June 2020

Filament Winding Composite Airframes for Sounding Rockets

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Introduction

The primary objective of the Honeycomb Integration into Rocket Airframes (HIRA) research project is to design and manufacture high performance and reliable structural airframes for sounding rockets. This report details the findings of the first stage of the project, which determined the feasibility of using an X-Winder commercial filament winder to manufacture sounding rocket airframes. The research completed during the first stage occurred during the Spring semester of 2017 and the Spring semester of 2018 at Embry-Riddle Aeronautical University under the supervision of Dr. Eric Perrell. Future stages of the project will include manufacturing cylindrical sandwich structures and comparing their performance to the monocoque cylinders manufactured in the first stage of the project.

In the first stage of the project, the X-Winder was purchased and assembled, different winding methods were experimented with until a satisfactory wind was achieved, multiple tubes were wound, and these tubes were either tested to failure in compression or used in a flight test. The greatest challenge in this stage of the project was learning how to use the X-Winder and experimenting with the different winding methods; however, once this was accomplished, the team was quickly able to manufacture and test multiple tubes. All but one of these tubes were tested to failure in compression in order to determine their failure mode and load-carrying capacity. While the tubes exhibited different failure modes, they all carried an average load of approximately 9,800 lbf. One of the tubes was used as the structural airframe in a small 'Demo Rocket' which successfully flew to approximately 4,000 ft in altitude. While the tests were all successful, more testing needs to be done in order to confirm trends with a higher statistical sample size.

Methods

The primary source of funding for the HIRA research came from Embry Riddle Aeronautical University's (ERAU) IGNITE grant. IGNITE awarded HIRA $5,500 to use towards the research, and this funding was used to buy the bulk of the composites material and safety equipment used in the research. The research was performed by members of the Embry-Riddle Future Space Explorers and Developers Society (ERFSEDS) and used the lab space available to them. HIRA members also referred to ERAU's college of engineering faculty for guidance throughout the research project.

The primary rationale for choosing filament winding as the manufacturing method for the rocket airframes is that it is automated. An automated system removes a majority of the opportunity for human error and is also the most likely option to produce the most consistent and reliable results. A filament wound rocket body is also advantageous because it is a fully woven material and therefore cannot delaminate. The X-Winder 4 axis commercial filament winder was chosen as a filament winder because it was within the project budget and its structure was composed of 8020, which would be easy to modify and fix. The X-Winder Community page was occasionally referred to solve some of the logistical issues with the X-Winder.

The matrix used to manufacture all of the composite tubes is Aeropoxy's PR2032 Resin and PH3663 Hardener. The specific resin systems were chosen based on Aeropoxy's recommendation for the project's application. The Carbon Fiber tow was purchased from ACP composites. A 12k tow size was selected per X-Winder's recommendation as the largest tow size which the X-Winder could handle without modification. The mandrel which the carbon fiber tow was wrapped around to manufacture the tubes was an aluminum tool which was fabricated using a lathe. Frekote was used as a mold release agent and was applied to the mandrel prior to all manufacturing.

In order to accomplish the specific goals of the first stage of the project, the following tests were planned:

1. Coupon element testing
2. Manufacturing testing
3. Destructive compression testing
4. Flight testing

The coupon element tests were planned to experimentally determine the material properties of the matrix and carbon fiber; however, testing the epoxy and carbon fiber to ASTM standards became much more difficult and time intensive than originally anticipated. There were two primary blockers to completing this test campaign: 1) Lack of technical infrastructure at ERAU labs, and 2) difficulty manufacturing test coupons from the carbon tow. Because these tests were holding up the rest of the research, and they were not critical to accomplishing the primary goal of the first stage of this research project, the team decided to stop pursuing completion of the coupon element tests.

The manufacturing tests were planned to determine the quality of the carbon fiber tubes produced by the X-Winder. The team's approach was to manufacture a single layer tube and then visually inspect it for any voids or other manufacturing defects. The team used a method referred to as "dry winding" to save resources during this step, where carbon tow was wound around the mandrel replicating the manufacturing process, but with no epoxy. After a satisfactory single layer tube was manufactured, multi-layer tubes were manufactured. The team experimented with 2 different winding styles available on the 4-axis X-Winder: Helical Winding and Hoop Winding. The helical winding style was used first because it was a more versatile winding style that could be used to wind around pressure vessels in the future. After successfully winding a multi-layered tube with the helical winding style, the team switched to the hoop winding style and manufactured multiple tubes which were used in the destructive compression testing. Because a high confidence in single layer winding was developed during helical winding development, single layer tubes were dry wound with hoop winding and only multi-layer tubes were manufactured with hoop winding.

