Human Powered Helicopter: Spars

by

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List of Nomenclature

Abbreviations:
- ADCC: Aircraft Design and Construction Club
- CFRP: Carbon-fiber-reinforced polymer
- CTE: Coefficient of thermal expansion
- HPH: Human Powered Helicopter
- PP: Polypropylene

Definitions:
- Bending Stiffness: A spar’s ability to resist bending loads
- Bottleneck: Transition sleeve between 3” to 2.5” spar sections
- Bushings: Rotative rings that allow one spar to rotate inside the other
- Collars: Prevent axial movement of the bushings
- Coning: The rotor tip deflection as a result of lift and centripetal forces.
- $E_1$: The stiffness of the carbon fibers in the axial direction
- $E_2$: The stiffness of the carbon fibers perpendicular to their axes in the plane of the fibers
- Guy-wire: String used to restrain spars during flight
- Laminate Layup: The layer code of a composite part
- Landing Gear: Pole used to support spars and act as pin-connection at joints
- Mandrel: Part that gives carbon fiber its shape
- Pre-preg: Previously resin-impregnated carbon fiber
- Rotisserie: Jig that allowed for rotating spar and/or mandrel
- Rotor: The airfoil of the helicopter
- Shrink Tape: Plastic tape that shrinks upon heating
- Sleeve: Tube that joins spar sections together
- Spar: Structural member of the rotor
- Torsional Stiffness: A spar’s ability to resist torsional loads
- Upturn: Human powered helicopter donated to Cal Poly by Neal Saiki
- Upturn II: ADCC’s iteration of Upturn
Executive Summary

Neal Saiki, a Cal Poly alumnus, donated a human powered helicopter to the Cal Poly Aircraft Design and Construction Club in Fall Quarter 2012. To achieve the requirements of the Igor Sikorsky Human Powered Helicopter Competition, this senior project was tasked with reducing the weight of the load-bearing spars without changing geometry.

The aluminum spars were replaced with carbon fiber. The spars were designed to maintain the bending and torsional stiffnesses. Twelve sections of carbon fiber tubes ranging from 8 to 12 ft in length and 2” to 3” in inner diameter were made using pre-preg carbon fiber wrapped on aluminum male mandrels. Sleeves joining spars of dissimilar diameters were made with carbon fiber using a male polypropylene mandrel. Sleeves joining spars of equal diameter were purchased to save production time.

A test was conducted on a section of 2.5” diameter tube to verify that the bending stiffness requirements were met. Although multiple tests were conducted, a conclusive bending stiffness was not determined. Although the spar did not fail under twice the flight load, the weight of the spars was only reduced by 2%.

This report explains the design and manufacturing processes that led to the first completed iteration of the helicopter spars.
1 Introduction

The Aircraft Design and Construction Club (ADCC) at California Polytechnic State University, San Luis Obispo was given the Upturn human powered helicopter (HPH) designed by Neal Saiki, a Cal Poly alumnus. The ADCC’s goal was to reduce the weight of Upturn from 96 pounds to 80 pounds in attempt to win the Igor Sikorsky Human Powered Helicopter Competition prize of $250,000[1].

The Igor Sikorsky Human Powered Helicopter Competition prize was initiated in 1980 and has yet to be claimed due to the challenging set of requirements. The first team to win the HPH competition must complete the three following tasks during one flight [1]: hover for 60 seconds, stay within a 10m square during its flight, and momentarily exceed 3m (~10ft) above the ground.

1.1 Sponsor Background and Need

This team’s sponsor, Dr. Kurt Colvin, has been working with numerous teams on projects pertaining to human powered helicopters. With the donation of Upturn, ADCC was able to focus on improving the previous design. Their main goal was to reduce the weight of the helicopter from 96 lbs to 80 lbs.

1.2 Problem Statement

On a helicopter, a spar is the load bearing member of the rotor assembly. With the previous aluminum spars, the helicopter required an input of 1 hp from a single human pilot to acquire lift. These spars accounted for 47% of the helicopter’s weight, making it nearly impossible for a single person to provide the necessary power output. Team Flying Octopus was tasked with designing lighter spars.

1.3 Objectives

The team’s goals were organized into Phase I and Phase II. The objectives of Phase I were to design and construct a set of spars that are 30% lighter and maintain the original geometry, and stiffness and strength. Phase II consisted of redesigning the spar geometry while further reducing the weight. Due to delays, Phase II was not realized. Refer to the Conclusions and Recommendations section for a detailed explanation.

1.4 Project Management

Team Flying Octopus acted as a contractor to ADCC. The club consisted of multiple senior project groups including a spar team, a rotor team, a controls team, and various individual senior projects. The senior project groups held weekly technical meetings outside of regular club meetings to set and maintain deadlines. The club was available for manufacturing delegation.

This group was subdivided into analysis and manufacturing teams. Daniel Logue, a manufacturing engineer, was added to this team to assist in spar manufacturing design.
2 Background

Cal Poly is competing with other HPH teams to claim the Sikorsky Prize. The teams that are closest to achieving the prize’s requirements are University of Maryland and AeroVelo.

2.1 University of Maryland's Gamera and Gamera II

The University of Maryland’s Gamera series of human powered helicopters has a unique spar design. As shown in Figure 2-1[2], Gamera employs a quad-rotor configuration with two blades at the end of each rotor.

![Figure 2-1. University of Maryland’s Gamera II](image)

The University of Maryland team ascertained that micro-trusses are more efficient at distributing flight loads than circular tubes, rectangular tubes, and I-beams[3]. This led to a truss made of unidirectional carbon fiber composite tubes to provide maximum stability. This truss design is displayed in Figure 2-2[5].

![Figure 2-2. Gamera Spar Truss Design](image)
To complete the truss design, the team wrote a “generic algorithm targeting minimum weight while ensuring sufficient stiffness was utilized”[4]. This micro-truss structure provided a “620% increase in buckling efficiency over a single tube of equivalent weight. These carbon fiber truss structures significantly outperformed traditional composite tubes and were used for the most highly loaded primary structures, including the blade spars and airframe root compression member”[4]. Through further iterations of the algorithm, Gamera II uses micro-truss technology to bear the highest compression loading and, as a result, is 34% lighter than Gamera I (32.1 kg) and is capable of hovering for 60 seconds and reaching approximately 10 feet.

2.2 AeroVelo’s Atlas

AeroVelo started from a pair of engineering students from the University of Toronto and is the most recent team to start building their HPH, which started construction as early as January 2012. In as little as 18 months, the Atlas team has reached a peak height of roughly 3 meters and a maximum flight time of 47 seconds.

![Figure 2-3. AeroVelo’s Atlas](image)

Similar to the Gamera, the Atlas also uses a quad-rotor truss system design (see Figure 2-3[7]) made out of carbon fiber. “This was based on a lower predicted power requirement, the stability of the configuration and the ease of construction based on many parts with production-line repeatability”[6].

2.3 Current State of the Art: NTSWorks’ Upturn

The Upturn features 12 discrete sections of spars that change diameter as the spars branch out from the hub. These discrete sections allow portability and storage. The spars are mounted inside foam rotors which create lift. The foam is coated with colored plastic shrink wrap to reduce drag. As seen in Figure 2-4, the blue side, which is identical to the red side, consists of four aluminum tubular spars that extend 522 inches (43.5 feet) from the hub. Similarly, the yellow side is identical to the green side and two spars radiate 288 inches (24 feet) from the hub. The spars are restrained during flight by a system of guy-wires to prevent coning.
A single pilot inputs power to the helicopter via bicycle cranks. The power is used to turn propellers that are mounted at the ends of the green and yellow spars. The propellers generate thrust that causes the rotor and spar assembly to rotate, generating lift. A fly-by-wire control system rotates the Small Foam spars on the red and blue rotors along with the ailerons attached to the green and yellow rotors. Spar nomenclature is defined in Figure 2-5.

The geometry of each spar is listed in Table 2-1.
Table 2-1. Spar Geometry

<table>
<thead>
<tr>
<th>Spar</th>
<th>Diameter (in)</th>
<th>Length (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blue/Red</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bare</td>
<td>3.0</td>
<td>144</td>
</tr>
<tr>
<td>Large Foam</td>
<td>3.0</td>
<td>144</td>
</tr>
<tr>
<td>Med. Foam</td>
<td>2.5</td>
<td>144</td>
</tr>
<tr>
<td>Small Foam</td>
<td>2.0</td>
<td>90</td>
</tr>
<tr>
<td>Yellow/Green</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bare</td>
<td>2.5</td>
<td>144</td>
</tr>
<tr>
<td>Foam</td>
<td>2.5</td>
<td>144</td>
</tr>
</tbody>
</table>

Table 2-2 lists the aluminum spar weights. Note that the blue spars are equal in weight to the red spars. Similarly, the yellow spars are equal in weight to the green spars.

