Design, Manufacturing, and Integration of Fins for 2017-2018 OSU ESRA 30k Rocket

by
Emma Renee Fraley

A THESIS

submitted to

Oregon State University

Honors College

in partial fulfillment of
the requirements for the
degree of

Honors Baccalaureate of Science in Mechanical Engineering
(Honors Scholar)

Presented October 19, 2018
Commencement June 2019

AN ABSTRACT OF THE THESIS OF

Emma Fraley for the degree of Honors Baccalaureate of Science in Mechanical Engineering
presented on October 19, 2018. Title: Design, Manufacturing, and Integration of Fins for
2017-2018 OSU ESRA 30k Rocket.

Abstract approved:_______________________________________

Nancy Squires

The Oregon State University (OSU) Experimental Sounding Rocket Association (ESRA) 30k Rocket Team is a student run rocket team that competes in the Intercollegiate Rocket Engineering Competition at Spaceport America. The goal of the competition is to launch a student designed, manufactured, and tested experimental sounding rocket to 30,000 ft carrying a 10 lb. scientific payload. One component of the rocket is the fins which provide stability for the rocket. The 2017-2018 OSU ESRA 30k rocket fins are composite fins with a clipped delta planform and a double diamond cross-section. The purpose of this thesis to present the design, manufacturing, integration, and testing processes for the 2017-2018 OSU ESRA 30k rocket fins. The goal is that this thesis will be a reference and a guide for future OSU rocket teams. Background research on fins and optimal fin design is presented and the manufacturing and integration processes are described in detail. Test results are also presented. Additionally, the many lesson learned throughout the process of designing, manufacturing, integrating, and testing the fins are presented to help future teams build better fins and avoid common mistakes.

Key Words: ESRA, Rocket, Fins, Design, Manufacturing, Integration, Composites

Corresponding e-mail address: fraleye@oregonstate.edu

©Copyright by Emma Renee Fraley
October 19, 2018

Design, Manufacturing, and Integration of Fins for 2017-2018 OSU ESRA 30k Rocket

by
Emma Renee Fraley

A THESIS

submitted to

Oregon State University

Honors College

in partial fulfillment of
the requirements for the
degree of

Honors Baccalaureate of Science in Mechanical Engineering
(Honors Scholar)

Presented October 19, 2018
Commencement June 2019

Honors Baccalaureate of Science in Mechanical Engineering project of Emma Renee Fraley presented on October 19, 2018.

APPROVED:

Nancy Squires, Mentor, representing Mechanical Engineering

Rob Stone, Committee Member, representing Mechanical Engineering

Bob Paasch, Committee Member, representing Mechanical Engineering

Toni Doolen, Dean, Oregon State University Honors College

I understand that my project will become part of the permanent collection of Oregon State University, Honors College. My signature below authorizes release of my project to any reader upon request.

Emma Renee Fraley, Author

Table of Contents

I. Introduction

The Oregon State University (OSU) Experimental Sounding Rocket Association (ESRA) 30k Rocket Team is one of four rocket teams under the OSU American Institute of Aeronautics and Astronautics (AIAA) Club. OSU AIAA is a student chapter of the national AIAA professional society and the only aerospace engineering club at OSU. The OSU ESRA 30k Rocket Team competes in the Spaceport America Cup (SA Cup), an Intercollegiate Rocket Engineering Competition (IREC) event hosted by ESRA, an organization that promotes hands-on rocket engineering. An experimental sounding rocket is a rocket that falls between "experimental" high power rocketry and a sounding rocket that can reach space [1]. The SA Cup is held at Spaceport America, New Mexico in June. The competition is divided into six categories: 10k-Commercial Off-the-Shelf (COTS) motors, 30k-COTS motors, 10k-Student Researched and Designed (SRAD) solid motors, 30k-SRAD solid motors, 10k-SRAD hybrid/liquid motors, and 30k-SRAD hybrid/liquid motors. The 2017-2018 OSU ESRA 30k Rocket Team competed in the 30k-SRAD solid motors category. The goal of the 30k-SRAD solid motor category is to launch a rocket with a student designed and built solid motor capable of carrying a 10 lb. payload to 30,000 ft. Teams are scored on how close the actual altitude is to the target altitude, if the rocket is recovered in a re-flyable condition, design and implementation, a technical report, and progress reports.

The 2017-2018 OSU ESRA 30k rocket is single stage, minimum diameter design. The motor is an SRAD O-class solid motor with a total impulse of 26,500 Ns. The rocket structure consists of a carbon fiber lower airframe, a fiberglass upper airframe, Kevlar nose cone, boat tail, and couplers, and composite sandwich fins. The rocket has a dual deploy recovery system that uses black powder ejection charges triggered by pressure readings from StratoLoggers. The telemetry system for the rocket uses live GPS which allows for both data decoding and direction finding. The rocket carries two payloads, a deployable payload and a fixed payload. Both payloads are standard CubeSat dimensions. The 3U deployable payload has a standard wide-lens camera and a wide-view infrared camera that are used to identify and track wildfires. The 1U fixed CubeSat contains a microbiology experiment. The rocket can be divided into four main sections: the nose cone, upper airframe, mid-bay coupler, and lower airframe. The lower airframe can be further broken up into an upper and lower section. The subsystem components housed in the different sections are listed below. The numbers listed below correspond to the numbered components in Figure 1, a section view of the rocket.

Rocket Subsystems and Components

Nose Cone

1. Rocket telemetry electronics
2. Non-deployable payload

Upper Airframe

3. Deployable payload
4. Drogue parachute
5. Drogue parachute black powder ejection charges

Mid-Bay Coupler

6. Drogue and main parachute recovery system electronics

Lower Airframe (upper section)

7. Main parachute black powder ejection charges
8. Main parachute

Lower Airframe (lower section)

9. Solid motor

Additional Components

10. Fins
11. Boat tail

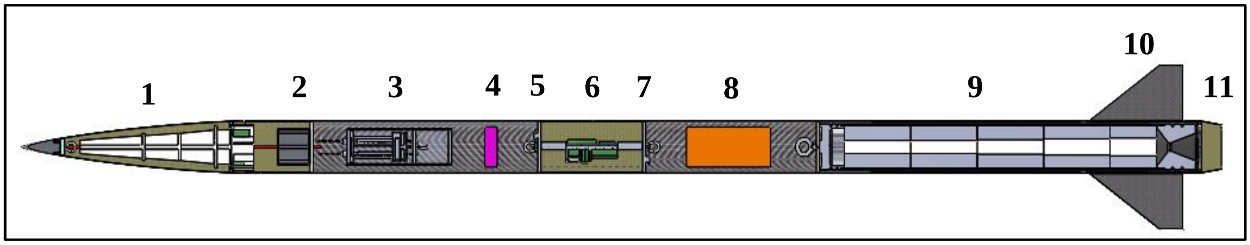


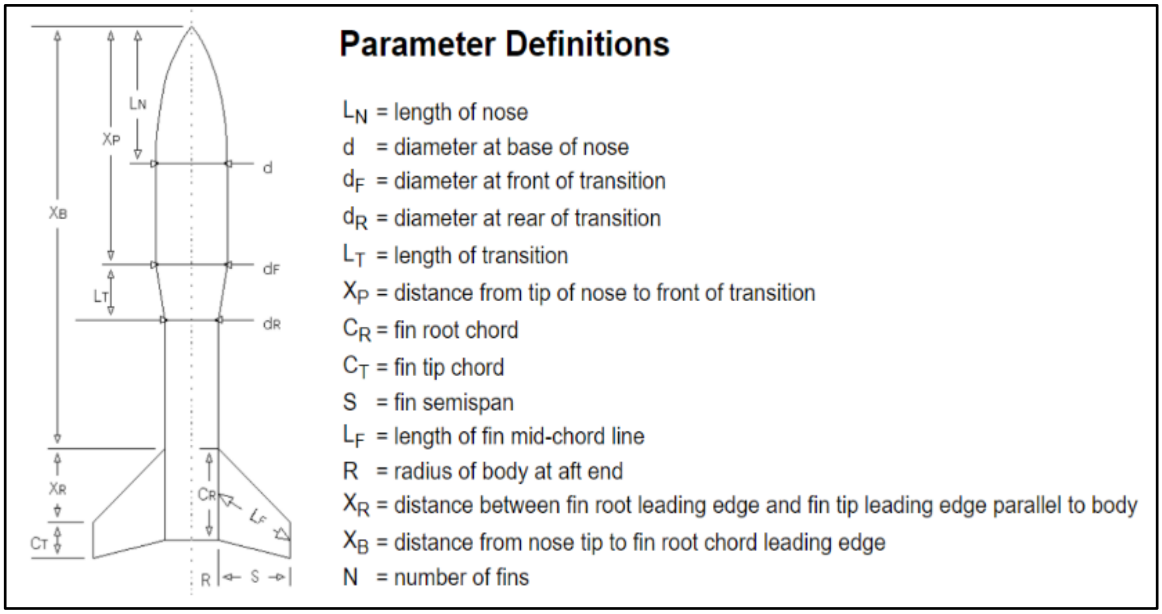
Figure 1: Solidworks model of fully integrated 2017-2018 ESRA 30k rocket with labeled components.

The 2017-2018 OSU ESRA 30k Rocket Team consisted of eighteen seniors in Mechanical Engineering (ME), Electrical Engineering (EE), and Computer Science (CS). The eighteen students were split into six sub teams (with three students per sub team) that are responsible for different aspects of the rocket. The sub teams are Aerodynamics and Recovery, Structures and Integration, Propulsion, Payload, Avionics - EE, and Avionics - CS. The structures and Integration Sub-Team is responsible for the design, manufacturing, and testing of the rockets structural components which include the airframe, nose cone, boat tail, fins, couplers, and bulkheads as well as overseeing the integration process. This paper will focus on the design, manufacturing, testing, and integration of the fins for the 2017-2018 ESRA 30k rocket as well as background research and lessons learned. The goal is that this paper can be used as a resource by future OSU rocket teams.

II. Background Research

A. Purpose of Rocket Fins

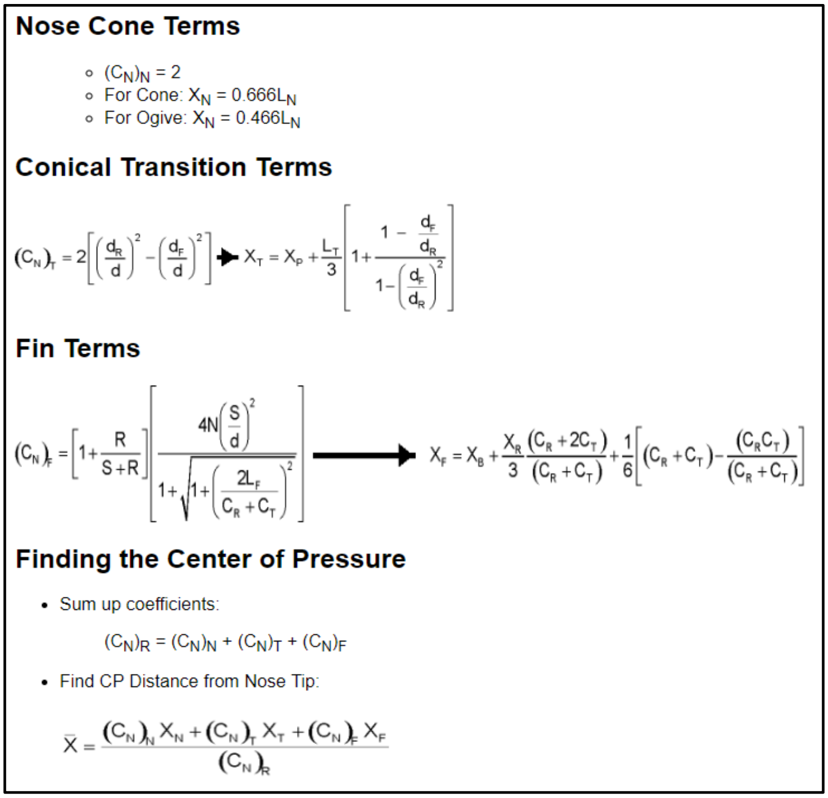
The purpose of fins on rockets is to increase stability by moving the center of pressure (Cp) behind the center of gravity (Cg). The Cg is a geometric property defined as by a single point that is the average location of the weight of an object [2]. If a rocket was placed on a thin rod the Cg would be the location of the rocket where it balances on the rod. The balance method can be used to estimate the center of gravity for smaller objects but a more accurate calculation of the Cg of an object can be determined by calculus: $Cg * m = \iiint x * \rho\,(x,y,z)\;dxdydz$ where m is the mass of the object, x is the distance from a reference line, and ρ is density [2]. The Cg is the point at which the force of gravity acts and the point that free floating objects rotate about. The Cp is a single point where aerodynamic forces, caused by pressure variations around the surface of the rocket, act through [3]. The Cp is calculated by the Barrowman Equations. The Barrowman equations are a series of equations developed by James Barrowman that output the longitudinal center of pressure measured from the nose tip [4]. The Barrowman equations are presented below in figures 2 and 3:



Parameter Definitions

L_N = length of nose
d = diameter at base of nose
d_F = diameter at front of transition
d_R = diameter at rear of transition
L_T = length of transition
X_P = distance from tip of nose to front of transition
C_R = fin root chord
C_T = fin tip chord
S = fin semispan
L_F = length of fin mid-chord line
R = radius of body at aft end
X_R = distance between fin root leading edge and fin tip leading edge parallel to body
X_B = distance from nose tip to fin root chord leading edge
N = number of fins

Figure 2: Parameter definitions for the Barrowman Equations [5].