The destructive compression tests were planned to determine the failure mode and compressive strength of the tubes. A variety of tube lengths and wind angles were tested to determine any strong correlations between those parameters and compressive strength. The tubes were crushed at a constant rate of compression between 2 flat platens in a Tinius Olsen LoCap Testing Machine. According to Singer, Arbocz, and Weller in Buckling Experiments, the failure mode of each tube is impacted by the boundary conditions of the tube during testing; however, the team did not have resources to manufacture a clamp to ensure consistent boundary conditions among all samples (875). This was identified as a major source of error in the test data prior to the experiment, but because the boundary conditions of the tubes are not tightly constrained in flight, the unconstrained boundary conditions were considered to more accurately mimic flight conditions. The data recorded from these tests is the Force vs Displacement curves for each sample tested, and no strain data was recorded.

The flight test was planned to test a filament wound tube to the full environment it would experience as a structural airframe in a sounding rocket. As there are many environmental conditions that are difficult to test simultaneously on the ground, such as vibration and dynamic loading, an actual flight test was the most practical way to test the tube. The rocket was designed in OpenRocket, and a J355 motor was arbitrarily chosen to test the tube with. There were many design parameters that went in to the rocket, and while many of them were arbitrarily chosen based off past experiences with sounding rockets, the overall goal to which the rocket was designed to was to induce the highest stresses in the airframe to test as conservatively as possible.

Results

Coupon element testing

The material testing lab used to test the material coupons did not have a data acquisition system to record strain gauge input, and ASTM standards could not be followed without directly recording strain on the specimen during testing. An attempt was made to make a data acquisition system using an Arduino; however, development tests with the Arduino showed that there was some calibration error in the system. In order to test the carbon fiber tow material properties, the team tried to modify an ASTM standard for unidirectional carbon fiber tape, as there was not an ASTM standard for carbon fiber tow available to the team. This attempt was largely unsuccessful due to issues layering the tow and resin distribution through the thickness of the sample.

The epoxy coupons were manufactured in a plastic mold and then crushed. Figure 1 shows an epoxy coupon in the test configuration before compression, and Figure 2 shows an epoxy sample after it had been compressed passed its yield strength.

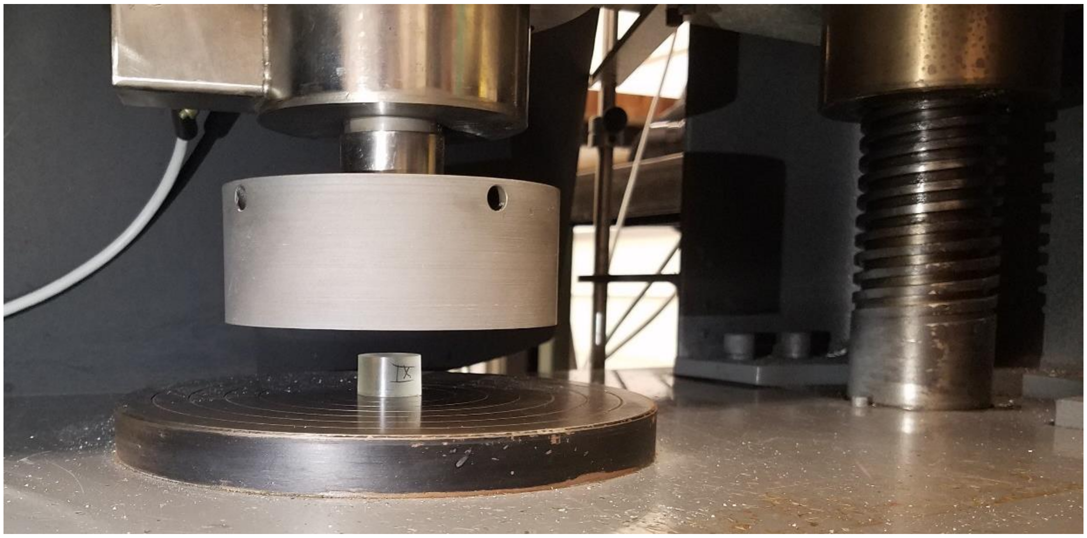

Figure 1: An Epoxy Coupon is set up in its test configuration prior to compression. Coupons were numbered with permanent marker prior to testing.