Table 2-2. Spar Weights

<table>
<thead>
<tr>
<th>Spar</th>
<th>Weight (lb.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blue/Red</td>
<td></td>
</tr>
<tr>
<td>Bare</td>
<td>4.58</td>
</tr>
<tr>
<td>Large Foam</td>
<td>3.67</td>
</tr>
<tr>
<td>Med. Foam</td>
<td>3.05</td>
</tr>
<tr>
<td>Small Foam</td>
<td>1.52</td>
</tr>
<tr>
<td>Yellow/Green</td>
<td></td>
</tr>
<tr>
<td>Bare</td>
<td>3.05</td>
</tr>
<tr>
<td>Foam</td>
<td>3.05</td>
</tr>
<tr>
<td>All Spars</td>
<td>41.83</td>
</tr>
</tbody>
</table>

The weight of the spars total 47% of the *Upturrn*’s weight. Excluding the pilot, the spars account for a plurality of the weight. An improved spar design can significantly reduce the weight of the helicopter.
3 Design Development

Due to the nature of this project, conventional design methodology was not followed. Instead, manufacturing was initiated before adequate loading analysis was completed and the spars were designed to match the stiffness properties of the previous spars. After several spars were manufactured, sufficient analysis that determined flight loads was completed. To compensate for additional loading, the manufacturing process was altered.

3.1 Loading Analysis

Since only the blue and red spars generate appreciable lift, they were the only spars considered during loading analysis. Due to symmetry, these spars experience the same flight loads. Therefore, a single blue spar was considered for a complete flight loading analysis (see Figure 2-5). Calculations were facilitated with the use of an EES code which can be found in Appendix C – Detailed Supporting Analysis. It was determined that a maximum bending moment of 6100 in-lbf and a maximum shearing force of 100 lb occurred at the rotating hub. This analysis assumed values of tension forces in the guy-wires. Therefore, a more accurate model was desired.

An FEA model of the helicopter was created using Abaqus CAE to obtain maximum loads in each section of spar as well as the loads in the constant diameter sleeves. The blue spar was modeled with guy-wires and landing gears. However, the results from this model were not valid. The spar reaction to loading is nonlinear and using small deflection theory yielded large errors. Abaqus was unable to evaluate the system with non-linear geometry. Results from the EES model were used for design because of the invalid FEA results. See Appendix C – Detailed Supporting Analysis for a detailed report of the FEA modeling process and results.

3.2 Spar Material Selection

The aluminum spars were to be replaced with a lighter material without sacrificing the ability to handle flight loads. Carbon-fiber-reinforced polymer (CFRP) was chosen as the spar material because its specific stiffness and specific strength properties exceed those of aluminum (see Table 3-1[8]). A discussion of the spar material selection process can be found in Appendix A – Manufacturing Decision Processes.

<table>
<thead>
<tr>
<th>Material</th>
<th>Density, ρ (lb/in³)</th>
<th>Specific Stiffness ($\times 10^{10}$ psi/(lb/in³))</th>
<th>Specific Strength, $S_{ut}$ ($\times 10^8$ psi/(lb/in³))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>0.098</td>
<td>4.030</td>
<td>1.650</td>
</tr>
<tr>
<td>Carbon Fiber (unidirectional, single ply)</td>
<td>0.065</td>
<td>17.520</td>
<td>12.17</td>
</tr>
</tbody>
</table>

From Table 3-1, carbon fiber has much higher specific stiffness and specific strength than aluminum. However, the data is valid for carbon fiber subject to one direction of loading. The mechanical properties of a carbon fiber part are determined by the laminate layup.
3.3 Component Design

For successful replication of the spar system, different components were designed. Some components were designed by similarity while new components were designed for optimization.

3.3.1 Spars

The design of the spars entailed global dimensions and laminate layups. The global dimensions governed how the spars interfaced with themselves and other helicopter components. The laminate layups determined the mechanical properties of the spars.

3.3.1.1 Dimension

The dimensions of the spars included the inside and outside diameters and landing-gear holes. Due to the selected manufacturing process, the spars had a controlled inside diameter. To maintain the nominal outside diameter of the previous spars, the aluminum mandrels would need to be turned down on a lathe, mandrels with custom outside diameters would need to be purchased, or a new manufacturing process would need to be chosen. However, since new rotors were being designed and manufactured in tandem, it was decided to use nominal inside diameters. Outside diameters were then determined by the laminate layups.

Holes were machined in the previous spars to interface with landing gears. Figure 3-1 shows a landing gear pole and an interfacing hole.

![Landing gear pin connection.](image)

The landing gears created pin connections for the guy-wires. To maintain the same guy-wire joint locations, the landing-gear holes were positioned in the same location as in the previous spars. To avoid stress concentrations, the holes were located three inches from the edge of the spars. From this, the lengths of the spars were derived. Appendix B – Drawings contains all of the drawings for each of the spars.

3.3.1.2 Mechanical Properties Analysis

Quatro Composites donated NCT301 TR50s G150 1M 35±3% unidirectional carbon fiber pre-preg which was used for spar manufacturing. The product data sheet containing the carbon fiber properties is shown in Appendix A – Manufacturing Decision Processes. Aside from the elastic moduli $E_1$ and $E_2$, all mechanical properties were assumed to be the same as AS4 fiber with the 301 resin system because of the similarity of the two fiber and resin systems. Table 3-2 summarizes all composite properties used in the design of the laminate layup of each spar.
Table 3-2. Carbon fiber properties used for designing spar layup.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value (×10^6 lb/in^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E_1</td>
<td>20.4</td>
</tr>
<tr>
<td>E_2</td>
<td>1.2</td>
</tr>
<tr>
<td>ν_{12}</td>
<td>0.304</td>
</tr>
<tr>
<td>G_{12}</td>
<td>0.64</td>
</tr>
</tbody>
</table>

The mechanical properties shown in Table 3-2 are for a single ply of unidirectional fiber. The mechanical properties of a laminate layup were determined by the number of layers and their orientation relative to the loading directions.

Table 3-3 contains the laminate codes for each spar.

Table 3-3. Laminate codes for each spar.

<table>
<thead>
<tr>
<th>Spar</th>
<th>Layup</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blue/Red</td>
<td></td>
</tr>
<tr>
<td>Bare</td>
<td>[0/±45]</td>
</tr>
<tr>
<td>Large Foam</td>
<td>[0/±45 /0/±45/0]</td>
</tr>
<tr>
<td>Med. Foam</td>
<td>[0/±45 /0/±45/0]</td>
</tr>
<tr>
<td>Small Foam</td>
<td>[0/±45 /0/±45/0]</td>
</tr>
<tr>
<td>Yellow/Green</td>
<td></td>
</tr>
<tr>
<td>Bare</td>
<td>[0/±45 /0/±45/0]</td>
</tr>
<tr>
<td>Foam</td>
<td>[0/±45 /0/±45/0]</td>
</tr>
</tbody>
</table>

Each laminate is symmetric, which decouples the laminate’s reactions to loading. The number of plies were determined for each spar based on its individual loading. In addition to these laminate codes, 12 inches of [90]_S reinforcement fibers were required on the ends of the spars to withstand contact loads from the joints. Detailed drawings of each section can be found in Appendix B – Drawings.

The weight of each section of the designed spars is tabulated in Table 3-4 along with their aluminum counterparts.

Table 3-4. A weight comparison of the proposed carbon fiber spars to the aluminum spars.

<table>
<thead>
<tr>
<th>Spar</th>
<th>Weight (lb)</th>
<th>% Weight Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Aluminum</td>
<td>Carbon Fiber</td>
</tr>
<tr>
<td>Red/Blue</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bare</td>
<td>4.58</td>
<td>3.30</td>
</tr>
<tr>
<td>Large Foam</td>
<td>3.67</td>
<td>2.88</td>
</tr>
<tr>
<td>Med. Foam</td>
<td>3.05</td>
<td>2.41</td>
</tr>
<tr>
<td>Small Foam</td>
<td>1.52</td>
<td>1.21</td>
</tr>
<tr>
<td>Green/Yellow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bare</td>
<td>3.05</td>
<td>2.41</td>
</tr>
<tr>
<td>Foam</td>
<td>3.05</td>
<td>2.41</td>
</tr>
<tr>
<td>Combined</td>
<td>37.84</td>
<td>29.24</td>
</tr>
</tbody>
</table>
Although these results do not yield the desired 30% weight reduction, a 23% (8.6 lb) weight reduction was determined acceptable for a first iteration. A comparison of the bending and torsional stiffnesses between the previous aluminum spars and the proposed carbon fiber spars are tabulated in Table 3-5.