Nose Cone Terms

- $(C_N)_N = 2$
- For Cone: $X_N = 0.666L_N$
- For Ogive: $X_N = 0.466L_N$

Conical Transition Terms

$$(C_N)_T = 2\left[\left(\frac{d_R}{d}\right)^2 - \left(\frac{d_F}{d}\right)^2\right] \rightarrow X_T = X_P + \frac{L_T}{3}\left[1 + \frac{1 - \frac{d_F}{d_R}}{1 - \left(\frac{d_F}{d_R}\right)^2}\right]$$

Fin Terms

$$(C_N)_F = \left[1 + \frac{R}{S+R}\right]\left[\frac{4N\left(\frac{S}{d}\right)^2}{1 + \sqrt{1 + \left(\frac{2L_F}{C_R + C_T}\right)^2}}\right] \longrightarrow X_F = X_B + \frac{X_R}{3}\frac{(C_R + 2C_T)}{(C_R + C_T)} + \frac{1}{6}\left[(C_R + C_T) - \frac{(C_R C_T)}{(C_R + C_T)}\right]$$

Finding the Center of Pressure

- Sum up coefficients:

  $(C_N)_R = (C_N)_N + (C_N)_T + (C_N)_F$

- Find CP Distance from Nose Tip:

$$\bar{X} = \frac{(C_N)_N X_N + (C_N)_T X_T + (C_N)_F X_F}{(C_N)_R}$$

Figure 3: Barrowman Equations [5].

The Cp needs to be behind the Cg because it creates a restoring force that provides stability [6]. In an ideal state there are no external forces on a rocket and all forces act through the Cg as the rocket travels linearly along the line of thrust [7]. In real application there are almost always external forces such as wind. External forces cause a change in the pressure forces around that rocket that act through the Cp [7]. This creates a moment about the Cg and the rocket rotates slightly, or changes its angle of attack, and a lift force is generated [7]. When the Cp is behind the Cg the lift force combines with the drag force creates a torque around the center of pressure that cause the tail of the rocket to swing in the direction of the lift force which adjusts the nose back in the direction of the nominal flight path [6]. The lift and drag forces are the restoring force that provides stability to the rocket [8]. When the Cp is in front of the Cg the torque acts in the opposite direction and further rotates the nose off the flight path causing the rocket to become unstable [6].

The Cp should, in general, be at least one caliber, or body diameter, behind the Cg. If the Cp and Cg are too close the rocket can become dynamically underdamped [1]. The larger the mass of the rocket the further the distance between the Cp and Cg should be to compensate for the greater momentum created by the higher mass [7]. If the distance between the Cp and Cg is too far apart though the rocket becomes over-stable which can cause weather cocking [7]. When there are winds at launch, the greater distance between the Cp and Cg creates a larger lever arm when the lift force is generated which can rotate the rocket far enough that it turns sideways. The Cg shifts upward during flight as propellant is used. The Cp also changes during flight as the angle of attack changes which alters the pressure forces around the rocket. Simulation software can be used to predict how the Cg and Cp will change during flight for different flight conditions. Fins are used to locate the Cp behind the Cg because they provide the required restoring force [9]. Fins increase aerodynamic forces at the aft end of a rocket and have a high restoring lift force which helps to ensure that the restoring force is strong enough to counteract external forces [7]. While fins provide stability to the rocket the tradeoff is they increase drag which hurts the performance of the rocket [9].

B. Fin Design

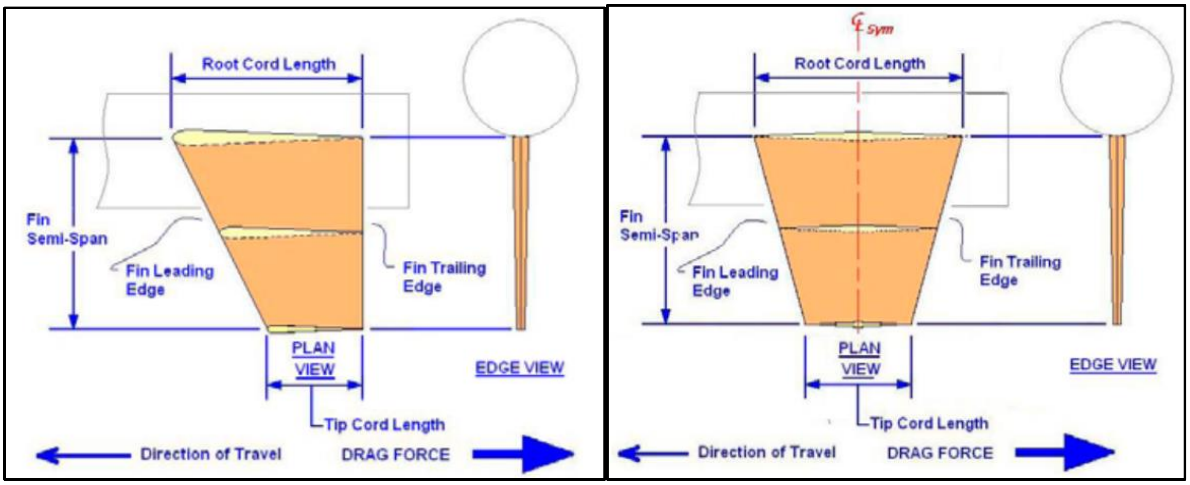
The design of the fins must be optimized to provide sufficient stability but also minimize drag. There are several aspects of rocket fin design to consider including the fin planform shape, geometry, aspect ratio, and the fin cross-section. The most common fin planform shapes for experimental high-powered and experimental sounding rockets are clipped delta, trapezoidal, and elliptical. The optimal planform shape depends on the speeds that the rocket is designed to fly at. Rocketry speeds are often described by Mach number. Mach number is a ratio of the local speed of a gas (relative to an object) to the speed of sound in that gas at the local conditions [9]. Ranges of Mach numbers are classified into Mach number regimes as seen in table 1, below.

Table 1: Mach Regime Classification [10]

Regime	**Mach Number**
Subsonic	< 0.8
Transonic	0.8 - 1.2
Sonic (speed of sound)	1
Supersonic	1.2 - 5
Hypersonic	5 - 10
High-Hypersonic	> 10

An elliptical planform is the most efficient at subsonic or transonic speeds but is difficult to manufacture due to the curved edge [11]. In simulations a clipped delta planform is less efficient then an elliptical planform at subsonic and transonic speeds but in actual flight the difference is negligible [11]. Clipped delta fins are easier to manufacture than elliptical fins as there are no curved edges and since the performance difference between the two planforms are negligible, clipped delta fins are usually preferred. At supersonic speeds, symmetric trapezoidal fins are more efficient [11].

Figures 4a and 4b show the fin geometry for a clipped delta and symmetric trapezoidal planform, respectively. The leading edge is the top of the fin and the trailing edge is the bottom of the fin. The root chord is the edge that attaches to or through the airframe and the tip chord is parallel to the root chord on the opposite edge of the fin. The semi-span is the perpendicular distance from the root cord and root tip.



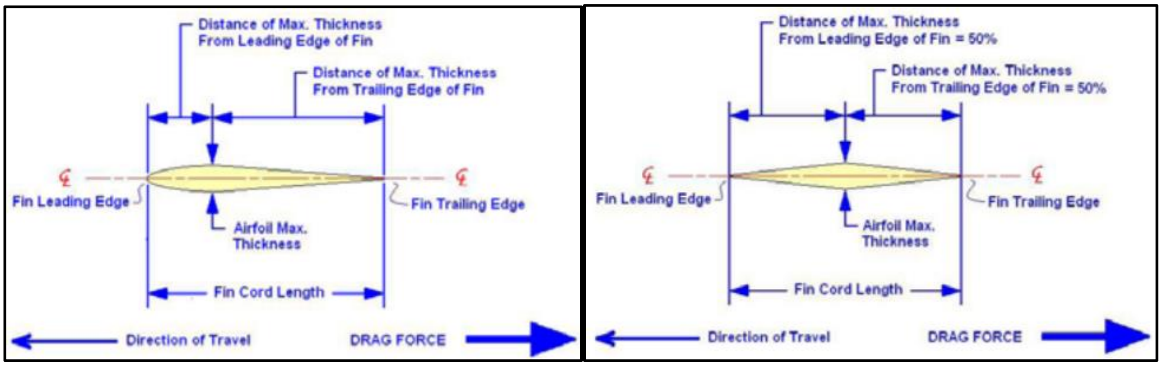
(a) Clipped delta planform

(b) Symmetric trapezoidal planform

Figure 4: Fin geometry for (a) a clipped delta planform and (b) a symmetric trapezoidal planform [11].

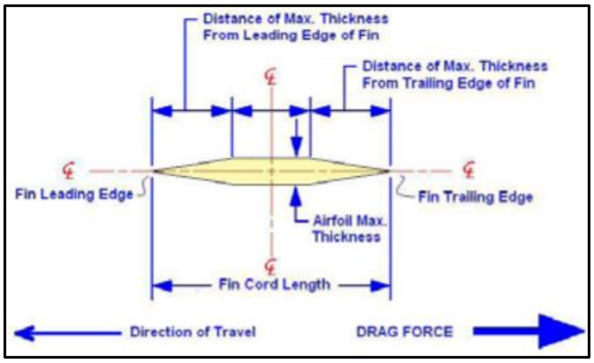
Two main aspects of fin geometry to consider are the fin surface area and the fin aspect ratio. As fin surface area increases drag increases. An optimization study on Brazilian sounding rocket fins found that surface area often has more of an impact on drag and the performance of the rocket than the fin planform shape [12]. The fin aspect ratio is related to surface area as it is the fin semi-span squared divided by the fin surface area [11]. Higher aspect ratios are more aerodynamically efficient than lower aspect ratios [11]. The closer the air is to the airframe the more turbulent it is, and fins are less efficient in turbulent flow. If the fins have a higher aspect ratio, they extend further from the airframe so more of the fin is outside of the more turbulent region. While fins with high aspect ratios are more efficient they tend to be structurally weaker than fins with low aspect ratios since they have a greater bending moment [11].