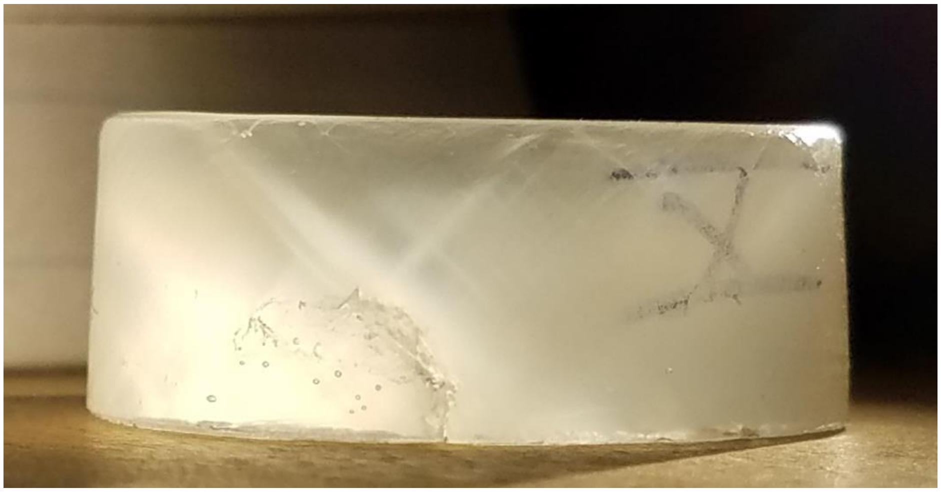

Figure 2: A picture of an epoxy coupon after it had been compressed past its yield strength.

The carbon fiber coupon samples were manufactured in a wooden mold and then vacuum bagged. Figure 3 shows the coupons in the manufacturing process just prior to vacuum bagging, and Figure 4 shows three of the samples which were manufactured. These samples did not have a consistent cross-sectional shape, nor did they have consistent fiber distribution throughout the sample. Because of these inconsistencies in the samples the failure of the coupon would not be characteristic of the material strength or stiffness.

Manufacturing Testing

As discussed in the methods section, the two types of wind patterns used were helical and hoop winding. They will be discussed separately in this results section for clarity.

Figure 3: A picture of the carbon fiber coupons in manufacturing prior to vacuum bagging.

Figure 4: Finished product of carbon fiber coupons cut to length. These were never tested due to poor quality of manufacturing.

Figure 5: The X-Winder filament winder set up for manufacturing.

Helical Winding

The helical winding pattern presented the most challenges of the two winding patterns because it wrapped around the ends of the mandrel. This presented two challenges: 1) removing the mandrel after the part had cured, and 2) the fiber slipping on the edges of the mandrel.

The first problem was solved by manufacturing endcaps with a groove on the outer diameter, allowing for a tool to cut the ends of the tube off without damaging the mandrel (see Figure 5). The process involved with removing the ends of the tube was very difficult and time intensive as the cutting groove in the endcaps was not visible after the tube had been wound, so its location had to be approximated. Even after the groove had been cut, removing the end of the tube was still difficult because epoxy would get into the groove, and carbon buildup on the endcaps would encompass the nuts constraining the tool on the threaded rod. Overall the process of removing the mandrel was successful, but very time intensive and difficult.

The second problem was difficult to solve because it was caused by a combination of the tensioning system on the X-Winder losing tension as it wrapped around the endcaps and the edges of the endcap being very smooth. The tensioning system on the X-Winder compresses a spring to create tension on the tow, which is resisted by a Velcro belt around the carbon fiber reel. Overall the system performed poorly and needed an entire redesign to fix the problem. The team experimented with wrapping a few materials around the edge of the endcaps to prevent the tow from slipping. Electrical tape performed the best but did not solve the problem entirely. A permanent solution was never found, and the temporary solution was to manually hold the fiber in place while the X-Winder was wrapping around the edges. The temporary solution to this problem was to have a team member physically hold the tow in place as the filament winder wound around the endcaps; however, this was labor intensive and tricky and was the ultimate reason the team switched to the hoop winding pattern.

The team ultimately manufactured 4 tubes: 3 iterations of single-layer tubes, and 1 multi-layer tube (see Figure 6). Iteration 1 was manufactured first on a smaller development mandrel and did not finish the winding process because an internal error in the code, the source of which was never identified. Iterations 2 through 4 were manufactured on a larger 4-inch diameter mandrel seen in Figure 5. Iteration 2 had many voids in the single layer. Upon visual inspection of the tube, the primary cause of this was determined to be a difference in thickness of the tow when it is dry and after it had been wetted with epoxy. To account for this, the filament width input in the X-Winder software was changed to the smallest width measured in iteration 2. The results of this change in input resulted in iteration 3. This tube had significantly fewer and much smaller voids, although they were still detectable with a simple visual inspection. Because a majority of the tube did not have voids, the voids that were present were determined to be an effect of either the fiber slipping around an endcap or inconsistencies within X-Winder’s code. Iteration 4 was manufactured with the same inputs as iteration 3 with the exception of winding multiple layers instead of 1 layer. There were no visible voids in this iteration and the tube and overall it seemed stiff and rigid. Iteration 4 was used as the structural airframe in the flight test and performed nominally.

Figure 6: Tubes are arranged in order of iteration. From left to right: Iteration 1, Iteration 2, Iteration 3, Iteration 4. Iteration 4 was used as the airframe in the flight test. A 12-inch ruler is positioned along the bottom for scale.