Table 3-5. Comparison of Bending and Torsional Stiffness of Spars

<table>
<thead>
<tr>
<th>Spar</th>
<th>Bending Stiffness, EI (×10^6 lb·in²)</th>
<th>Torsional Stiffness, GJ (×10^6 lb·in²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Aluminum</td>
<td>Carbon Fiber</td>
</tr>
<tr>
<td>Red/Blue</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bare</td>
<td>3.59</td>
<td>3.89</td>
</tr>
<tr>
<td>Large Foam</td>
<td>2.89</td>
<td>3.76</td>
</tr>
<tr>
<td>Medium Foam</td>
<td>1.66</td>
<td>2.16</td>
</tr>
<tr>
<td>Small Foam</td>
<td>0.84</td>
<td>1.09</td>
</tr>
<tr>
<td>Green/Yellow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bare</td>
<td>1.66</td>
<td>2.16</td>
</tr>
<tr>
<td>Foam</td>
<td>1.66</td>
<td>2.16</td>
</tr>
</tbody>
</table>

It can be seen that each spar will exceed the bending and torsional stiffness of their aluminum counterparts, allowing them to withstand flight loads with reduced weight. However, in each case, the spars are overdesigned which means further weight reduction is possible for future iterations.

As described in section 8.2, the chosen spar manufacturing process requires a male mandrel that must separate from the part after curing. The ability to separate is dependent on the coefficient of thermal expansion (CTE) of each material and the temperature change after curing. The CTE of each laminate was calculated and the results are tabulated in Table 3-6. Since each laminate layup’s CTE is smaller than that of aluminum for a given diameter, it will be possible to separate the cured carbon fiber spars from the aluminum mandrels.

Table 3-6. Spar Coefficients of Thermal Expansion

<table>
<thead>
<tr>
<th>Spar</th>
<th>Nominal Diameter (in)</th>
<th>Coefficient of Thermal Expansion, α (×10^-6 in/in °F)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Aluminum</td>
</tr>
<tr>
<td>Red/Blue</td>
<td></td>
<td>3.0</td>
</tr>
<tr>
<td>Bare</td>
<td></td>
<td>3.0</td>
</tr>
<tr>
<td>Large Foam</td>
<td></td>
<td>2.5</td>
</tr>
<tr>
<td>Med. Foam</td>
<td></td>
<td>2.5</td>
</tr>
<tr>
<td>Small Foam</td>
<td></td>
<td>2.5</td>
</tr>
<tr>
<td>Green/Yellow</td>
<td></td>
<td>2.5</td>
</tr>
<tr>
<td>Bare</td>
<td></td>
<td>2.5</td>
</tr>
<tr>
<td>Foam</td>
<td></td>
<td>2.5</td>
</tr>
</tbody>
</table>

From this analysis, the expected weight reduction was only 7% short of the desired goal. This was a satisfactory result. The analysis satisfied two of the three requirements previously set in section 1.3.
3.3.2 Bottleneck Sleeve

A sleeve was needed to join 3” diameter spars to 2.5” diameter spars. Like the spars, the sleeves needed to be constructed from a stiff, strong, and lightweight material. A discussion of the sleeve’s key features is presented below.

3.3.2.1 Geometry

The sleeve fits inside of each spar. It is permanently adhered to the 2.5” spar. The sleeve is 2 feet long. A gradual transition between diameters prevents stress concentrations. Through-holes of 5/8” were drilled into the free end of the sleeve and the 3” spar. To form a joint, a landing gear pole was inserted into the holes. The sleeve is shown in Figure 3-2.

![Figure 3-2. CAD model of the bottleneck sleeve.](image)

The landing gear pole forms a close running fit with the spar and sleeve holes.

3.3.2.2 Laminate Layup

Due to the interface between sleeves and spars, contact stress must be considered in the laminate design. Carbon fiber contact stresses are more complex than that of other engineering materials. Due to the complexity of analysis, the sleeves were designed by similarity to the aluminum spars. If the carbon fiber has strength in the hoop direction comparable to the old aluminum spars, they will not fail. Both the sleeve and the spar must have this hoop strength in the area of contact.

The bottleneck sleeve experiences a bending moment of 1160 in-lb and a negligible shearing force. Analysis showed that for the sleeves to achieve minimum bending stiffness and hoop strength, the required layup was: [0/90]_s. The required hoop reinforcement for all spars in the area of contact with sleeves was determined to be 0.04” of hoop fiber, approximately [90_s].

3.3.3 Collars and Bushings

The controls system features servos that rotate the Small Foam spars. To preserve the functionality of the controls system, the joint from the previous helicopter was implemented in this design. Shown in Figure 3-3 is the collars and bushings system.
The collars and bushings are made from polypropylene. The collars are fixed to the 2” spar to axially constrain the collars. The bushings are free to rotate on the 2” spar. A hose clamp on the sleeve of the 2.5” spar prevents relative motion between the collar and the 2.5” spar, but allows the 2” spar to freely rotate.
4 Product Realization

Manufacturing of the spars was coordinated with Daniel Logue, the manufacturing engineer on the team. To successfully replicate the helicopter spars, the manufacturing processes of the spars and the joining sleeves were carefully designed.

4.1 Spars

In order to produce the full set of spars for the helicopter, numerous manufacturing operations were carried out. The manufacturing processes are organized into three sections: pre-cure, cure, and post-cure. A detailed description of each task is listed in Appendix A – Manufacturing Decision Processes and Appendix D – Manufacturing Operations.

4.1.1 Pre Cure Process

The spars are manufactured by hand with pre-preg carbon fiber as determined from section 8.3.4. The pre-cure process involved the following steps: mandrel preparation, cutting carbon fiber, wrapping the mandrel, and curing the spars.

4.1.1.1 Mandrel Preparation

As described in sections 8.1 and 8.2, a male aluminum mandrel was chosen to give shape to the carbon fiber spars. The mandrels were wet-sanded to a 15-micron surface finish to allow easy spar removal after curing.

4.1.1.2 Cutting

Figure 4-1 shows cutting of carbon fiber with a razor and a straight-edge.

The dimensions of each layer are shown on the corresponding drawing in Appendix B – Drawings. Note how the width of the strips increases with each layer to compensate for the increase in spar diameter after each applied layer.
4.1.1.3 Wrapping

The mandrel was set up in the rotisserie-jig and coated with release agent. Shown in Figure 4-2, the axial layers were applied first because they were easier to lay on the slick mandrel.

![Figure 4-2. Wrapping an axial layer.](image)

After all the axial layers were placed, the 45° layers were added. Application of a 45° layer is shown in Figure 4-3. These layers form a 45° angle with the axis of the mandrel. As prescribed in the laminate code of Table 3-3, the 45° layers alternated in angle; a -45 layer proceeded a +45 layer. All 45° layers had a slight overlap to prevent voids and air pockets.

![Figure 4-3. Wrapping carbon fiber at a 45° angle.](image)

After each layer was applied, the spar was examined for any air bubbles or wrinkles. These defects were carefully removed. It was paramount that the mandrel was not damaged during the pre-cure process.

4.1.1.4 Shrink Tape

Pressure must be applied to carbon fiber during curing to distribute the resin and to give shape to the part. Shrink tape was used to apply this pressure. The carbon fiber layers compact as the shrink tape shrinks and the mandrel expands in the curing oven. The geometry of the
tape, the tension at which the shrink tape is applied, and overlap percentage affect the quality of the cured spar. Application of shrink tape is shown in Figure 4-4.

![Figure 4-4. Wrapping shrink tape to completed layup.](image)

It is difficult to maintain a constant overlap percentage while wrapping the spar in shrink tape. Wrapping was done at slow rotating speeds to prevent wrinkles and other defects.

### 4.1.1.5 Curing

The carbon fiber spars require a large oven for curing. The team was able to use a custom oven (see Figure 4-5) from Kirke Leonard, a carbon fiber enthusiast and Los Osos resident. The oven was 15-feet long and was constructed from wood with insulation covering all inside surfaces. A variac controlled electric current that ran through baling wire routed along the walls of the oven to provide heat.

![Figure 4-5. Spar entering the curing oven.](image)

The spars were placed in the oven, which was then sealed and locked. The oven was gradually heated to 250° F, and held at that temperature for sixty minutes. The oven was then
opened and the spars were allowed to air-cool. The oven cured up to four spars at a time. The curing process took between 1.5 hours and 3 hours.