Fin cross sections should be symmetrical and the same for all fins to prevent asymmetrical lift or drag that could cause the rocket to spin or rotate off course [11]. Similar to the fin planform shape, the optimal fin cross-section depends on the speed of the rocket. At subsonic speeds an airfoil (figure 5a) is the best cross-section as it has a low drag profile and good dynamic response [11]. For an airfoil cross-section the maximum thickness should be at 25% to 33% of the chord length (referenced from leading edge). At transonic and supersonic speeds, a diamond cross-section (figure 5b) is most efficient because at high speeds sharp edges are better at reducing drag then round edges [11]. For a diamond cross-section the maximum thickness should be at 50% of the chord length. One issue with the diamond cross-section is that it has very thin edges which reduces the strength and stiffness of the fin. To counteract this issue a double diamond cross-section (figure 5c) can be used instead [11]. It increases the thickness, therefore increasing the strength and stiffness but still provides sharp edges. The maximum thickness for a double diamond cross-section should be 10% to 50% the chord length (from both the trailing and leading edges). The lower the percentage, the stronger and stiffer the fin will be.



(a) Airfoil cross-section

(b) Diamond cross-section



(c) Double diamond cross-section

Figure 5: Diagrams of (a) airfoil, (b) diamond, and (c) double diamond fin cross-sections [11].

There are design guidelines for fins based on the speed they are expected to reach but to predict how a design will affect the performance of a rocket, simulations are used. Rocket simulation software programs allow the user to select or design the components of their rocket and define the components' geometry, dimensions, and materials. The user then adds flight conditions such as launch altitude and angle and wind speeds and runs the program. The program provides output performance data over flight time such as center of pressure, altitude, velocity, drag, and stability based on the design and flight conditions. The design of the components and the flight conditions can then be adjusted: for example, the fin shape could be changed from a clipped delta planform to a trapezoidal planform or the launch angle could increase, and the results of the new simulation can be compared to the previous simulation. Multiple parameters can be changed at the same time to determine the optimal design for different components based on the flight conditions. Three common rocket simulation software programs used for experimental sounding rockets are OpenRocket, RASAero, and RockSim. Each software has slightly different features and capabilities and it is often a good idea to run simulations in multiple programs and compare the performance data for more accurate results.

One aspect of rocket fins that is difficult to account for in simulations is fin flutter. Fin flutter, also known as bending-torsion flutter, occurs when torsional vibrations cause lift forces that are equal to or greater than the damping forces caused by bending vibrations [13] The damping forces caused by the bending vibrations become insufficient and the oscillations grow until they destroy the fins. To determine if fin flutter is likely to occur during flight, the velocity at which fin flutter is likely to occur, referred to as the "fin flutter velocity", can be calculated and compared to the simulated flight velocity of the rocket [14]. If the simulated flight velocity is less than the fin flutter velocity, fin flutter should not occur. The NASA safety factor for fin flutter velocity requires the predicted fin flutter velocity to be 15% greater than the flight velocity [15]. The fin flutter velocity can be estimated by equation 1, below, which was derived in NACA Technical Note 4179. The equations variables are defined below the equation in table 2.

$$v_f = a * \sqrt{\frac{G_E}{\frac{39.3A^3}{(\frac{t}{c})^3(A+2)}(\frac{\lambda+1}{2})(\frac{P}{P_o})}} \quad (1)\ [16]$$

Table 2: Variable Definitions for Fin Flutter Velocity Equation [16]

Variable	Definition
A	Aspect ratio (semi-span^2/fin area)
a	Speed of sound
c	Average of root chord and tip chord
G_E	Effective shear modulus
P_o	Air pressure at sea level
P	Air pressure at altitude
t	Fin thickness
v_f	Fin flutter velocity
λ	Taper ratio (ratio of tip chord to root chord)

If the shear modulus G_E and the simulated altitude are known, the fin flutter velocity can be calculated for the flight since pressure can be found as a function of altitude and the fin flutter velocity can be compared to the simulated flight velocity. A NASA handbook on aeroelasticity states that the one way to increase the fin flutter speed and therefore decrease the chance of fin flutter is to increase the torsional stiffness. Increasing torsional stiffness reduces the torsional vibrations and prevents the lift forces from becoming greater than the damping forces [13]. Torsional stiffness increases as thickness increases and a study conducted at the Istanbul Technical University found that the fin flutter velocity increases linearly as fin thickness increases [17]. The study also found that the fin flutter velocity increases as the aspect ratio decreases [17]. This makes sense since fins with smaller aspect ratios are structurally stronger than fin with larger aspect ratios. Therefore, increasing the thickness and decreasing the aspect ratio of fins can reduce the risk of fin flutter. Again, optimization must be considered since these actions also increase drag. The use of multiple materials also reduces the chance of fin flutter since each material has a different resonance frequency, which prevents the fins from vibrating at a single frequency to the point of failure [14].

C. Fin Materials

Model rockets often use balsa wood or plastic for fins since they are lightweight materials that are easy to work with. Experimental sounding rockets are traveling at much higher speeds than model rockets and require stronger, stiffer materials. Many of the original sounding rockets used aluminum or magnesium fins. A NASA report on sounding rockets from 1965 describes three sounding rockets and includes information about their fins. The Aerobee 150A, a hybrid sounding rocket developed to carry scientific payloads, had four fins with magnesium skin and spars, a stainless steel leading edge cuff, and an aluminum box structure base for attachment [18]. The Astrobee 1500, a two-stage solid motor sounding rocket developed to carry scientific payloads, had fins covered in a layer of ablative material to protect them from motor exhaust plume heating [18]. The Javelin, a four-stage solid fuel research sounding rocket, used fiberglass and Inconel, a nickel alloy that contains chromium and iron, along the leading edge and the fin surface of the second and third stage fins for thermal protection [18].

Today, experimental sounding rockets usually use aluminum or composite fins. Common composite fins are carbon fiber covered G10 fiberglass fins [19][20] or composite sandwich fins. Composite sandwich structures consist of three components. The first component is the skins, often metal or composite material, that are selected for in-plane strength and stiffness [21]. For rocket fins carbon fiber is often used. The second component is a low-density core that is typically at least four times thicker than the skin [21]. Common core materials include aramid or aluminum honeycomb, polyurethane foam, PVC foam, balsa wood, or cedar wood [22]. The third component is the bondline which provides an adhesive interface between the core and the skins [21]. It is difficult to manufacture a composite sandwich structure with an aerodynamic leading edge, so a frame is often used. The frame, often aluminum or G10 fiberglass, is placed around the edge of the core and provides impact resistance and an aerodynamic edge with only a minor increase in weight. The past three OSU ESRA 30k rocket teams have used composite sandwich fins and the OSU High Altitude Rocket Team (HART) used carbon fiber covered G10 fiberglass fins last year.

III. 2017-2018 OSU ESRA 30k Rocket Fins

A. Fin Design Selection

The number of fins and fin planform shape, cross-section and dimensions were determined by the Aerodynamics and Recovery sub-team with the aerodynamic simulation software, OpenRocket. The three fin planform shapes discussed in section II B were initially considered. Elliptical fins were not used due to the potential difficulties manufacturing the curved profile and the choice was narrowed down to symmetrical trapezoidal and clipped delta fins. To determine which of the two remaining fin shapes would be the most efficient for the 2017-2018 OSU ESRA 30k rocket, both shapes were modeled in OpenRocket. The dimensions for each fin shape were modified until the optimal aerodynamic design for each shape was determined. Simulations for each fin shape were run with three and four fin rocket designs. From the simulation results it was determined that clipped delta fins were the optimal shape. The three-fin design was slightly more efficient than the four-fin design, but the four-fin design was selected because the difference in flight performance was negligible and four fins are easier to align. This minimizes the chance that fins will be misaligned when they are attached to the rocket. The final dimensions for the fins can be seen in Table 3.

Table 3: Fin Dimensions (Clipped Delta)

Parameter	**Dimension**
Semi-Span	6.00” (15.24 cm)
Root Chord	11.38” (28.91 cm)
Tip Chord	2.84” (7.23 cm)
Thickness	0.22” (0.55 cm)

Based on OpenRocket simulations the optimal cross-sectional area is an airfoil, but it was determined that the increase in performance was not worth the increased manufacturing complexity. A rectangular cross-section with beveled edges (double diamond cross-section) was selected. Based on the results of the OpenRocket simulation a bevel with an angle of 10° and a length of 0.36” was selected.

B. Fin Materials Selection

A composite design consisting of three materials was selected for the fins. The three materials selected were a G10 FR4 fiberglass frame, an Aramid honeycomb core, and a prepreg T800 carbon fiber skin. The composite fin design was selected because it is lighter than Aluminum but still strong. Additionally, the use of three materials reduces the risk of fin flutter. Standard Cell Aramid Honeycomb from ACP Composites was selected for the honeycomb core as it has a high strength-to-weight ratio, high stiffness, and bonds easily [23]. The honeycomb core is also coated in a heat resistant phenolic resin that increases its strength and thermal properties [23] which helps protect the fins from the high motor temperatures. The T800 carbon fiber selected is a unidirectional carbon fiber manufactured by Toray Composite Materials America, Inc. with high tensile properties [24]. T800 is also designed to be lightweight specifically for aerospace application. Prepreg carbon fiber was selected as it is easier to layup then dry fibers. G10 FR4 fiberglass from ePlastics was selected for the frame as it is designed to have high mechanical properties and because FR4 is a fire-retardant grade of G10 fiberglass [25] which, similar to the aramid honeycomb, protects the fins from the high motor temperatures. While the fiberglass frame increases the weight of the composite sandwich fin design it also provides an aerodynamic leading edge and impact resistance.

C. Fin Manufacturing

1. *Fin Frame*

The fiberglass fin frame was machined on a Bridgeport CNC mill in the MIME Machining and Product Realization Lab (MPRL). To machine the fin frame on the CNC, G-code had to be generated. The G-code was generated using Edgecam. A Solidworks model of the frame was created and opened in Edgecam. A drawing of the Solidworks part used can be seen in Appendix A. To set up the model, stock dimensions were added and then the orientation and datum were selected. To generate the tool path, the tool was first selected. The tool used to machine the frame was a ¼” diameter carbide end mill with a diamond coating. G10 fiberglass is abrasive and wears down tools quickly. Diamond coated carbide tools are designed for non-ferrous materials and have the hardest coating [26] which increases the ease of manufacturing and reduces wear on the tool. Two profile milling cycles were selected to generate the tool path, one for the outer edge of the frame and one for the inner edge of the frame. Using speed and feed calculations, the proper speed and feed for fiberglass and a ¼” diamond coated carbide tool are 11,460 RPM and 46 in/min respectively. The Bridgeport CNC has a max speed of 3200 RPM which is slower than the calculated speed.

After talking with the MPRL manager, the feedrate was calculated using the max speed of 3200 RPM and the new feedrate was 13 in/min. Once the milling cycle and feed and speed rates were set, the G-code was generated and saved as a TXT file to a floppy disk.

To machine the frame, the G-code was loaded into the CNC and the stock material was fixtured with four strap clamps around the edges of the material. A piece of scrap wood was placed under the stock to protect the machine during the final pass. After the stock was fixtured, the part and tool offsets were set based on the datum that was selected in Edgecam and then a dry run was performed to ensure the code worked correctly and would not run into the machine or the part. If there was an issue with the dry run the code was adjusted and reloaded. If there were no issues the code was run. An image of a fin frame being machined can be seen in figure 6.

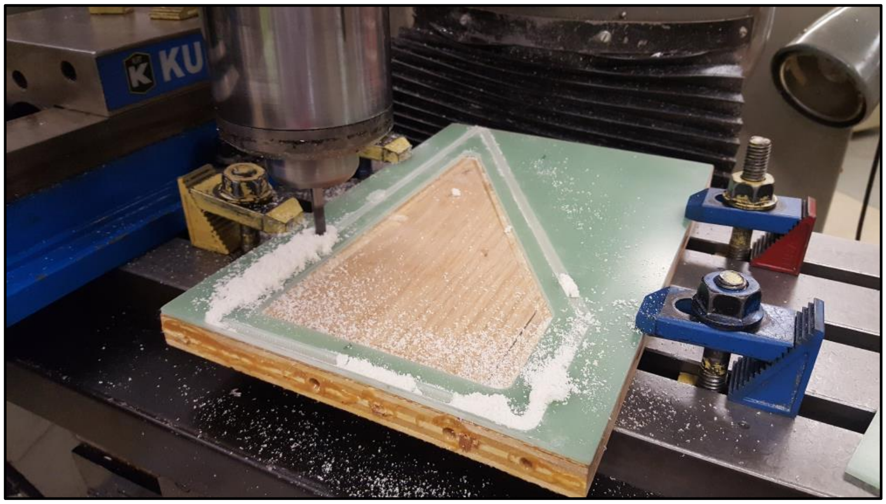


Figure 6: Machining G10 fiberglass fin frame on Bridgeport CNC.