Hoop Winding

The hoop winding pattern presented 2 minor challenges which affected the quality of the tubes produced: 1) the fiber would slide on the surface of the mandrel near the ends, and 2) there was significant fiber buildup around the ends of the mandrel such that the fiber buildup impacted the delivery head. The effect of the fiber sliding was minimal during the first two layers; however, as the fiber buildup became significant around the ends, the fiber would slip more. The fiber sliding from this only had an effect on 3 to 6 inches on each end of the tube, and the section of tube affected by this was cut off and discarded after the tube had cured. Each of the 3 tubes manufactured with the hoop winding pattern was wound with a different wind angle to see if this had an impact on the fiber sliding around the end. The fiber slip tended to increase as wind angle decreased. The short term solution to the fiber buildup problem was to manually spread out the fiber buildup so that it was no longer interfering with the delivery head, and the long term solution was to make new endcaps that had a large groove for the fiber to buildup in, but these endcaps were never tested as there was not enough time left for another manufacturing test.

Three tubes were manufactured with the hoop winding pattern: Tube A, Tube B, and Tube C. The characteristics of each tube are listed in Table 1:

Table 1: A description of each tube manufactured with the hoop winding pattern.

Tube designation	Wind Angle (degrees)	Vacuum Bagged (Yes/No)
Tube A	45	Yes (low vacuum)
Tube B	55	Yes
Tube C	65	No

Tube A was vacuum bagged with a low vacuum because the vacuum pump started smoking soon after it pulled a vacuum, so it was shut off and the bag was sealed; however, there was a small leak evident by the bag having lost its vacuum when it was checked the next day. Tube C was intentionally not vacuum bagged to see if vacuum bagging affected failure mode.

Destructive Compression Testing

A total of 5 samples were tested in compression to failure. Each tube tested was labeled with a number indicating the sample number as well as a letter indicating which tube it had been cut from (ex. Tube 4C is sample number 4 and was cut from Tube C). Originally only 3 samples were going to be crushed; however, tubes B and C had enough extra length after being cut, and 2 shorter samples were cut. Tube A did not have enough extra length because a lot of length was cut away and discarded due to fiber slipping caused by the low wind angle.
Table 2 includes data on each sample:

Table 2: Test results for each test sample. The average maximum compressive strength for each tube was 9,854 lbf.

Test Sample Number	Length (in)	Max Compressive Strength (lbf)	Wind Angle (degrees)
1A	10	10,110	45
2B	10	9,632	55
3C	10	9,816	65
4C	5	10,093	65
5B	5	9,619	55

Pictures of each tube before and after are included in Figures 7 through 12, while Figure 13 shows a picture of tube 3C in its test configuration just prior to testing.

Figure 7: Tubes 1 through 5 prior to testing

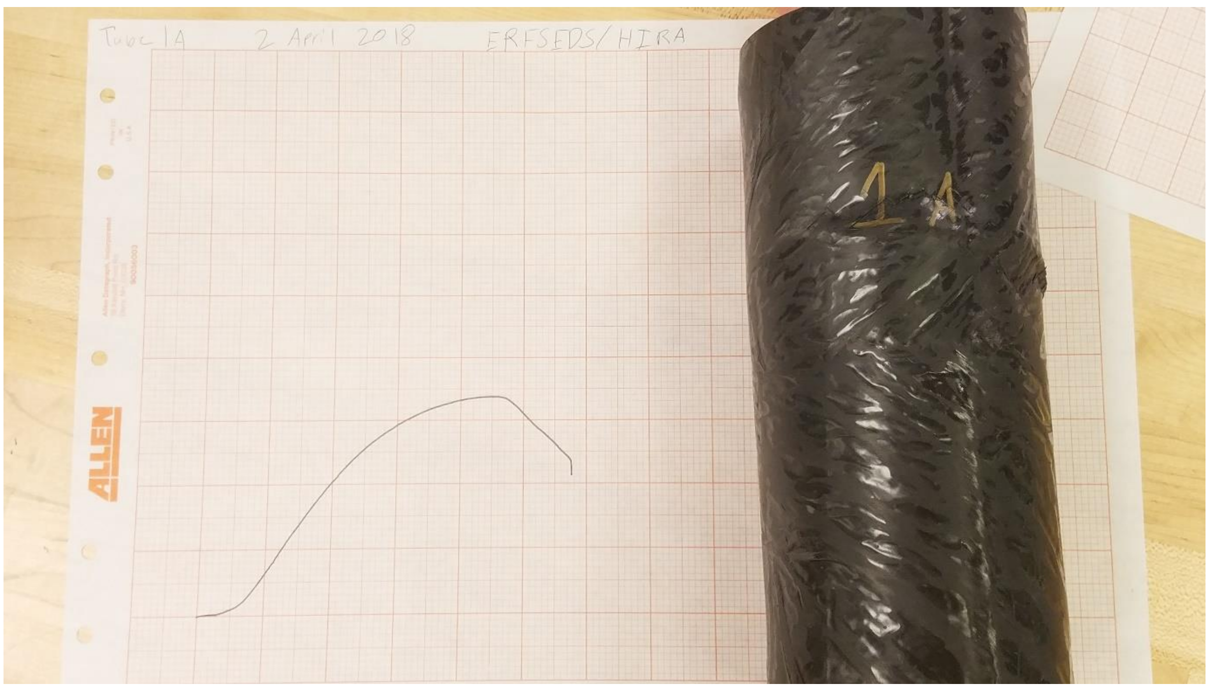

Figure 8: Tube 1A after it had been through its compression test with its Force VS Displacement curve