4.1.1.6 Removal
The cured spars were removed from the aluminum mandrels by hand. To aid in removal, a 5/8” through-hole was drilled through the mandrel at one end and a 1-foot steel rod was inserted. The mandrel was set in a vise (see Figure 4-6) and anchored as five people yanked on the cured carbon fiber spar.

![Figure 4-6. Mandrel fixed in vise.](image)

The spars were successfully removed from the mandrel. The effort required to separate cured spars is dependent on the surface finish of the mandrel and the amount of release agent applied to the mandrel. The removal process does not damage the spars. Care was taken to hold the mandrel as the end of the spar was removed to avoid dropping the mandrel.

4.1.2 Post Cure Process
After curing, the spars were machined for interfacing. The sequence of steps involved in these post-cure processes is described below. All machining processes create harmful carbon fiber dust. Masks must be worn by the machinists working on carbon fiber.

4.1.2.1 Sanding
After curing, the shrink tape must be removed from the spar. While most of the shrink tape can be removed by hand, approximately 50% of the shrink tape will remain on the spar surface. The remaining shrink tape adds unnecessary weight to the spars and was removed by sanding. Sanding is also used to achieve an appropriate surface finish for integration with the rotors. Figure 4-7 shows a sanded spar.
Sanding was done on the rotisserie jig, which allowed faster processing times. Belt sanders were used as sanding tools due to the high rate of material removal. Sanding was done as needed until the desired part diameters and surface finish was acquired.

4.1.2.2 Cutting

Once the spar was fully sanded, it was cut to length on a tile saw. Wrapping often produced uneven ends due to the carbon fiber 45° layer application (See Figure 11-3). These edges must be removed for spar integration. Figure 4-8 shows a cut spar.

Although Figure 4-8 shows an aluminum insert in the spar, it was not needed when the spars were cut. This iteration of the spar was stiff and strong enough to withstand the cutting tool loads.
4.1.2.3 Drilling

Drilling was the final process before integration and assembly. All holes were drilled with a drill press. Through-holes of 5/8" and 3/4" were drilled for landing gear pin connections. 1.25" through holes were drilled for propeller mounts. Figure 4-9 shows a typical hole.

![Figure 4-9. 5/8" hole.](image)

Drilling was done using a gradual increase in diameter. To prevent cracking and splintering, dowels were placed inside the spar to provide internal support. Since carbon fiber is hard, copious amounts of cutting fluid were required to keep the drill bits cool. A shop-vacuum was used to remove hazardous chips and dust.

4.2 Joint Manufacturing

Joints were manufactured in tandem with the spars. Each joint is described below.

4.2.1 Bottleneck Sleeves: 3" - 2.5"

The bottleneck sleeve was made out of carbon fiber in a similar process to the spars. PP was used instead of aluminum because of its higher coefficient of thermal expansion (CTE) allowing for easier extraction. The short length of the 2-foot mandrel was not subject to the bowing and deflection issues of the longer mandrels. The bottleneck sleeve is shown in Figure 4-10.

![Figure 4-10. Cured bottleneck sleeve.](image)
The mandrel was machined on a CNC lathe in order to give it the curved feature. The G-code for the mandrel is provided in section 11.5.1. After lathing, the mandrel was lightly hand sanded and prepared for wrapping.

The sleeve was wrapped using uni-directional pre-preg according to the laminate codes in section 3.3.2.2. The sleeves were cured in an autoclave in the Cal Poly composites lab.

4.2.2 Same Diameter Sleeves: 3" - 3" and 2.5" - 2.5"

The same size transition sleeves were purchased from Rock West Composites. The sleeves were filament wound and centerless-ground. The sleeves were 1/16" in thickness and sufficiently strong and stiff to be used as connecting joints. A typical sleeve is shown in Figure 4-11.

![Figure 4-11. 3" diameter transition sleeve.](image)

The sleeves were slightly larger than their nominal diameter. They were sanded down to the required diameter until a close running fit was achieved. Holes were drilled into the sleeves to allow the landing gear to form a pin connection. A 3/4" through-hole was drilled in the sleeve connecting 3" spars and a 5/8" through hole was drilled in the sleeve connecting 2.5" spars.

4.2.3 Bushings and Collars: 2.5" - 2.0"

The bushings and collars were machined out of polypropylene stock chucked in a lathe and turned down, bored to the desired diameters, and parted to the correct lengths. The pieces were sanded as needed. Figure 4-12 shows a bushing and collar assembly integrated on the spar.

![Figure 4-12. One set of bushings and collars interfaced with a 2" diameter spar.](image)

Each transition required two sets of the bushings and collars systems. Refer to Figure 3-3.
5 Testing of Design

During flight, the spars are subject to bending moments from the distributed lift forces, a torque as a result of the aerodynamic center differing from the spar location in the rotor, and shearing and axial forces exerted by the guy-wires. Bending moments are the most significant loading. The amount a spar deflects in bending is a function of the applied load and the spar bending stiffness.

5.1 Desired Outcomes

Due to the nature of the flight loads, only bending stiffness was measured. Because the spars are not located at the aerodynamic center of the rotors, a torque is generated in the rotors and partially transmitted to the spars. A deflection under this torque would change the angle of attack and alter the lift force. However, it was determined that this torque was negligible compared to the bending load because the rotors would deform from the load rather than transmit the load to the spars. The guy-wire loading is small and negligible.

The bending stiffness was the only desired property of the spars from testing. A sufficient bending stiffness will prevent coning and loss of lift. The bending stiffness was used to verify the properties of the carbon fiber spars and check the quality of the layup.

5.2 Apparatus

Three tests were conducted to verify the bending stiffness of the spars. A successful test is described in section 5.2.1. The two failed tests are described in section 5.2.2.

5.2.1 Approved Test

The test apparatus is shown in Figure 5-1 was the method used to determine the actual spar bending stiffness.

![Test Apparatus](image)

Figure 5-1. Test Apparatus

The test fixture shown in Figure 5-2 was built to fix one end of the spar as a cantilever beam. This test fixture was welded using 3/8” carbon steel plates and a 3/8” carbon steel tube to fit inside the spar. A copy of the CAD drawing can be found in Appendix B – Drawings.
Figure 5-2. Test Fixture

The fixture was MIG welded by Kevin Williams of the IME department at Cal Poly. The test fixture was mounted to the strong floor with three 5/8” bolts. The bolts were tightened until the fixture would not deflect under the maximum testing load of 3200 in-lb.

A 62.5” long, 2.5” diameter spar section was mounted to the fixture. The steel fixture held the spar while an actuator, connected in series with an Omega LC402-100 load cell and a nylon strap, pulled the end of the spar. The load cell data was recorded from a digital read-out. Two 120-ohm strain gauges, like the one shown in Figure 5-3, were mounted to the tensile and compressive sides of the spar, respectively.

Figure 5-3. Typical strain gauge mounted to test section.

These strain gauges were wired as quarter bridges and linked to a Vishay P3 Strain Indicator and Recorder DAQ shown in Figure 5-4. Separate readouts for tensile strain and compressive strain were recorded from the Vishay P3.
After connecting the strain gauges to the DAQ, they were balanced. Testing was initiated.

5.2.2 Failed Tests
The first test measured only tip deflection. Analysis of the testing results gave a bending stiffness of \(1.66 \times 10^6\) lb-in\(^2\). This result was much lower than the theoretical stiffness of \(2.90 \times 10^6\) lb-in\(^2\). This error could be attributed to any combination of the following: bending of fixture, degraded composite properties, ply angle inaccuracies, wrinkles and voids in layup, contact stresses from fixture/composite interface, debris in layup, load cell calibration errors, and unaccounted thermal strains from cool down after curing. An additional test was required.

A second test was conducted in an effort to eliminate fixture bending. Deflection was measured at two locations and the stiffness of the beam was calculated without contamination from fixture bending. This yielded an effective beam stiffness of \(1.77 \times 10^6\) lb-in\(^2\). This was still much smaller than the theoretical value. See Appendix C – Detailed Supporting Analysis for calculations.

5.3 Results
The results from the bending test described in section 5.2.1 are shown in Table 5-1. Test Results.
The strain gage in tension yielded a bending stiffness 17% lower than the theoretical value. However, the strain gage in compression gave a bending stiffness 45% higher than its theoretical counterpart. This error resulted from an incomplete bond between the gage and the spar surface. The table below summarizes the results from testing.

