returns to its initial configuration after the load is removed. The sample was then reloaded and achieved a buckling load of ~60 lbs or 85% of the initial buckling load, showing that there was not much damage. These two facts show that most of the energy is stored linear elastically in the boom and very little damage is actually occurring.
Fig. 6 Buckling load vs. deflection data along with buckled beam shape

With the current resin system long term storage poses a possible issue as some creep associated problems exist. Figure 7 shows what can happen to the booms after long term storage on one of the reels. One of the issues was that the matrix material was never post cured. Performing this post cure resulted in less creep and showed better performance, but changing resin systems should eliminate these issues.

Fig. 7 Creep Deformations after Prolonged Reeled Storage

4. Computational Model

A finite element model was created using the commercial software ABAQUS. Multiple models were created to simulate the different tests that were examined. The half boom model incorporated 2428 S4R elements. The shell elements were seeded with the orthotropic material properties using local coordinate systems for each material. Initial models focused on the flattening of the half-boom sections as this was the primary test performed in the selection process. Varying boundary conditions can be matched to constraints on the physical systems. Figure 8 shows the half-boom model setup in for a flattening test.
A whole boom was also modeled as can be seen in figure 9. Here the loading fixture to model the flattening of the boom can be seen as the two rollers that push on the end of the boom. The difficult with this test is that experimentally the boom was left un-attached and residual friction allowed for flattening. This is difficult to model therefore one corner of the boom at the free end was held fixed to eliminate the rigid body motion that was observed in the numerical simulations.

Development of an accurate computational model was contingent upon accurate determination of material properties. Experimental determination of material properties was accomplished for the final materials under consideration: VectorPly C-BX 0300 and ACP 1K plain weave. Test samples were created for each material (24 plies of the VP 0300 and 20 plies of the ACP 1K plain weave). Tension testing (ASTM D3039) produced the elastic modulus ($E_1$) along the longitudinal loading direction and flexural modulus ($E_{\text{flexural}}$). V-notch shear tests (ASTM D5379) produced the shear modulus ($G_{12}$). These results are tabulated in Table 3 along with an analytical estimate and selected result from literature (Ref. [5]). The analytical estimate was developed from thin laminate plate theory and representative properties for fiber and matrix (Ref. [5,6]).

<table>
<thead>
<tr>
<th>+/-45° orientation</th>
<th>$E_1$ [GPa]</th>
<th>$E_{\text{flexural}}$ [GPa]</th>
<th>$G_{12}$ [GPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental - VP 0300</td>
<td>9.79</td>
<td>3.67</td>
<td>36.27</td>
</tr>
<tr>
<td>Experimental - ACP 1K</td>
<td>8.00</td>
<td>2.05</td>
<td>40.54</td>
</tr>
<tr>
<td>Analytical Estimate</td>
<td>9.24</td>
<td>-</td>
<td>27.24</td>
</tr>
<tr>
<td>Literature (Ref. [5])</td>
<td>19.96</td>
<td>-</td>
<td>35.65</td>
</tr>
</tbody>
</table>

Figure 10a shows the experimental difference between the flexural and tensile modulus for the thin lamina. Additionally figure 10b shows the difference in the computational model based on the different effective moduli. These properties were configured as a shell material using the loading direction of the boom as the material
directions corresponding to the tests completed. Representing the material as a shell better characterized bending stiffness and improved correlation.

![Stress strain curves for different measurement of effective properties of thin composite materials](image1.png)

![Comparison of load deflection for 1/2 section of composite boom material](image2.png)

5. **Experimental and Computational Correlation**

The most successful prototype booms were fabricated from 1K woven carbon fiber. A single laminate was thin enough to provide the flexibility necessary for flattening and overlap of the woven fibers prevented warping during post-cure. Half-boom flattening was simulated with the computational model and duplicated experimentally. Figure 10 shows the correlation between model and experiment.

![Correlation of load deflection with experimental data](image3.png)

6. **Deployment/Support System**

The stored boom behaves exactly like a stored tape measure as there is elastically stored energy that wants to unfurl the boom. In order to overcome this energy some kind of fraction is needed to prevent the boom from...
A direct drive friction wheel was used to ensure that the boom remained on the reel until deployment (Figure 11). The friction roller is a direct drive mechanism drive by the rotation of the spool ensuring the same roll of speed at the interface of both parts of the mechanism. Work is still ongoing on the stepper motor deployment program.

7. Conclusions

Development of deployable carbon fiber booms for CubeSat applications is challenging due to the small scale of the booms and the relative thickness of the laminate. As such, thin carbon fiber fabric and a matrix material with a high strain to failure are required. Development of a computational model for the boom requires accurate and precise experimental determination of the material properties. The flexural modulus greatly impacts the flattening behavior and must be determined for a single lamina. Further work will focus on continuing to improve material properties definition for the model in order to obtain correlation between experiment and model. In addition, the deployer design will be advanced and optimized to provide maximum boom stiffness once deployed. Analysis of the stored boom configuration will be completed in order to better understand the creep behavior observed. Finally, static and dynamic analysis of the deployed boom will be completed in order to understand its behavior once deployed in a microgravity environment. The ultimate goal for this work is to demonstrate a deployable carbon fiber boom on a CubeSat mission and, in so doing, expand the scientific capacity of the CubeSat platform.

Acknowledgements

Funding for this work was provided by North Carolina Space Grant SPS # 2014-1782. The authors would like to thank Steve Cameron, Chris Celestino, Gary Lofton, Dr. Kara Peters, Stuart Philpott, Stephen West, and Xianyu Wu for their assistance with this work.

References