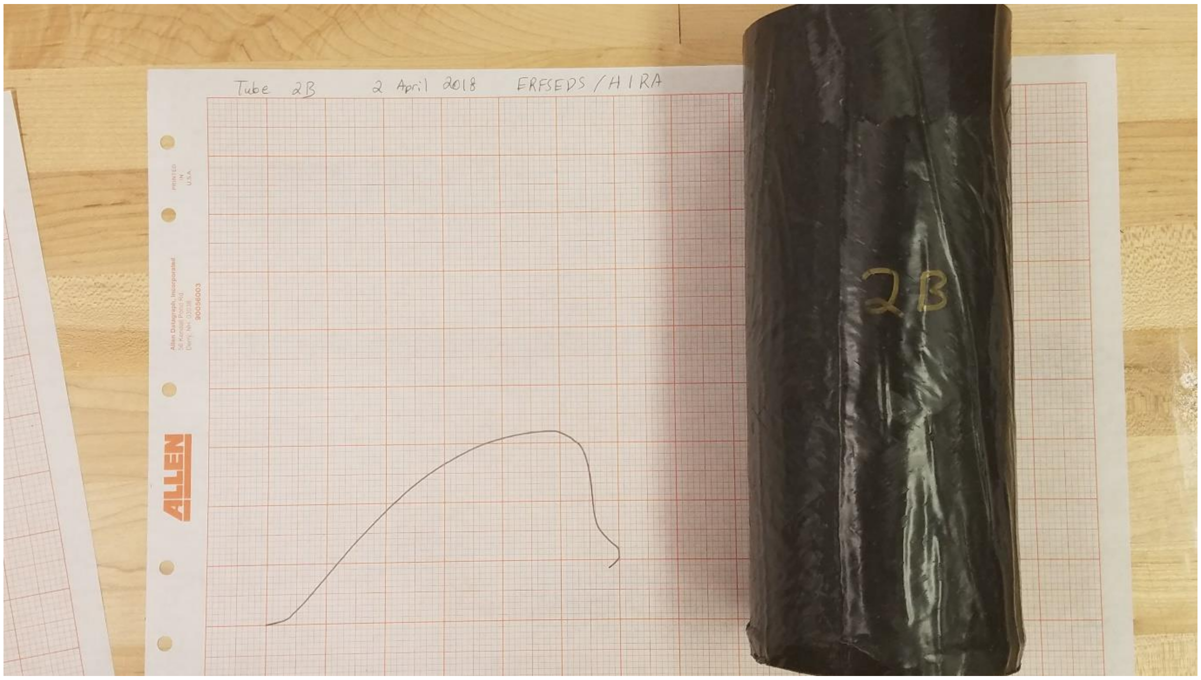

Figure 9: Tube 2B after it had been through its compression test with its Force VS Displacement curve

Figure 10: Tube 3C after it had been through its compression test with its Force VS Displacement curve