<table>
<thead>
<tr>
<th>Force (lb)</th>
<th>Moment (lb-in)</th>
<th>Tensile Micro Strain (×10⁶ in/in)</th>
<th>Compressive Micro Strain (×10⁶ in/in)</th>
<th>EI from Tensile Gage (×10⁶ lbf-in²)</th>
<th>EI from Compressive Gage (×10⁶ lbf-in²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.5</td>
<td>266.5</td>
<td>122</td>
<td>-74</td>
<td>2.783</td>
<td>4.264</td>
</tr>
<tr>
<td>12.0</td>
<td>492.0</td>
<td>242</td>
<td>-135</td>
<td>2.591</td>
<td>4.294</td>
</tr>
<tr>
<td>22.5</td>
<td>922.5</td>
<td>487</td>
<td>-256</td>
<td>2.414</td>
<td>4.251</td>
</tr>
<tr>
<td>26.7</td>
<td>1094.7</td>
<td>586</td>
<td>-303</td>
<td>2.379</td>
<td>4.261</td>
</tr>
<tr>
<td>32.9</td>
<td>1348.9</td>
<td>729</td>
<td>-374</td>
<td>2.355</td>
<td>4.257</td>
</tr>
<tr>
<td>38.1</td>
<td>1562.1</td>
<td>856</td>
<td>-437</td>
<td>2.322</td>
<td>4.215</td>
</tr>
<tr>
<td>43.9</td>
<td>1799.9</td>
<td>996</td>
<td>-508</td>
<td>2.301</td>
<td>4.181</td>
</tr>
<tr>
<td>50.2</td>
<td>2058.2</td>
<td>1153</td>
<td>-585</td>
<td>2.272</td>
<td>4.153</td>
</tr>
</tbody>
</table>

Average: 2.431  4.240

Due to measurement inaccuracies in the first two tests, their results were discarded. The tension and compression strain gages yielded differing results. The results from these tests were inconclusive. Further testing is recommended.
6 Conclusions and Recommendations

Throughout the course of this project, it was determined that the helicopter spar components, their manufacture, and their design verification could be improved. Conclusions from this project and recommendations for future projects are described below.

6.1 Components

Each component of the spars went through a single iteration of design. The design process provided insight into sources of error and possible areas for improvement.

6.1.1 Spars

The spars were the central component of design. Because the finished spars did not meet the requirements, enhancements to the design and manufacture are recommended.

6.1.1.1 Laminate Layup Errors

There were several errors in calculating the original laminate layup of the carbon fiber spars. For calculations, carbon fiber layer thicknesses of 0.005” was assumed. The actual layer thickness was later determined to be closer to 0.006” resulting in excessively stiff and heavy spars. The initial laminate layup was designed to handle torsional loads. However, these torsional loads were determined to be less significant because of the flexibility of the rotors. Unnecessary layers of carbon fiber were included in the original laminate layup yielding excess weight.

6.1.1.2 Manufacturing Errors

Each spar was manufactured by inexperienced students using three-year-old carbon fiber. Air pockets, wrinkles, and ply angle deviations of up to 5° caused inconsistencies between parts. The spars were cured for less than the desired 60-minute cure cycle. These combined to reduce the bending stiffness of the spars.

6.1.1.3 Actual Weight Savings

The total weights of the new carbon fiber spars are tabulated in Table 6-1. These results are compared to the previous aluminum spars.

Table 6-1. Actual Savings from First Iteration

<table>
<thead>
<tr>
<th>Spar</th>
<th>Weight (lb)</th>
<th>% Weight Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Aluminum</td>
<td>Carbon Fiber</td>
</tr>
<tr>
<td>Red/Blue</td>
<td>Bare</td>
<td>4.58</td>
</tr>
<tr>
<td></td>
<td>Large Foam</td>
<td>3.67</td>
</tr>
<tr>
<td></td>
<td>Med. Foam</td>
<td>3.05</td>
</tr>
<tr>
<td></td>
<td>Small Foam</td>
<td>1.52</td>
</tr>
<tr>
<td>Green/Yellow</td>
<td>Bare</td>
<td>3.05</td>
</tr>
<tr>
<td></td>
<td>Foam</td>
<td>3.05</td>
</tr>
<tr>
<td>Combined</td>
<td></td>
<td>37.84</td>
</tr>
</tbody>
</table>

The weight reduction goal was not achieved. Incorrect layer thickness was the cause for lack of weight reduction as explained in section 6.1.1.1.
6.1.1.4 Recommendations

Two possible optimized layups have been recommended using the same carbon fiber (NCT301 TR50s G150 1M 35±3%). One layup matches the carbon fiber torsional and bending stiffness of the previous aluminum spars (see Table 6-2); the other only matches bending stiffness (see Table 6-3).

Table 6-2. Recommended spar layups and other properties for a second iteration.

<table>
<thead>
<tr>
<th>Spar</th>
<th>Layup</th>
<th>Maximum Moment (lb-in)</th>
<th>Strength Safety Factor</th>
<th>Aluminum Bending Stiffness (×10⁶ lb·in²)</th>
<th>Carbon Fiber Bending Stiffness (×10⁶ lb·in²)</th>
<th>Aluminum Torsional Stiffness (×10⁶ lb·in²)</th>
<th>Carbon Fiber Torsional Stiffness (lb·in²×10⁶)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare</td>
<td>[0/±45/0]ₜₜ</td>
<td>6106</td>
<td>3.05</td>
<td>3.58</td>
<td>4.72</td>
<td>2.76</td>
<td>3.04</td>
</tr>
<tr>
<td>Large Foam</td>
<td>[0/±45]ₜₜ</td>
<td>3842</td>
<td>3.42</td>
<td>2.89</td>
<td>3.33</td>
<td>2.22</td>
<td>2.94</td>
</tr>
<tr>
<td>Med. Foam</td>
<td>[0/±45]ₜₜ</td>
<td>5238</td>
<td>1.97</td>
<td>1.66</td>
<td>1.94</td>
<td>1.28</td>
<td>1.71</td>
</tr>
<tr>
<td>Small Foam</td>
<td>[0/±45/0]ₜₜ</td>
<td>1157</td>
<td>7.14</td>
<td>1.04</td>
<td>1.43</td>
<td>0.802</td>
<td>0.92</td>
</tr>
</tbody>
</table>

This layup consists of one less axial layer of fiber except for the Small Foam section which has the same layup as before. This layup is more conservative and heavier than the second layup recommendation.

Table 6-3. Recommended spar laminate layups designed to match bending stiffness.

<table>
<thead>
<tr>
<th>Spar Location</th>
<th>Layup</th>
<th>Maximum Moment (lb-in)</th>
<th>Strength Safety Factor</th>
<th>Aluminum Bending Stiffness (×10⁶ lb·in²)</th>
<th>Carbon Fiber Bending Stiffness (×10⁶ lb·in²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare</td>
<td>[0₃]</td>
<td>6106</td>
<td>2.58</td>
<td>3.58</td>
<td>3.96</td>
</tr>
<tr>
<td>Large Foam</td>
<td>[0₃]</td>
<td>3842</td>
<td>4.10</td>
<td>2.89</td>
<td>3.96</td>
</tr>
<tr>
<td>Med. Foam</td>
<td>[0₃]</td>
<td>5238</td>
<td>2.08</td>
<td>1.66</td>
<td>2.30</td>
</tr>
<tr>
<td>Small Foam</td>
<td>[0₃]</td>
<td>1157</td>
<td>5.46</td>
<td>1.04</td>
<td>1.19</td>
</tr>
</tbody>
</table>

The second recommendation will result in lighter spars because only the minimum number of plies for each section were used to meet strength and bending stiffness requirements. However, the lack of a hoop-component will result in brittle spars that may not handle torsional loads. Neither of these layups include the additional hoop fibers to handle the contact stresses experienced at the joints. Further testing on these stresses is recommended for future iterations.

The expected weights from each of these layups is compared to the previous design in Table 6-4. Note that these values do not account for the additional hoop fibers for contact stresses which could add as much as 33% more weight.
Table 6-4. Spar Weight Comparison of Recommended Layups

<table>
<thead>
<tr>
<th>Carbon Fiber Weight (lb)</th>
<th>First Iteration</th>
<th>Recommendation 1</th>
<th>Recommendation 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>37.0</td>
<td>33.2</td>
<td>15.7</td>
</tr>
</tbody>
</table>

Recommendation 2 offers the largest weight savings at the expense of strength and stiffness. It is recommended that a small scale spar with this layup be tested before implementation.

6.1.2 Bottleneck Sleeves
The geometry of the bottleneck was satisfactory. It allowed for easy interface between joining spars. Future iterations of this sleeve should match the layup of the joining spars.
Wrapping carbon fiber on the bottleneck mandrel proved to be difficult, leading to many wrinkles, air pockets, and large regions of layer overlap. For these sleeves, different manufacturing processes should be researched and tested.