The inner part of the frame was machined first and then the outer edge. During the final pass of the outer edge, once the tool passed a clamp it would be moved so that it was fixtured to the frame itself. This prevents the frame from moving as it was no longer attached to the stock which was the only part that was clamped. This method was selected so that the entire piece did not have to be re-fixtured between machining the inner and outer edges which saved time and minimized errors. Once one frame was machined it was removed and the process was repeated for the next frame.

2. *Composite Layup*

The layup schedule for the fins is [0/45/-45/90/c/90/-45/45/0]. A symmetric, quasi-isotropic layup schedule was selected to prevent warping and provide equal strength in all directions in the plane of the part [27]. The carbon fiber plies were cut on the ply cutter in the MIME Composites Lab. A Solidworks model of one of the plies was created and saved as a DXF file. A drawing of the DXF file can be seen in Appendix A. The DXF file was opened in the ply cutter software program and the number of plies and the orientation of the plies were set. The carbon fiber was laid out on the ply cutter and the blade depth was adjusted for the selected material. Once the ply cutter was set up, the program was run. Two pieces of adhesive film for each fin were cut out in the same way. The honeycomb core was cut with a razor blade using the inner section of the fin frame as a stencil.

A moldless layup was used for the fins. The fin frame was placed on the table and then a honeycomb core was placed inside of the fin frame so that it was aligned with the inner section of the frame. A piece of film release was pressed onto the side of the fin that was facing upwards. A heat gun was used to increase the tackiness of the film release so that it would stick to the frame and core. Four carbon fiber plies were laid up one at a time on the side of the fin facing upwards, following the layup schedule (starting with the 90° ply and ending with the 0° ply). The fin was then turned over and the film adhesive and carbon layup was repeated. This process was completed for each fin. Once the fins were laid up, they were vacuum bagged. First, the fins were placed inside a folded piece of peel ply so that the entirety of each fin was covered. The peel ply wrapped fins were then placed inside a folded piece of perforated film release. Peel ply leaves a smooth surface finish [28] while release film is perforated to allow excess air and epoxy to escape [29]. The fins were then placed together on a large sheet of vacuum bag. Strips of breather cloth were placed underneath and on top of the fins. Breather cloth is used as a bleeder material to absorb excess resin [30]. The lower section of a vacuum bag fitting was set on top of the breather strips. The vacuum bag was folded over the fins and sealant tape was used to seal the open edges of the bag. The upper part of the vacuum fitting was then screwed into the lower section and the fins were placed in the Composites Lab oven to cure. The cure cycle information for the fins is presented in table 4 and the vacuum bagged fins can be seen in figure 7.

Table 4: Cure Cycle Information for Fins

Ramp Up to Gel Temp	180°F/hr
Gel Temp	180°F
Gel Time	1.5 hrs
Ramp Up to Cure Temp	180°F/hr
Cure Temp	270°F
Cure Time	2 hrs
Ramp Down	300°F/hr

Figure 7: Vacuum bagged fins.

3. Post-Processing

The first post-processing step was to remove the vacuum bagging material from the fins and trim any excess carbon fiber with a razor blade. The next step was to bevel the edges of the fins using a table saw. To safely bevel the edges a fixture, seen in figure 8, was manufactured.

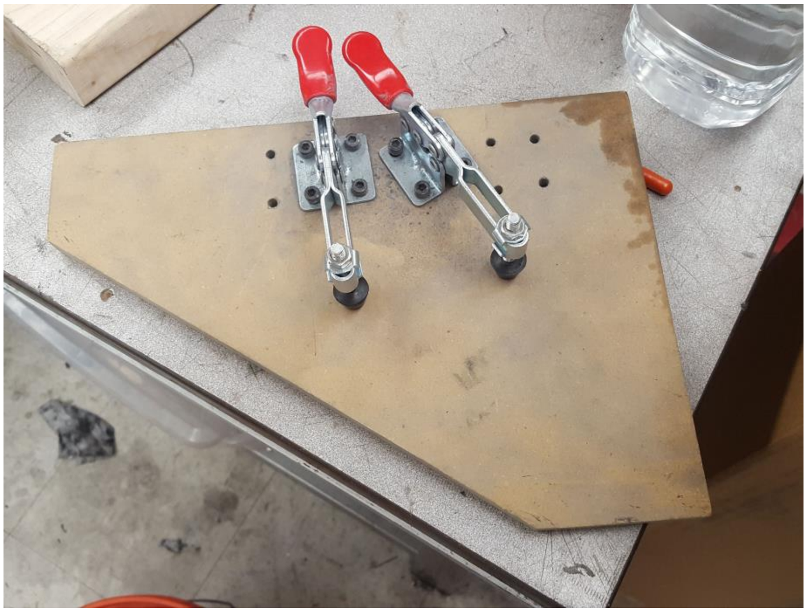


Figure 8: Fin bevel fixture.

The fixture was designed so that the clamps can be switched to the other side of the board allowing both sides of the fin can be beveled. A diamond blade was used to cut through the G10 fiberglass and carbon fiber. The table saw blade was set at a 10° angle and the blade height was set at 1”. The distance from the base of the blade to the fence was 0.563” which is half the thickness of the fin (0.0625”) plus the thickness of the fixture (0.5”) so that the bevel is even on each side of the fin. To cut the bevel, the fin was clamped into the fixture and each of the three edges was run through the table saw. If the edge did not bevel correctly it was run through the table saw again. All the fins were beveled on one side and then the clamps were switched and the other side of the fins were beveled. After the edges were beveled they were coated in a thin layer of RocketPoxy to fill in sections that were cut too thin and to prevent the delamination. When the RocketPoxy was fully cured the edges were sanded until they were smooth and the RocketPoxy was flush with the fin.

D. Fin Integration

1. *Fin Integration Selection*

The fins are integrated into the airframe with epoxy fillets and reinforced with tip-to-tip layup. The fins could not be attached through the airframe since it is minimum diameter so external epoxy fillets were selected. To ensure that fins were aligned correctly when the epoxy fillets were applied, a fin alignment guide was designed and manufactured. Since the fins are only attached at one point on the airframe, a tip-to-tip layup was also selected to reinforce the attachment. Tip-to-tip layup increases the stiffness of the fins and the attachment points which prevents fin flutter and reduces the chance of the fins breaking during flight or on impact. Based on the OpenRocket simulation the optimal location for the fins on the airframe is at the aft end of the airframe so that the trailing edge of the fins are flush with the end of the airframe.

2. *Fin Alignment Guide*

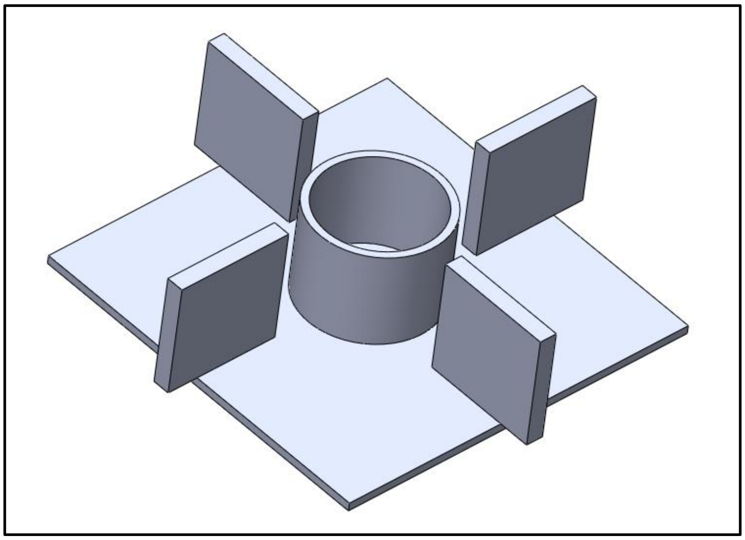


Figure 9: Solidworks model of fin alignment guide.

A Solidworks model of the fin alignment guide can be seen above, in Figure 9. The airframe rests on the center guide and fins are held against the four alignments blocks with clamps. The four alignment blocks are 90° apart and are off-center by 0.11” (half the thickness of the fins) to ensure that the fins are in line with each other. The center guide and alignment blocks are attached to the base plate from the bottom of the plate with screws. For the center guide, a section of a 6” aluminum tube was machined down to an outer diameter of 5.68” on a lathe. The screw holes were machined on a Bridgeport CNC mill and tapped by hand. A ⅜” aluminum plate was used for the base and the screw clearance holes were machined on a Fadal VMC 4525 CNC. For the alignment blocks a ½” aluminum plate was cut into four sections on the vertical band saw. The blocks were squared on a Bridgeport manual mill and the screw holes were machined on a Bridgeport CNC mill and tapped by hand. The process to machine the holes in the components was similar to that of the fin frames except that the hole milling cycle was used and the tools, feeds, and speeds were selected based on the screw size. Once the components were machined the alignment guide was assembled.

3. *Fin Attachment and Epoxy Fillets*

The completed alignment guide was used to hold the airframe and fins in place while the fins were attached to the airframe with an initial set of epoxy fillets as seen in figure 10. After the initial fillets were cured, the airframe with the fins was removed from the alignment guide and placed on a horizontal rocket stand and thick epoxy fillets were applied. Two fillets were done at a time and 1” PVC pipes covered in wax paper were placed on top of the fillets and held in place by clamps to create smooth, ½” fillets. This process can be seen in figure 11. The epoxy fillets were cured for two days and then the fins were reinforced with a tip-to-tip layup.

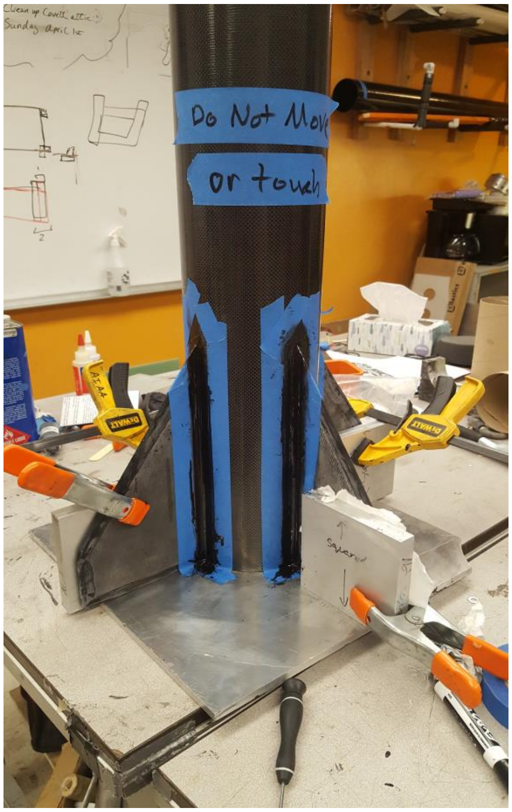


Figure 10: Fin alignment and initial epoxy fillets.

Figure 11: ½” epoxy fillet setup.