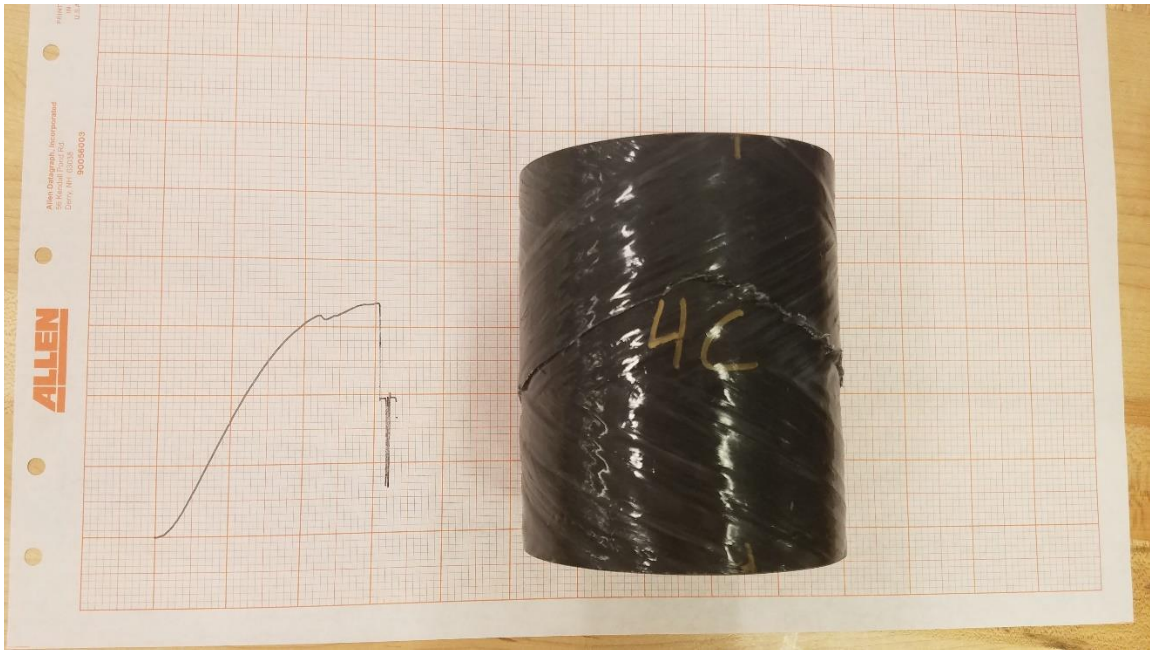

Figure 11: Tube 4C after it had been through its compression test with its Force VS Displacement curve

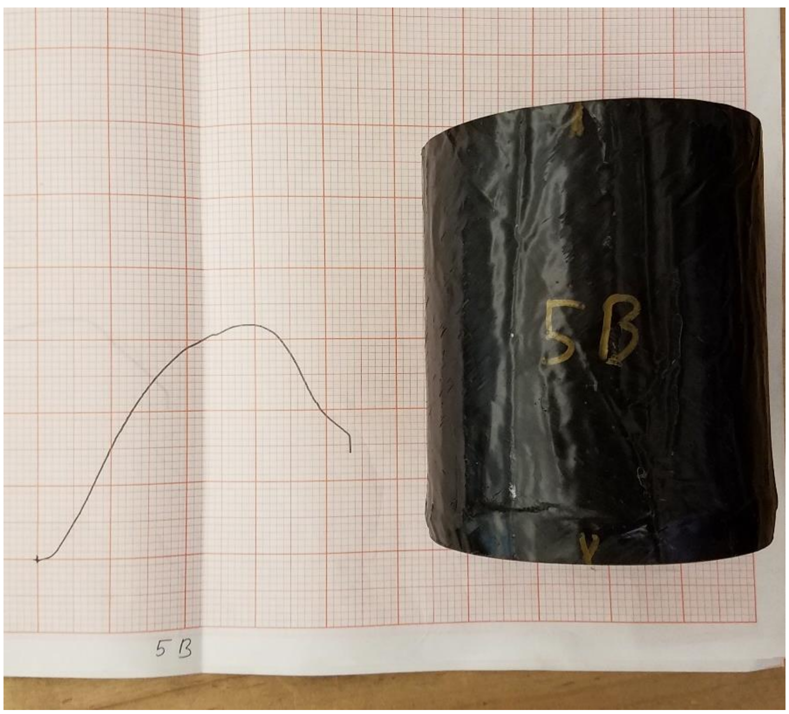

Figure 12: Tube 5B after it had been through its compression test with its Force VS Displacement curve