6.1.3 Bushings and Collars
The PP used to manufacture the bushings and collars was difficult to machine. Bonding PP is not easily accomplished. The sanded finish of the PP bushings was rough requiring a larger torque to rotate the spar. Research into other engineering plastics that are easier to manufacture and bond to the spars with a lower coefficient of friction should be considered.

6.2 Manufacturing
The shrink tape application method used required large amounts of sanding. Tests were attempted to determine the overlap and tension applied to yield the optimal surface finish. However, these tests were inconclusive. A better method for applying shrink tape and a superior tape are recommended.
The cure time of the carbon fiber spars should be no less than 60 minutes regardless of the age of the fiber. It is also recommended that in-house oven be built or purchased to reduce time needed for transportation during the curing process.
Carbon fiber’s mechanical properties make it difficult to machine. Fewer layers would reduce the cutting and drilling times. Carbon fiber quickly dulls cutting equipment requiring many drill bits and saw blades. Wooden dowels should continue to be used for drilling and especially cutting with smaller laminate layups.

6.3 Testing
More tests need to be conducted before the next iteration of spars is built. This includes shrink tape tests (see section 6.2) and bending tests (see chapter 5). A more accurate bending test should be designed for the spars produced by this project and future projects. Also, a more sophisticated method of measuring spar deflection and applied loads is required.
7 References


8 Appendix A – Manufacturing Decision Processes

Before the spars were manufactured, trade studies pertaining to the manufacturing details were made.

8.1 Spar Material Selection

The primary objective of this project was to reduce the weight of the spars while maintaining the previous geometry. There were two ways to accomplish weight savings: reducing aluminum tube sizing or switching the spar material. Multiple materials were compared for optimal weight savings and their properties were assembled in Table 8-1[8].

Table 8-1. Possible Spar Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Density, ρ (lb/in³)</th>
<th>Specific Modulus (×10¹⁰ psi/(lb/in³))</th>
<th>Specific Strength, $S_{ul}$ (×10⁸ psi/(lb/in³))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>0.284</td>
<td>3.944</td>
<td>1.621</td>
</tr>
<tr>
<td>Aluminum</td>
<td>0.098</td>
<td>4.030</td>
<td>1.650</td>
</tr>
<tr>
<td>Carbon Fiber (unidirectional, single sheet)</td>
<td>0.065</td>
<td>17.520</td>
<td>12.17</td>
</tr>
<tr>
<td>Titanium</td>
<td>0.163</td>
<td>3.875</td>
<td>0.76²</td>
</tr>
</tbody>
</table>

Composite materials clearly have a higher specific strength and stiffness. Carbon fiber was chosen to build the spars because it is lighter and stronger than other commercially available materials. Carbon fiber has been thoroughly researched and documented in engineering applications.

Figure 8-1 below is the data sheet pertaining to the donated carbon fiber from Quatro Composites.
Figure 8-1. Pre-preg carbon fiber data.

NCT301 TR50s G150 1M 35±3% was used to construct the spars.

8.2 Mandrel Trade Study

A trade study was created to analyze the different mandrel options and objectively select the best choice. The findings can be seen below in Table 8-2, Table 8-3, and Table 8-4.
Table 8-2. Trade Study of Different Mandrel Types

<table>
<thead>
<tr>
<th>Mandrel Description</th>
<th>Cost of 8ft Section ($)</th>
<th>Weighted Cost Factor</th>
<th>Weighted Length Factor</th>
<th>Time to Manufacture 8ft Mandrel (hr)</th>
<th>Weighted Mandrel Manufacturing Factor</th>
<th>Time to Extract 8ft Mandrel from Carbon Fiber (hr)</th>
<th>Weighted Time to Extract Mandrel Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collapsible Mandrel</td>
<td>230</td>
<td>1.8</td>
<td>12</td>
<td>10</td>
<td>12</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>Foam Sheath on a Solid Cylinder</td>
<td>80</td>
<td>5.1</td>
<td>10</td>
<td>8</td>
<td>5</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>Foam and Acid</td>
<td>90</td>
<td>4.6</td>
<td>12</td>
<td>10</td>
<td>0</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td>Inflatable Bladder</td>
<td>110</td>
<td>3.7</td>
<td>12</td>
<td>10</td>
<td>7</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Aluminum Rigid Mandrel</td>
<td>41</td>
<td>10.0</td>
<td>12</td>
<td>10</td>
<td>0</td>
<td>10</td>
<td>7.5</td>
</tr>
<tr>
<td>Polycarbonate Rigid Mandrel</td>
<td>85</td>
<td>4.8</td>
<td>8</td>
<td>7</td>
<td>0</td>
<td>10</td>
<td>0.5</td>
</tr>
<tr>
<td>Polypropylene Rigid Mandrel</td>
<td>184</td>
<td>2.2</td>
<td>8</td>
<td>7</td>
<td>0</td>
<td>10</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Table 8-3. Estimated gap between carbon fiber spar and mandrel after curing.

<table>
<thead>
<tr>
<th>Mandrel Description</th>
<th>CTE (micro-inch/inch°F)</th>
<th>Mandrel Carbon Fiber Gap 70F to 250F For 2&quot; OD Mandrel</th>
<th>Mandrel Carbon Fiber Gap 70F to 250F For 3&quot; OD Mandrel</th>
<th>Smaller of the Two Gaps with a maximum of .0044</th>
<th>Weight Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collapsible Mandrel</td>
<td>NA</td>
<td>0.1</td>
<td>0.007</td>
<td>0.0044</td>
<td>10</td>
</tr>
<tr>
<td>Foam Sheath on a Solid Cylinder</td>
<td>NA</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Foam and Acid</td>
<td>NA</td>
<td>2</td>
<td>3</td>
<td>0.0044</td>
<td>10</td>
</tr>
<tr>
<td>Inflatable Bladder</td>
<td>NA</td>
<td>2</td>
<td>2</td>
<td>0.0044</td>
<td>10</td>
</tr>
<tr>
<td>Aluminum Rigid Mandrel</td>
<td>12.5</td>
<td>0.0016</td>
<td>0.0025</td>
<td>0.0016</td>
<td>3.6</td>
</tr>
<tr>
<td>Polycarbonate Rigid Mandrel</td>
<td>39</td>
<td>0.0064</td>
<td>0.0096</td>
<td>0.0044</td>
<td>10</td>
</tr>
<tr>
<td>Polypropylene Rigid Mandrel</td>
<td>48</td>
<td>0.008</td>
<td>0.012</td>
<td>0.0044</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 8-4. Summary of Trade Study Results

<table>
<thead>
<tr>
<th>10 = High Performance 1 = Low Performance</th>
<th>Cost</th>
<th>Mandrel Carbon Fiber Gap After Curing</th>
<th>Maximum Length</th>
<th>Time to Manufacture Mandrel</th>
<th>Time to Manufacture Carbon Fiber</th>
<th>Heat Deflection Temperature (Must be Above 275)</th>
<th>Safety</th>
<th>Reusability of Mandrel</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collapsible Mandrel</td>
<td>1.8</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>Pass</td>
<td>7</td>
<td>10</td>
<td>711</td>
<td></td>
</tr>
<tr>
<td>Foam Sheath on a Solid Cylinder</td>
<td>5.1</td>
<td>0</td>
<td>8</td>
<td>6</td>
<td>1</td>
<td>Pass</td>
<td>8</td>
<td>10</td>
<td>443</td>
</tr>
<tr>
<td>Foam and Acid</td>
<td>4.6</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>1</td>
<td>Pass</td>
<td>3</td>
<td>0</td>
<td>626</td>
</tr>
<tr>
<td>Inflatable Bladder</td>
<td>3.7</td>
<td>10</td>
<td>10</td>
<td>4</td>
<td>5</td>
<td>Pass</td>
<td>8</td>
<td>0</td>
<td>649</td>
</tr>
<tr>
<td>Aluminum Rigid Mandrel</td>
<td>10.0</td>
<td>3.6</td>
<td>10</td>
<td>10</td>
<td>7.5</td>
<td>Pass</td>
<td>7</td>
<td>10</td>
<td>717</td>
</tr>
<tr>
<td>Polycarbonate Rigid Mandrel</td>
<td>4.8</td>
<td>10</td>
<td>7</td>
<td>10</td>
<td>10</td>
<td>Pass</td>
<td>9</td>
<td>10</td>
<td>786</td>
</tr>
<tr>
<td>Polypropylene Rigid Mandrel</td>
<td>2.2</td>
<td>10</td>
<td>7</td>
<td>10</td>
<td>10</td>
<td>Pass</td>
<td>9</td>
<td>10</td>
<td>735</td>
</tr>
<tr>
<td>Weight Factor (total 100)</td>
<td>20</td>
<td>30</td>
<td>15</td>
<td>5</td>
<td>5</td>
<td>Pass/Fail</td>
<td>10</td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