4. *Tip-To-Tip Layup*

The layup schedule for the tip-to-tip integration is $[90_4]$ with three plies of prepreg Kevlar and one ply of prepreg twill carbon fiber on top. The plies were different sizes to create a tapered effect at the edges. This helps to reduce the thickness of the fin edges and therefore reduces drag. The first (innermost) ply ended 1.5” from the tips of the fins, the second ply ended 1” from the tips of the fins, the third ply ended 0.5” from the tips of the fins, and the last (carbon fiber) ply ended at the tips of the fins. The plies were cut on the ply cutter and drawings of the DXF files used to cut out the plies can be seen in Appendix A. The plies were laid up, one at a time, from the start point of one fin (1.5”, 1”, 0.5”, or 0” from the tip) to the base of that fin, around the body tube to the base of the next fin, and up to the end point (1.5”, 1”, 0.5”, or 0” from the tip) of that fin. After all four plies were laid up the end of the airframe and the fins were vacuum bagged. Sections of peel ply and then film release were places over the fins using the tip-to-tip layup method. Breather was run along the fins and up one section of the body tube where the vacuum fitting was placed. A section of vacuum bag was attached along the inside of the airframe at the bottom end with sealant tape and a second section was attached above the fins on the outside of the airframe. The two sections were sealed together just below the bottom of the airframe so that the fins were completely sealed. Once the vacuum bag was sealed the airframe and fins were placed in the Composites Lab oven to cure. The cure cycle information for the tip-to-tip layup is presented in table 5 and the vacuum bagged airframe and fins can be seen in figure 12.

Table 5: Cure Cycle Information for Fins

Ramp Up to Gel Temp	180°F/hr
Gel Temp	235°F
Gel Time	0 hrs
Ramp Up to Cure Temp	180°F/hr
Cure Temp	235°F
Cure Time	8 hrs
Ramp Down	300°F/hr

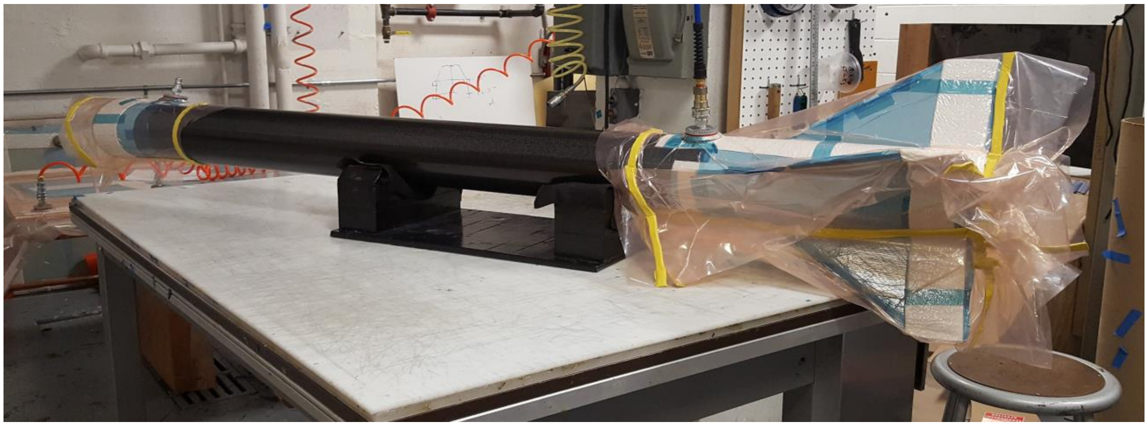


Figure 12: Vacuum bagged tip-to-tip layup.

5. Post-Processing

Once the tip-to-tip layup was cured and the vacuum bagging material was removed, the fin edges were trimmed with a razor blade to remove any excess material. Next, a thin layer of RocketPoxy was applied to the edges to prevent delamination. When the RocketPoxy was fully cured the edges were sanded until they were smooth and RocketPoxy was flush with the fins. The fins were coated in engine enamel to help protect the fins from heat and surface damage. figure 13, below, shows the completed tip-to-tip layup.

Figure 13: Completed tip-to-tip layup

E. Testing

1. *3-Point Bend Test*

Before the final fins were manufactured 3-point bend tests were performed on a set of test fins on an Instron machine in the Materials Science Lab. Three fins were tested following ASTM C393 standards and a plot of force versus displacement for the three fins can be seen in figure 14. The three fins withstood an average maximum force of 2.24 kN. The core shear ultimate stress and the facing stress were also calculated from the test data according to the ASTM standard. The average core shear ultimate stress for the three fins was 2.52 MPa and the average facing stress was 171.71 MPa.

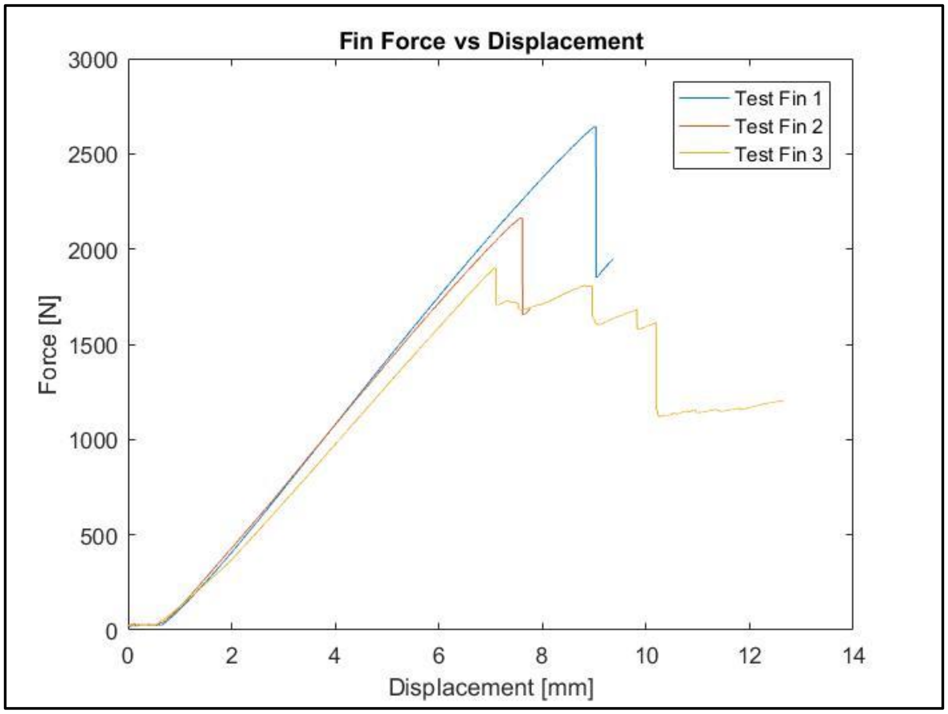


Figure 14: Plot of force vs displacement from 3-point bend test (ASTM C393) data.

2. *Test Flight*

A test launch was completed on May 13th at a launch site near Brothers, Oregon. This was the first test of the fins in flight. The rocket reached an altitude of 24,200 ft and a max speed of Mach 1.55. The recovery system worked nominally and the rocket landed at 10 ft/sec. Once the rocket was recovered the fins were inspected for damage. All the fins were still attached to the airframe and none of the fins were broken. Visual inspection and a wiggle test showed that there was no damage to the epoxy fillets beneath the tip-to-tip layup and that there was no delamination. The only damage was scratches on the surface and edges of the fins where they scrape against the ground. The fins post-flight can be seen in figure 15. The overall performance of the fins was optimal and the fins withstood the forces throughout the flight.

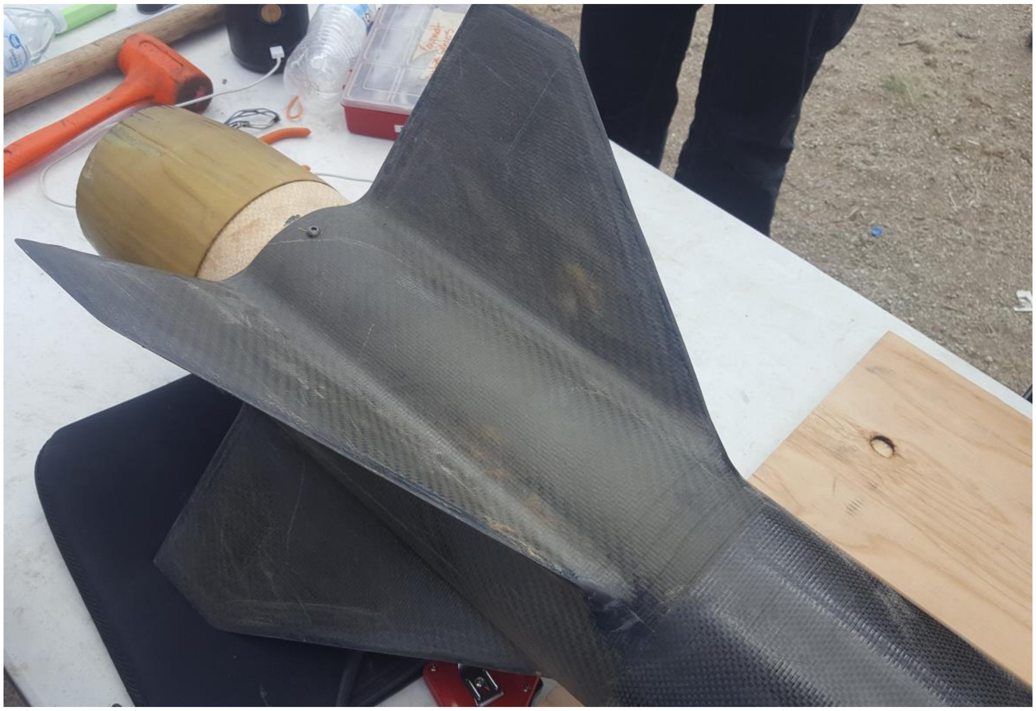


Figure 15: Fins post-flight (test launch).

IV. Conclusion and Lessons Learned

After a year of research, design, manufacturing, integration, and testing the 2017-2018 OSU ESRA 30k Rocket Team traveled to Spaceport, New Mexico to compete in the 2018 SA Cup. The OSU ESRA 30k rocket launched on June 22nd, the second day of competition. About one second after launch a motor failure caused the lower airframe to rapidly accelerate into the upper airframe, shredding the upper airframe and destroying the parachutes. The rocket came down ballistically in pieces. While the upper airframe, parachutes, and 3D printed structures were destroyed, several, mostly intact, pieces of the rocket were recovered including the nose cone, the payload, some of the electronics, and most of the lower airframe with the motor still inside and the fins intact. An image of the recovered lower airframe with fins intact can be seen in figure 16.

Figure 16: Lower airframe and fins post competition launch

While the outcome of the competition was not what was expected or hoped for, being on the 2017-2018 OSU ESRA 30k Rocket Team was an incredible and invaluable experience. This thesis is a compilation of the knowledge and experience gained designing and manufacturing the rocket fins. Background research on the purpose of fins, fin geometry, fin flutter, and fin materials is presented. The manufacturing of the fin frames, the composite layup for the fins, and the fin post processing as well as the epoxy fillet and tip-to-tip integration processes for the fins are described in detail. Fin tests and test results are also presented. Finally, as the intention of this thesis is to serve as a resource for future OSU rocket teams, several lessons learned are presented below ranging from helpful tips to suggestions for improvement.