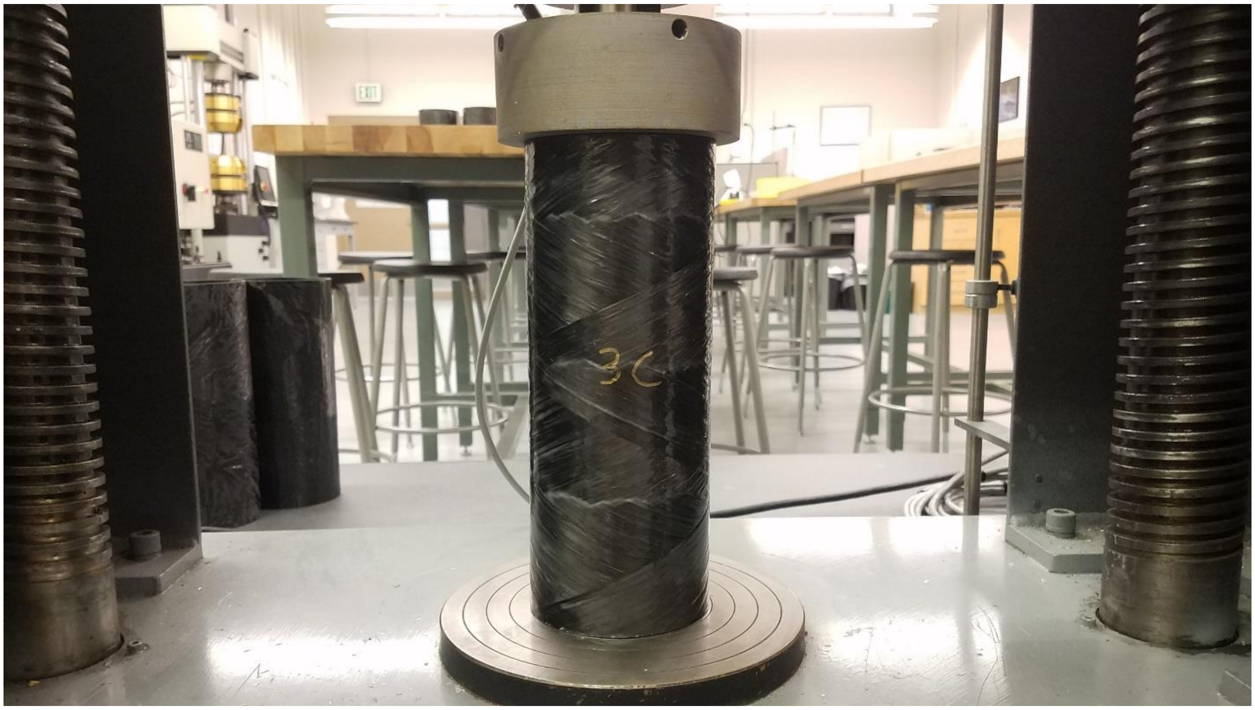

Figure 13: Tube 3C in its test configuration in the Tinius Olsen LoCap Testing Machine just prior to test.

Each of the plots shown in Figures 7 through 12 were digitized and plotted on top of each other in Figure 14. This showed that the shorter tubes (4C and 5B) had a stiffer reaction than the rest of the longer tubes. Tubes 1A, 2B, and 3C all had approximately the same stiffness despite their differences in wind angle and vacuum bagging. It is important to notice that tubes 3C and 4C both had more brittle failure modes while the rest of the tubes had more ductile failure modes. It is inconclusive whether this was due to the wind angle, the vacuum bagging, or some unknown parameter affecting the failure mode.

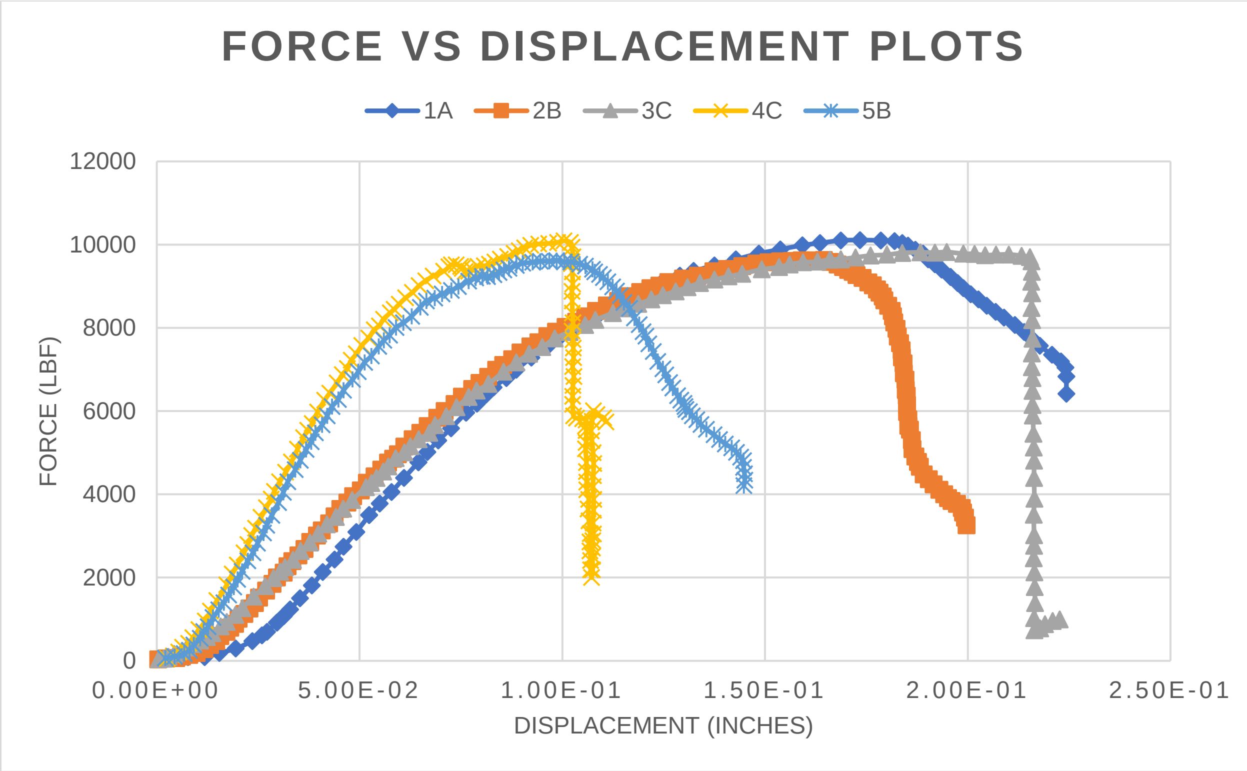

Figure 14: This plot shows the Force VS Displacement data for each of the compression tests.