Mandrel expansion has a maximum allowable value of 0.0044” because any value above this is unnecessary. This is based on the research of a senior project conducted in 2011 where a 5-foot spar was created using polypropylene as the mandrel with a 3/4” outer diameter.
Three spar sections were created using different orientations of unidirectional carbon fiber. The section with the highest CTE consisted of 5 layers of unidirectional with a thickness of 0.006” per layer. That layup pattern yielded a CTE of 15 micro-inch/inch°F. The carbon fiber cured at 250°F, so the change in radius of the carbon fiber was 0.0010” (assuming a room temperature of 70°F). The CTE of polypropylene is 48 micro-inch/inch°F, so its change in radius was 0.0032”. This yielded a final radial gap of 0.0022” between the carbon fiber and the mandrel. Because the mandrel easily slid out of the cured carbon fiber, it can be assumed that any gap larger than 0.0022 inches is unnecessary. For a safety factor, the gap is doubled. Using this reasoning, any gap larger than 0.0044” is unnecessary and therefore the trade study gap between the carbon fiber and mandrel was capped at 0.0044”.

The highest CTE laminate layup for the 2-inch outer diameter spar was 3.57 micro-inch/inch°F, which yielded a change in radius of 0.00068”. The highest CTE laminate layup for the 3-inch outer diameter spar was 3.31 micro-inch/inch°F, which yielded a change in radius of 0.000894”. The mandrel-carbon fiber gap for both cases was computed and the smaller of the two was selected for the trade study to ensure that the minimum gap encountered during production was the gap considered in the trade study. The reason the foam sheath on a solid mandrel was given a 0 for mandrel carbon fiber gap is because the foam compresses on the mandrel. The purpose of the foam is to decrease the force of the carbon fiber on the mandrel originating from the shrink tape. The foam compresses, taking some of the load of the carbon fiber that would have been a normal force exerted on the mandrel. However, even a small pressure exerted by the foam onto the mandrel will compound greatly along the length of the mandrel. The foam and acid mandrel was given a maximum mandrel carbon fiber gap because the acid melts out the mandrel entirely. The inflatable bladder was given a maximum mandrel carbon fiber gap because after curing, the bladder was deflated and taken out. The outer tube was then taken off by separating it into two separate pieces.

A large part of the manufacturing process of the spars was safety. Unfortunately, safety can be difficult to quantify. Correctly following the procedures and taking the necessary precautions drastically decreases the odds of an accident. Therefore, the trade study incorporated safety as a subjectively evaluated aspect.

The safest mandrels were the plastic rigid mandrels. These mandrels both received a score of 9 out of 10 because they did not have sharp burs that could cut the user. Additionally, they provided a large carbon-fiber-to-mandrel gap during the removal stage making it less likely for the user to harm him/her-self while extracting the mandrel. However, the main concern for the plastic mandrels is the glass transition point. The glass transition point is defined as the temperature at which the plastic begins to soften to a rubber-like state and loses stiffness. Therefore, it was imperative to choose plastics that have a high glass transition point temperature, such as polycarbonate or polypropylene, which can withstand the temperatures of 250°F. The melting point of plastics is always higher than the glass transition point, so melting is not the primary concern.

The mandrel with the next highest-rated safety was the foam sheath on a solid cylinder and inflatable bladder. These were given a score of 8 out of 10. The foam sheath acts as a barrier between the solid cylinder mandrel and the composite. During removal, the foam can suddenly release during the removal process, resulting in erratic and unpredictable movements
for those removing the cured composite part, which could lead to stumbling and injury. The inflatable bladder also received a safety score of 8 out of 10 due to the working process of inflatable bladders. The bladder expands to the desired formation and when curing is complete, the bladder deflates and the material is removed. Because an inflatable mandrel is a female mold, with the composite material on the inside of the mold, there could be difficulty in removing the cured composite.

The collapsible mandrel and the aluminum rigid mandrel received scores of 7 out of 10. The aluminum rigid mandrel did not receive a higher safety score simply because the carbon fiber gap after curing is extremely small. This small gap over a large distance (12 feet) would make it difficult to remove. The carbon fiber ends can cut hands during the removal process. Although inserting dry ice into the aluminum tube to achieve a greater temperature difference creates a larger gap between the mandrel and the spar, it would also lower the safety score as it is necessary to follow precautions when handling the dry ice. The collapsible mandrel also received a score of 7 out of 10 due to the potential difficulty of collapsing the mandrel in the middle of the spar. This method does provide a relatively easy and guaranteed method of removing the cured composite from the mandrel, but with the diameters ranging in size from 2 to 3 inches and in length from 8 to 12 feet, it might take a lot of force to collapse. Sticking fingers into the mandrel to try to make the mandrel collapse on itself is a serious safety concern.

The lowest scoring safety was the foam and acid at 3 out of 10. This was simply due to the handling of the acid and the requirement for having a large enough storage place for the acid. The acid should be strong enough to dissolve the foam but not strong enough to dissolve the storage of the bath or the carbon fiber spar. Numerous safety precautions would have to be enforced when placing and removing the spar from the acid bath. However, this method would produce the easiest results to remove the mandrel from the spar, but at great risk to those doing so.

8.3 Manufacturing Decisions

Carbon fiber parts are created using molds or mandrels. These tools dictate the shape of the part and provide structure during the curing process. In the case of manufacturing circular tubes, a cylindrical mandrel is used. There are three methods of constructing carbon fiber tubes: layup, resin infusion, and filament winding.

8.3.1 Layup

Layup can be done using either dry carbon cloth or pre-preg. Layup is the process of hand wrapping fiber strips directly onto the mandrel. The procedures for each differ and are detailed below.

8.3.1.1 Wet Layup

Wet layup is the process of applying successive layers of resin and dry sheets of carbon fiber. These sheets are cut into strips and then wrapped around the mandrel. The size of the strips is dictated by the diameter of the mandrel. Resin is applied with a hand brush and spread around the fiber using rollers to produce even coatings as shown in Figure 8-2.
Most types of liquid resin do not require elevated temperature, which means that varying thermal expansion properties in the carbon fiber will not affect the spar. The composite will cure at room temperature, so use of an autoclave (a machine that elevates temperature and pressure) or an oven is not required. During the curing process, the part can either be vacuum-bagged or wrapped in tape. This applies pressure to the part allowing it to maintain its shape and prevent shifting of the cloth strips. If done with tape, holes or slits must be cut into the tape to allow excess resin to escape. Failure to allow the excess resin to bleed out results in bulges of resin compiling between the tape seams. Vacuum-bagging produces a more consistent finish, as even pressure is ensured throughout the part during curing.

Wet layup is a difficult process to produce high-quality parts. The cloth is difficult to cut into straight and even sections and it stretches easily, deforming its shape. When wrapping the cloth around the mandrel, it is difficult to get even layering, as loose strands are often moved during the application and rolling of the resin.

8.3.1.2 Pre-preg
Pre-resin impregnated carbon fiber (or pre-preg) already has resin in the reinforcement. This eliminates separate bonding of the reinforcement and matrix material. Pre-preg layers can be cut and laid directly onto the mandrel (see Figure 8-3). Pre-preg sheets are stiffer than dry fabric and are easier to apply. It also improves part quality by ensuring more control of reinforcement and matrix contents.
To fully cure, pre-preg must be heated evenly for a set amount of time and temperature. This requires an oven to fully contain the entire section of spar. The largest autoclave available on campus is eight feet long. This means that if spar sections longer than eight feet are desired, a customized oven would need to be created.

Thermal heat transfer coefficients of multidirectional carbon fiber vary greatly between directions. This results in carbon fiber expanding and contracting non-uniformly as it changes temperatures creating stress concentrations or bowing in the spar section. The required heating also limits the mandrel selection to materials that can maintain rigidity during this process.

Since pre-preg layers have expiration dates and must remain refrigerated, companies often discard old rolls. Pre-preg is more expensive than dry cloth, but can be easily acquired. Strength tests on outdated pre-preg show that the strength properties are not greatly compromised and it would be acceptable to use outdated pre-preg since a high-risk situation is not anticipated.