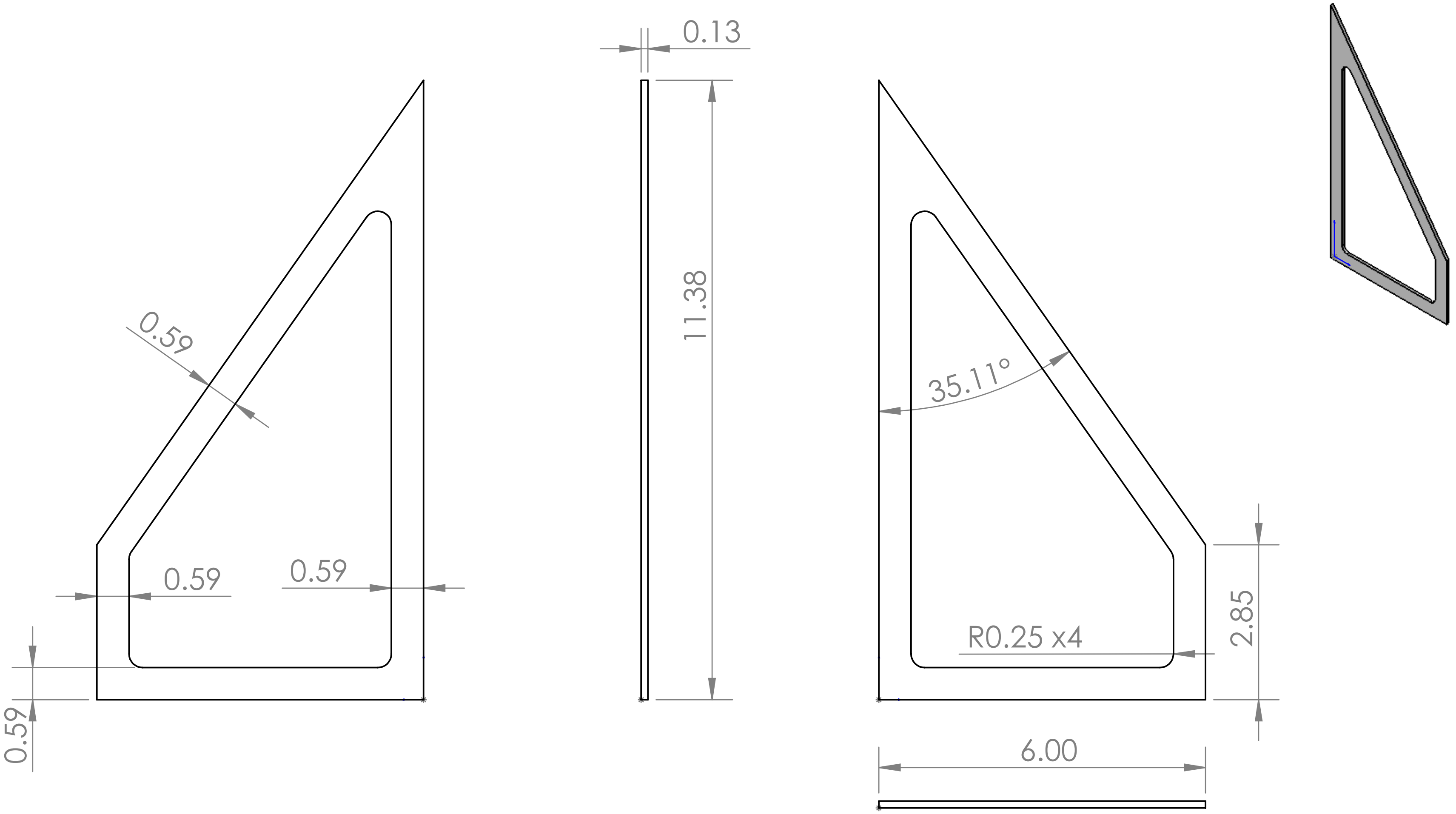
Lessons Learned

- Determine fin materials early in the design process and order them as soon as possible as they can take several weeks to arrive.
- Verify what material is available for AIAA in the Composites Lab before purchasing fiberglass, carbon fiber, or Kevlar.
- Maintain a good relationship with GFR. Many of the team members have a lot of knowledge about composites and are often willing to share/trade materials.
- If you have questions about fin design, manufacturing, or integrations don't be afraid to ask the OROC mentors. They have a lot of experience and advice.
- Get certified to use the CNCs and ply cutter in fall term (or earlier) so that you can begin manufacturing when the materials arrive. Also learn to use Edgecam (or other CAD CAM software) during fall term.
- Consider how the part will need to be fixtured during the manufacturing design process as it can change how the part is manufactured. For example, will you need to adjust the fixturing and if so how do you keep the part from moving? Do you need to manufacture a special fixture? etc.
- Plan to make more fins than you need. Things can go wrong during manufacturing and you don't want to have to wait for more material and delay testing and integration to remake one or two fins. This year a couple fin frames were scrapped during the CNC process, during the composite layup the backing on the carbon fiber for one of the fins was not removed so it cured incorrectly, and the bevel on one of the fins was inconsistent with the other. Additionally, if a fin breaks during a test flight, you have spares already made which saves repair time.
- If machining G10 fiberglass be sure to use a diamond coated carbide tool. There should be a couple in a drawer above the propulsion cupboards.
- Using Edgecam and the CNCs can be frustrating so be patient and remember it is ok if it takes several tries to get them to work correctly and, as with most things, it becomes easier the more you use them.
- If you need advice on manufacturing or fixturing don't be afraid to ask Brain Jensen, Darin Kempton, or Scott Campbell: they have a lot of experience and are usually willing to help.
- Research better ways (or better fixtures) to bevel fins so they are more consistent.

- When using an alignment guide to attach the fins with epoxy, place wax paper on the base so when the epoxy drips, it does not epoxy the fins or airframe to the alignment guide. If any part of the airframe or fins is epoxied to the alignment guide, use a screwdriver to chisel away the epoxy until they airframe or fins are free.
- Tip-to-tip layup is worth the extra work, especially for a minimum diameter rocket. Tip-to-tip layup significantly increases the strength and stiffness of the fins and the attachment point and only adds about two or three extra days of work. The most difficult part is vacuum bagging the fins and fitting the airframe in the oven but with some planning it is not that difficult.
- If you need to use an Intron for testing, ask Scott Campbell. He has access to the Introns and can teach you how to use them.
- Instead of using ASTM C393 for fin testing use ASTM D7250 or ASTM C273. Besides the bending force the fins can withstand, ASTM C393 does not provide much applicable information. The shear modulus can be found from both ASTM D7250 and ASTM C273 which can then be used to find the fin flutter velocity as described in section II B. If the fin flutter velocity is known, it can be compared to the simulated flight velocity to determine if fin flutter is likely to occur or not. While ASTM D7250 and ASTM C273 may require more work than ASTM C393 the ability to calculate and compare the fin flutter velocity would be worth it.

Appendix A: Solidworks Drawings

(Continue on next page.)



ESRA 30K 2017-18
STRUCTURES & INTEGRATION

FIN FRAME

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
DECIMAL .XX ±.010
DECIMAL .XXX ±.005
FRACTIONAL ±1/64
ANGULAR: ±1°

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL: G10 FIIBERGLASS

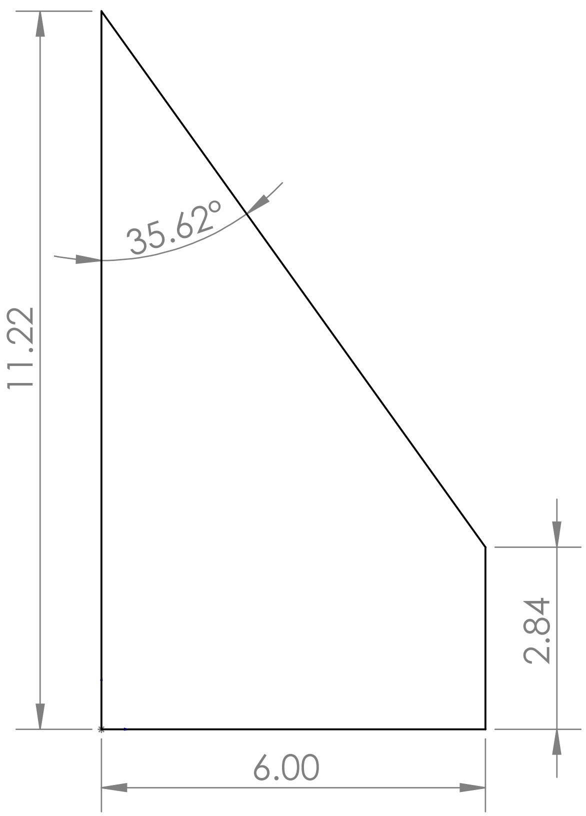
DO NOT SCALE DRAWING

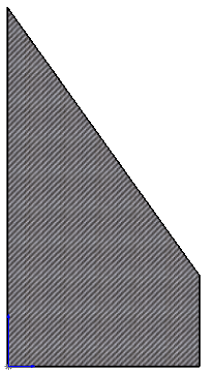
	NAME	DATE
DRAWN	EF	10/8/17
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

NEXT ASSY	USED ON
APPLICATION	

SIZE **A**
REV 0
SCALE: 1:3
SHEET 1 OF 1





	NAME	DATE
DRAWN	EF	11/16/17
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
DECIMAL .XX ±.010
DECIMAL .XXX ±.005
FRACTIONAL ±1/64
ANGULAR: ±1°