Flight Testing

The HIRA demo rocket used the tube produced in iteration 4 of helical winding as the primary structural airframe. The fins were surface mounted to the aft end of the tube, and a commercially purchased thrust plate created a direct load path between the motor and the tube. Figure 15 shows the rocket fully assembled for pre-flight inspection, and Figure 16 shows the rocket on the launch pad.

Figure 15: The rocket is fully assembled for pre-flight inspection.

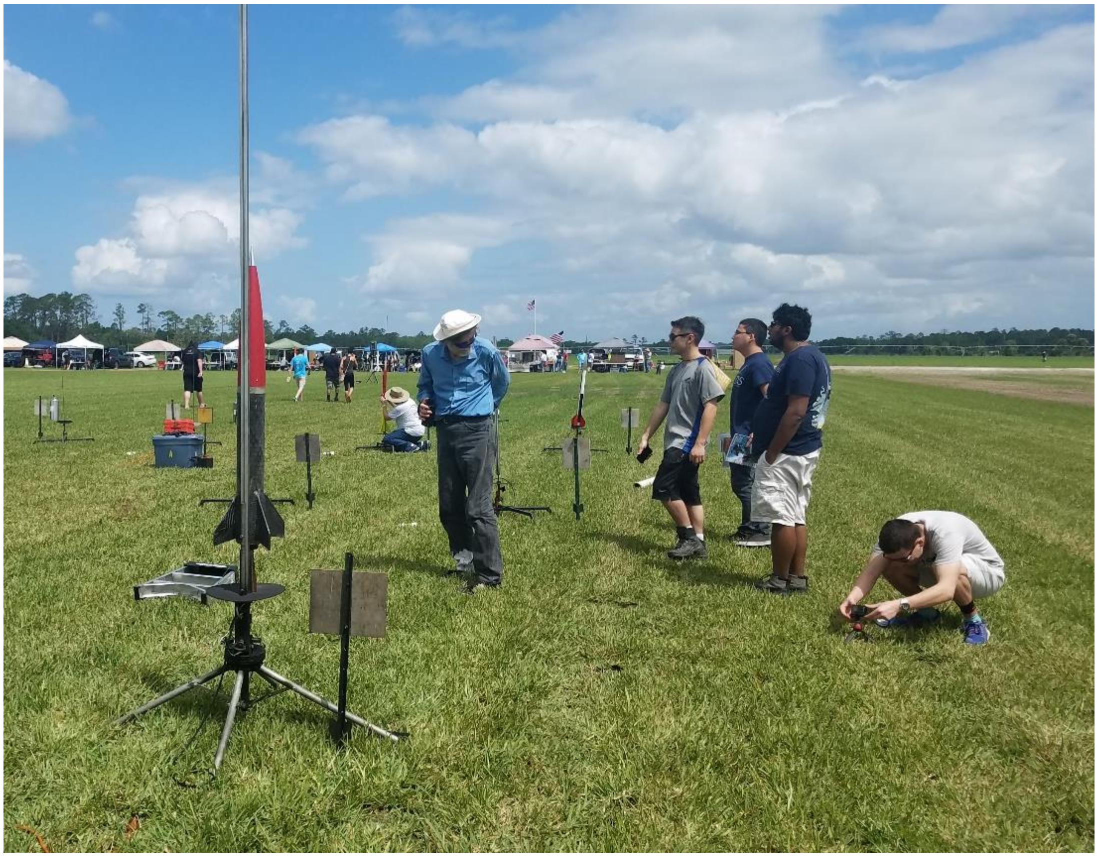

Figure 16: Team members prepare the rocket for flight on the launch rail. The rocket flew to 4,042 feet above ground level and recovered nominally.

The rocket flew to 4,042 feet above ground level and recovered nominally. A visual inspection after the flight showed no signs of damage to the tube, and the rocket is considered capable of flying again with no repairs needed.

Discussion

The results from both the destructive compression tests and the flight test confirm that manufacturing structural sounding rocket airframes using an X-Winder filament winder is feasible. More samples need to be manufactured and tested in order to fully characterize the structural capabilities of the tubes, but more funding needs to be secured before this can continue. The ERFSEDS club at ERAU is already planning on manufacturing a larger sounding rocket using the X-Winder filament winder as the primary manufacturing system for the airframe, and other projects and clubs are considering using the X-Winder as a part of their research projects.

The next stage of the HIRA research project will investigate manufacturing methods for integrating honeycomb into the filament winding process and comparing structural test results with the results from this research. This sandwich structure is theoretically much stiffer than the monocoque structures manufactured in the first stage of this project; however, there are many manufacturing challenges associated with sandwich structures as well as many more failure modes.

References

Josef Singer, Johann Arbocz, and Tanchum Weller. (2002). *Buckling Experiments* (Volume 2). John Wiley & Sons, Inc., NY