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL: CARBON FIBER

DO NOT SCALE DRAWING

NEXT ASSY	USED ON
APPLICATION	

ESRA 30K 2017-18
STRUCTURES & INTEGRATION

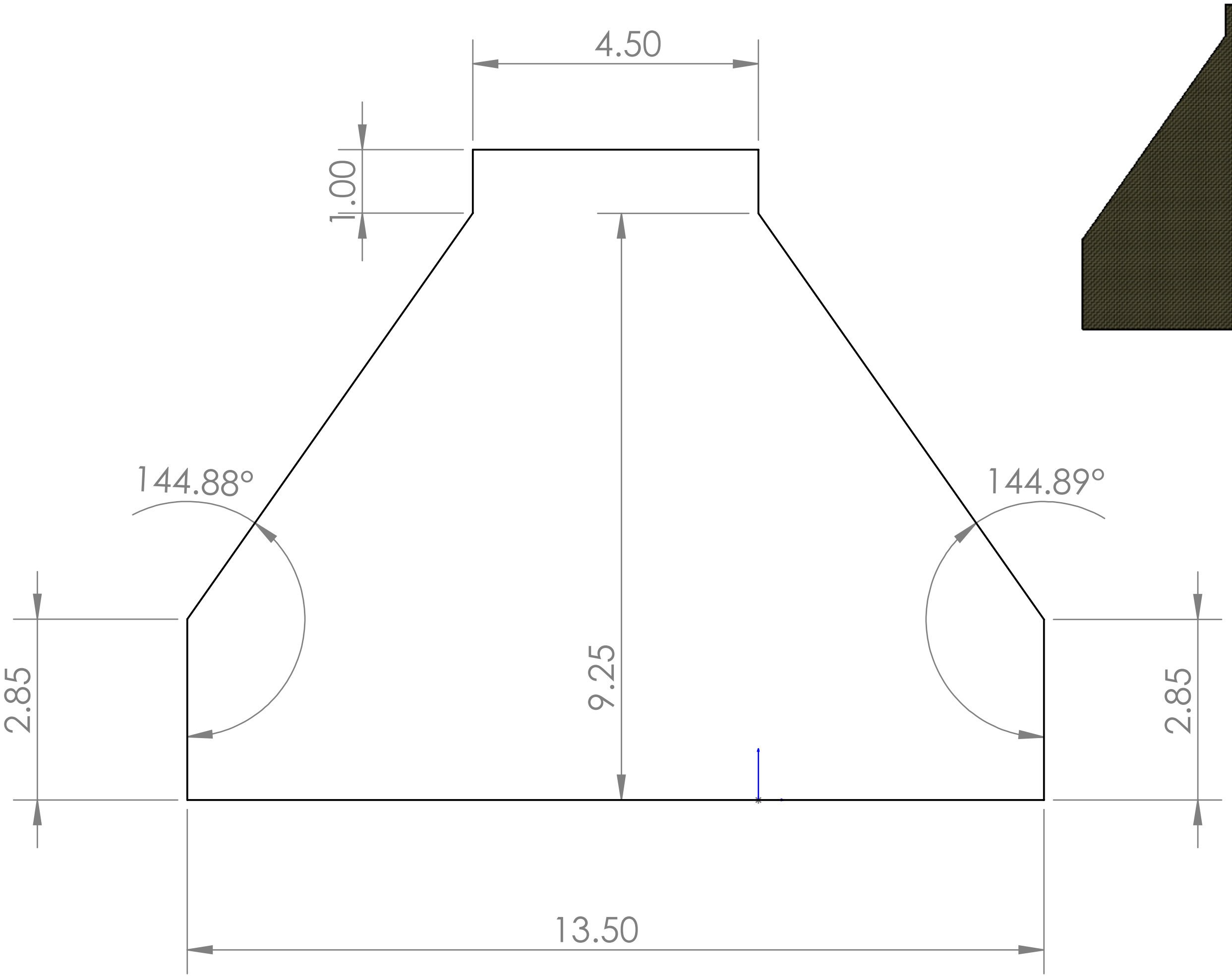
FIN LAYUP PLY

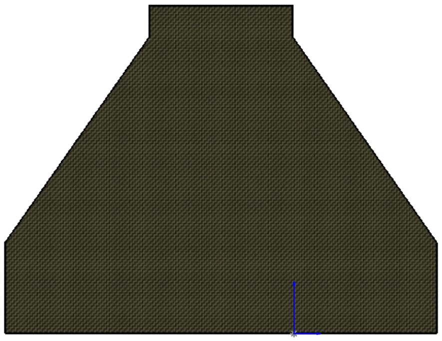
SIZE **A**

REV 0

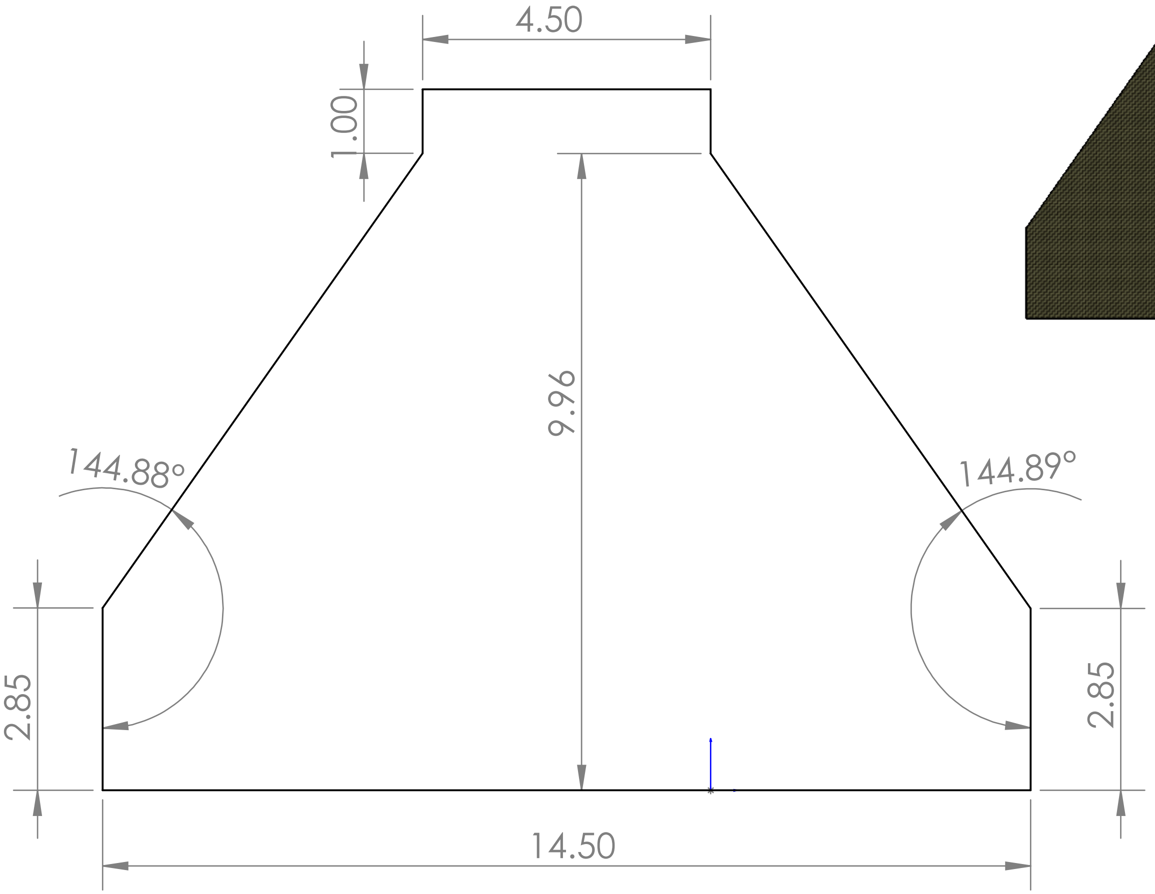
SCALE: 1:3

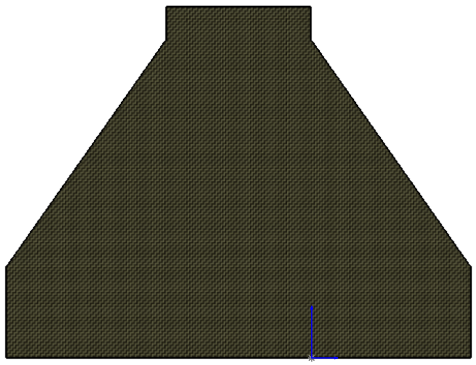
SHEET 1 OF 1





		UNLESS OTHERWISE SPECIFIED:		NAME	DATE	ESRA 30K 2017-18 STRUCTURES & INTEGRATION
		DIMENSIONS ARE IN INCHES TOLERANCES: DECIMAL .XX ±.010 DECIMAL .XXX ±.005 FRACTIONAL ±1/64 ANGULAR: ±1°	DRAWN	EF	4/27/18	
			CHECKED			TIP-TO-TIP LAYUP PLY 1
			ENG APPR.			
			MFG APPR.			
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
		MATERIAL: ARAMID FIBER	COMMENTS:			SIZE **A**
NEXT ASSY	USED ON					REV 0
APPLICATION		DO NOT SCALE DRAWING				SCALE: 1:3 SHEET 1 OF 1





ESRA 30K 2017-18
STRUCTURES & INTEGRATION

TIP-TO-TIP LAYUP PLY 2

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
DECIMAL .XX ±.010
DECIMAL .XXX ±.005
FRACTIONAL ±1/64
ANGULAR: ±1°

INTERPRET GEOMETRIC
TOLERANCING PER:

MATERIAL: ARAMID FIBER

	NAME	DATE
DRAWN	EF	4/27/18
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

SIZE **A**

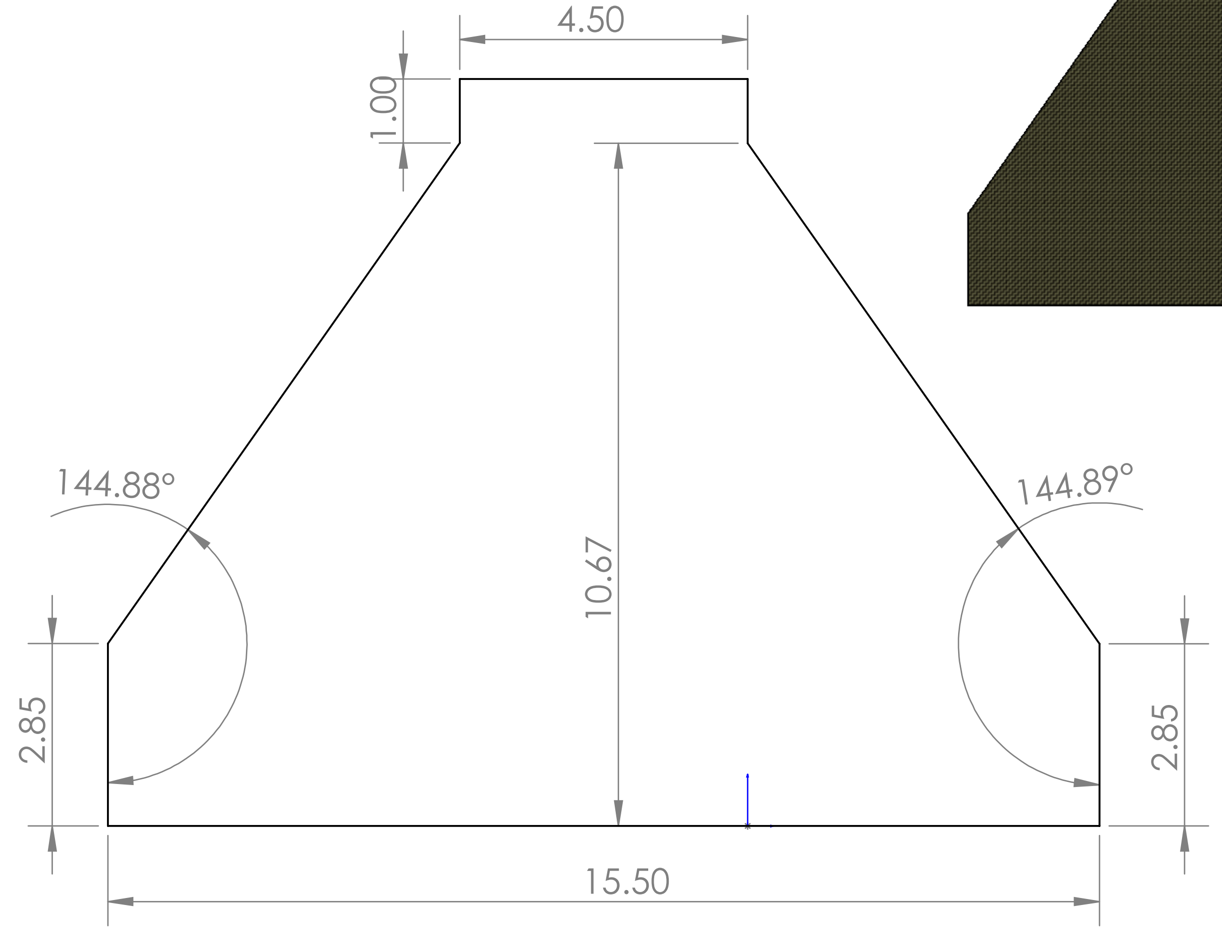
REV 0

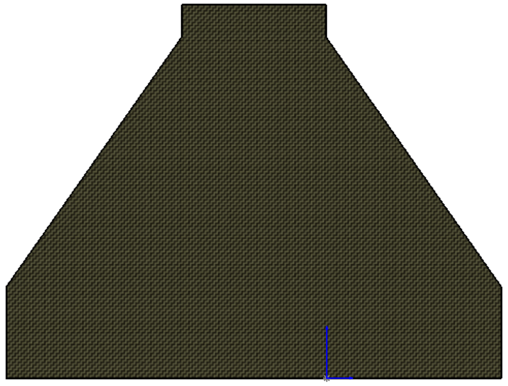
SCALE: 1:3

SHEET 1 OF 1

NEXT ASSY	USED ON
APPLICATION	

DO NOT SCALE DRAWING





	NAME	DATE		
DRAWN	EF	4/27/18		
CHECKED				
ENG APPR.				
MFG APPR.				
Q.A.				
COMMENTS:				

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
DECIMAL .XX ±.010
DECIMAL .XXX ±.005
FRACTIONAL ±1/64
ANGULAR: ± 1°

INTERPRET GEOMETRIC
TOLERANCING PER:

MATERIAL: ARAMID FIBER

NEXT ASSY	USED ON
APPLICATION	

DO NOT SCALE DRAWING

ESRA 30K 2017-18
STRUCTURES & INTEGRATION

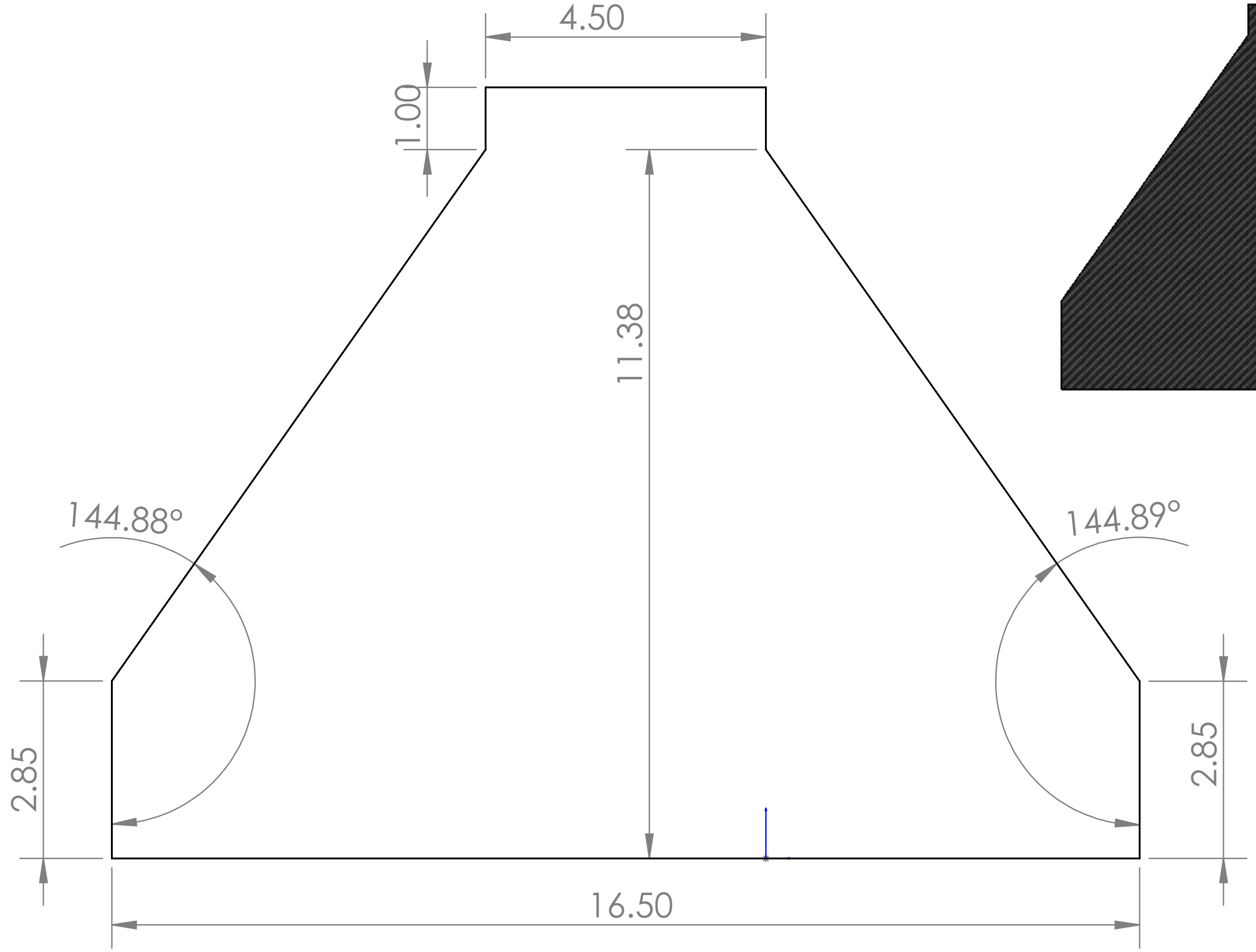
TIP-TO-TIP-LAYUP PLY 3

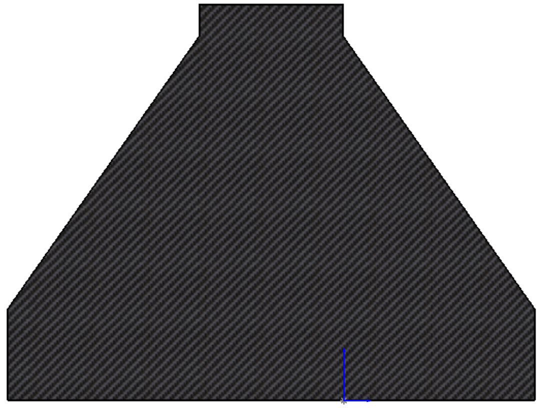
SIZE **A**

REV 0

SCALE: 1:3

SHEET 1 OF 1





		UNLESS OTHERWISE SPECIFIED:		NAME	DATE	ESRA 30K 2017-18 STRUCTURES & INTEGRATION
		DIMENSIONS ARE IN INCHES TOLERANCES: DECIMAL .XX ±.010 DECIMAL .XXX ±.005 FRACTIONAL ±1/64 ANGULAR: ± 1°	DRAWN	EF	4/27/18	
			CHECKED			TIP-TO-TIP LAYUP PLY 4
			ENG APPR.			
			MFG APPR.			
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
		MATERIAL: CARBON FIBER	COMMENTS:			SIZE **A**
NEXT ASSY	USED ON					REV 0
APPLICATION		DO NOT SCALE DRAWING				SCALE: 1:3 SHEET 1 OF 1

Acknowledgments

I would like to thank my thesis mentor, Dr. Nancy Squires for her support throughout this experience and over the past four years. Dr. Squires has done so much for the aerospace program at OSU and her work has provide many opportunities for students passionate about aerospace. Without her support and encouragement, the 2017-2018 OSU ESRA 30k Rocket Team and this thesis would not have been possible. Thank you for encouraging me to finish this thesis.

I would like to thank Dr. Rob Stone and Dr. Bob Paasch for being on my thesis committee. I would also like to thank the OSU Honors College advisor Rebekah Lancelin for her support and advice during the thesis process. Finally, I would like to thank Dad, Mom, and Gwyn for their love and encouragement.

References

[1] "Who We Are," *Experimental Sounding Rocket Association* [online], http://www.soundingrocket.org/ [retrieved July 2018].

[2] Hall, N., ed., "Center of Gravity," *NASA Glen Research Center* [online], May 2015, https://www.grc.nasa.gov/WWW/K-12/airplane/cg.html [retrieved July 2018].

[3] Benson, T., ed., "Determining Center of Pressure," *NASA Glen Research Center* [online], June 2014, https://www.grc.nasa.gov/WWW/k-12/rocket/rktcp.html [retrieved July 2018].

[4] Barrowman, J. S., "The Practical Calculation of the Aerodynamic Characteristics of Slender Finned Vehicles," *NASA Technical Reports Server* [online], NASA/TM-2001-209983, NAS 1.15:209983, March 1967, https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20010047838.pdf [retrieved July 2018].

[5] "Barrowman Equations for Computing the Rocket Center of Pressure," *Utah State University* [online], http://mae-nas.eng.usu.edu/MAE_5900_Web/5900/USLI_2010/Flight_Mechanics/Barrowman.html [retrieved July 2018].

[6] Benson, T., ed., "Rocket Stability," *NASA Glen Research Center* [online], June 2014, https://spaceflightsystems.grc.nasa.gov/education/rocket/rktstab.html [retrieved July 2018].

[7] Nakka, R., "Fins for Rocket Stability," *Experimental Rocketry* [online], https://www.nakkarocketry.net/fins.html [retrieved July 2018].

[8] Wertz, J. R., ed. and Larson, W. J., ed., "Launch Systems," *Space Mission Analysis and Design*, 3rd ed., Microcosm Press, Hawthorne, CA, and Springer, New York, NY, 1999, pp. 719-744.

[9] Sforza, P. M., "Launch Mechanics," *Manned Spacecraft Design Principles*, Elsevier Inc., Waltham, MA, pp. 199-302.

[10] "Mach Number," *Neutrium* [online], October 2014, https://neutrium.net/fluid_flow/mach-number/ [retrieved July 2018].

[11] Hennin, B., "Why Should You Airfoil Your Rocket's Fins," *Apogee Components: Peak of Flight Newsletter* [online], Issue 305, January 2012, https://www.apogeerockets.com/education/downloads/Newsletter305.pdf [retrieved July 2018].

[12] Barbosa, A. N. and Guimarães, L. N. F., "Multidisciplinary Design Optimization of Sounding Rocket Fins Shape Using a Tool Called MDO-SONDA," *Journal of Aerospace Technology and Management* [online], Vol. 4, No. 4, 2012, pp. 431-442.
doi: 10.5028/jatm.2012.04044412

[13] Ramsey, J. K., ed., "NASA Aeroelasticity Handbook Volume 2: Design Guides Part 2," *NASA Technical Reports Server* [online], NASA/TP-2006-212490-VOL2-PT 2, E-14035, November 2006, https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20070008370.pdf [retrieved July 2018].

[14] Simmons, J.R., "Aeroelastic Optimization of Sounding Rocket Fins," *Defense Technical Information Center* [online], June 2009, http://www.dtic.mil/dtic/tr/fulltext/u2/a502110.pdf [retrieved July 2018].

[15] Stroick, G., "Nose Cone & Fin Optimization," *Tripoli Minnesota* [online presentation slides], 2011, http://s605282183.onlinehome.us/wp-content/uploads/2016/01/Nose-Cone-Fin-Optimization.pdf [retrieved July 2018].

[16] Martin, D. J., "Summary of Flutter Experiences as a Guide to the Preliminary Design of Lifting Surfaces on Missiles," *NASA Technical Reports Server* [online], NACA-TN-4197, 1958, https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19930085030.pdf [retrieved July 2018].

[17] Tola, C. and Nikbay, M., “Investigation of the effect of thickness, taper ratio and aspect ratio on fin flutter velocity of a model rocket using response surface method,” *Proceedings of the 7th International Conference on Recent Advances in Space Technologies* [online], Istanbul, Turkey, June 2015, pp. 27-32, https://ieeexplore-ieee-org.ezproxy.proxy.library.oregonstate.edu/document/7208310/authors#authors [retrieved August 2018].

[18] Pressly, E. C., “Sounding Rockets,” *NASA Technical Reports Server* [online], NASA-TM-X-55123, X-670-65-2, 1965, https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19650006344.pdf [retrieved July 2018].

[19] Jarvis, J., “The Jarvis Illustrated Guide to Carbon Fiber Construction,” [online report], 2009, https://www.raketenmodellbau.org/repository/archive/167792?view=true [retrieved July 2018].

[20] Biba, K., Baker, C., Ebert, E., Green, B., Green, J., Raimondi, D., Rouse, D., and Wigfield, S., “Team AeroPac’s 2012 100k’ Rocket Program,” [online report], 2012, https://cdn.hackaday.io/files/22132946895488/AeroPac%202012%20100k'%20Program%20Report.compressed.pdf [retrieved July 2018].

[21] Heslehurst, R., “Composite Sandwich Structure Design Requirements,” *Composites Australia* [online], March 2015, https://www.compositesaustralia.com.au/wp-content/uploads/2015/05/Composite-Sandwich-Structures-Part-3-Terms-Defintions-Global-Properties-_web.pdf [retrieved July 2018].

[22] “Core Materials,” *Net Composites* [online], https://netcomposites.com/guide-tools/guide/core-materials/ [retrieved July 2018]

[23] “Standard Cell Aramid Honeycomb,” *ACP Composites* [online catalog], https://store.acpsales.com/products/3455/standard-cell-aramid-honeycomb [retrieved July 2018].

[24] “T800H Data Sheet,” *TORAYCA* [online data sheet], https://www.toraycma.com/file_viewer.php?id=4463 [retrieved July 2018].

[25] “0.125" X 12" X 12" Natural FR4 Sheet,” *ePlastics* [online catalog], https://www.eplastics.com/G10NAT-125X12X12 [retrieved July 2018].

[26] “1/4" Diam, 3/4" LOC, 1/4" Shank Diam, 2-1/2" OAL, 4 Flute Solid Carbide Square End Mill,” *MSC* [online catalog], https://www.mscdirect.com/product/details/87636270 [retrieved July 2018]

[27] Joyce, P., “Common Lay-up Terms and Conditions,” *United States Naval Academy* [online presentation slides], 2003,

https://www.usna.edu/Users/mecheng/pjoyce/composites/Short_Course_2003/7_PAX_Short_Course_Laminate-Orientation-Code.pdf [retrieved July 2018].

[28] “Peel Ply for Smooth Fiberglass Surfaces,” *Chesapeake Light* Craft [online catalog], https://www.clcboats.com/shoptips/epoxy_and_fiberglass/peel-ply-release-fabric.html [retrieved July 2018].

[29] “Release Film,” *ATM Composites* [online catalog], https://www.amtcomposites.co.za/products/vacuum-bag-infusion-consumables/release-film [retrieved July 2018].

[30] “Breather Cloth,” *ACP Composites* [online catalog], https://store.acpsales.com/products/2296/breather-cloth [retrieved July 2018].