8.3.2 Resin Infusion

Resin infusion is a similar process to wet layup. In this method, dry cloth strips or a braided sleeve is wrapped around the mandrel, using the same sequence as in the layup method. As seen in Figure 8-4, small amounts of resin are applied to keep the strips in place. Then the entire part is sealed in a vacuum bag. A vacuum is then introduced at one end of the tool and liquid resin is added through a hose at the other end. The vacuum pulls the resin across and through the layers of reinforcement. Once the resin has coated the entire part, the resin inlet is removed and the part is allowed to cure. The bagging is removed once curing is complete.
This is a very difficult process to set up, especially with the long pieces of tubing. As in wet layup, the dry cloth is difficult to work with and produces inconsistent results. With such a long part, the resin may not be applied evenly, and may end up thicker at the resin inlet end and thinner nearer the vacuum. This would cause inconsistencies in quality and mechanical properties of the part as well as variations in the part dimensions.

**8.3.3 Filament Winding**

Filament winding is an automated process done on a lathe or similar machinery. In filament winding, the mandrel is placed between two centers. Groups of individual strands of fiber are set up on the carriage. As the mandrel spins, the carriage moves horizontally along the mandrel, wrapping the strands around the mandrel, forming the layers of composite (Figure 8-5).

![Figure 8-5. Diagram of filament winding method.](image)

Filament winding splits into two categories: “wet winding” and “pre-preg winding”. In wet winding, the filament is pulled through liquid resin before spinning onto the mandrel. Pre-preg winding uses pre-preg fiber, eliminating the need for additional resin.

Filament winding is a fast process which is best used in large quantity productions. The Cal Poly campus did not have a functioning filament winding machine. Normal lathes require an extensive amount of conversion and special tooling to be capable of performing this process.

**8.3.4 Chosen Layup Method**

Pre-preg layup was chosen for the manufacturing process. Pre-preg has the most control of resin distribution. Although it requires monitoring during curing, it has the fastest set-up and run times. Pre-preg has the most repeatability in the process, and will provide the most consistent results, regardless of part dimensions.

Pre-preg layup is also the cheapest alternative. Filament winding and resin infusion require additional tooling and the pre-preg cloth may be acquired through donation or at discounted rates.
8.4 Spar Layup Process Decision

The manufacturing team was able to conduct two layup tests. A wet layup test and pre-preg test were performed to evaluate the feasibility of each process. Two-foot-long aluminum mandrels were selected for testing based on availability. A 3-inch outer diameter mandrel was used in the wet layup test and a 2-inch outer diameter mandrel was used in the pre-preg test. The results of all tests are discussed below.

8.4.1 Wet Layup

Figure 8-6 shows the result of the wet layup test. The entire process was messy and produced a low quality part.

For the wet layup test, fiberglass was used instead of carbon fiber. Although the material properties of fiberglass differ from carbon fiber, the wet layup process is the same.

First, a release agent was applied to the mandrel. Fiberglass was cut into appropriately-sized strips and wrapped around the mandrel. It was observed that unidirectional tape is very easy to cut to shape compared to bidirectional cloth. Once the strips were cut, the resin and hardener were mixed using a mixture ratio of 3:1. Masks and latex gloves were worn during the wet layup test. The resin acts as an irritant to skin and its fumes can be toxic. Working in a well-ventilated area is highly recommended.

Fiberglass layers tended to slide on the mandrel. Wrapping each layer individually around the tube at a slow rate helped overcome this issue. Distributing resin equally takes a large amount of effort. The laminate layup was [0/±45]. Electrical tape was wrapped around the fiberglass to compress it and to keep the shape of the mandrel. Holes were created in the tape to allow any excess resin to escape. The part required about four hours of curing. Once it cured, the electrical tape was unraveled and the aluminum mandrel was extracted. Upon inspection of
the final part, it was observed that there was an excess amount of resin that cured onto the fiberglass, making the surface very lumpy and uneven. The fiberglass was stuck to the mandrel because the coefficient of thermal expansion for the aluminum and fiberglass were very similar. There was little to no gap between the cured fiberglass and the aluminum. The only way to remove the fiberglass from the mandrel was to cut the part.

It was concluded that the wet hand layup method produces low quality parts and requires long manufacturing times.

8.4.2 Pre-preg

Figure 8-7 shows the result of the pre-preg test. This test was considered successful and was chosen as the spar manufacture method.

Unidirectional carbon fiber tape was used for this test. The laminate layup was [90/0]. Release agent was applied to the 2-inch mandrel. Pre-preg is typically stored in a freezer. The strips were blasted with a heat gun until they were sticky, which made it easier to wrap around the mandrel. Once the layers were completed, shrink tape was wrapped around the mandrel with a 50% overlap. The curing was done using the composites lab autoclave. The temperature ramped up to 250°F for an hour, held at that temperature for an hour, and the ramped down for 45 minutes. The part was then extracted from the autoclave, shrink tape was removed and the finished product was visually inspected to be superior to fiberglass. An advantage to the pre-preg process is a much more even distribution of resin layers compared to wet layup. However, the carbon fiber did not immediately separate from the mandrel. It was left for 5 days and then was removed from the aluminum mandrel with difficulty. The most probable explanation for the difficulty in removing the mandrel is the coarse finish of the mandrel.
Pre-preg is the superior manufacturing method. It gives more control over layer stacking and resin is distributed evenly. Pre-preg is also much cleaner than wet layup and less hazardous.

8.1 Mandrel

A mandrel is the object that gives carbon fiber its shape. Because the spars are circular tubes, the mandrel must be cylindrical. There are two types of mandrels, male and female. The outer surface of the male mandrel is used to shape the carbon fiber whereas the inside surface of the female mandrel is used. An example of a male mandrel is a solid rod wrapped in carbon fiber. An example of a female mandrel is a tube with carbon fiber lining the inside. The main challenge of creating a carbon fiber tube is extracting the mandrel from the cured carbon fiber. The spars will be 12 feet or longer and any interference between the cured carbon fiber and the mandrel will make it extremely difficult to extract the mandrel. Five types of mandrels were considered for the Phase I spars:

8.1.1.1 Collapsible Mandrel

As the name implies this mandrel can be collapsed for removal after the curing process has been completed. A mechanism inside is actuated (see Figure 8-8), causing one of the two lips on the mandrel to fold inward. This creates a gap between the cured carbon fiber and the mandrel.

![Figure 8-8. Collapsible mandrel.](image)

The advantages are that it is rigid and guaranteed to remove from the cured part. However, it is difficult and expensive to make.

8.1.1.2 Foam Sheath on a Solid Cylinder

For this method, a thin foam sheath is placed over a lubricated ridged cylinder such as an aluminum tube (see Figure 8-9). Pressure from the carbon fiber onto the mandrel (originating from the shrink tape) makes it difficult to extract a mandrel from the cured carbon fiber. However, with a compressible foam layer separating the two it could be easier to separate the mandrel from the cured carbon fiber. After the carbon fiber has cured, the lubricated cylinder is removed from the foam. With the cylinder removed the foam can be bent inward and slid out.

![Figure 8-9. Foam sheath on a solid mandrel.](image)
This mandrel is cheap and rigid in the axial direction. However, the force of foam on the inner rigid mandrel could make it difficult to extract from cured carbon fiber. Also, unequal compression of foam could result in variable outer diameter.

### 8.1.1.3 Foam and Acid

The mandrel is made of solid foam as shown in Figure 8-10. After the carbon fiber has cured, a solvent that dissolves the foam but not the carbon fiber or epoxy is poured in and the mandrel melts out.

![Figure 8-10. Foam mandrel.](image)

There is a guarantee of mandrel extraction and this method is cost-effective. But there is minimal axial rigidity and the acid has the potential to damage the spar. This method is also dangerous and hazardous to environment.

### 8.1.1.4 Inflatable Bladder

For this method, a bladder is inflated to provide a shape upon which to wrap carbon fiber. The bladder wrapped in carbon fiber is then slid into a tube using a slip fit. The bladder is then inflated to a higher pressure, which presses the carbon fiber against the inside of the tube. The tube is a two-part mandrel consisting of a tube that has been cut down its axis and held together by a hose clamp or tape. To extract the carbon fiber, the hose clamp or tape is taken off and the mandrel comes off of the carbon fiber in two pieces.

![Figure 8-11. CAD model of an inflatable bladder mandrel.](image)

This mandrel type allows for easiest spar extraction because the bladder can change its shape. However, custom-made bladders will be expensive and difficult to find.

### 8.1.1.5 Rigid Mandrel

The mandrel is a simple cylinder made of a rigid material such as aluminum or plastic without a taper or an outer coating of foam. The mandrel must have a higher coefficient of thermal expansion (CTE) than the carbon fiber. This difference in CTE combined with the room temperature and curing temperature differential creates a gap between the cured carbon fiber and the mandrel. This method is very simple, but as the surface area of the mandrel increases, the harder it can be to get the cured carbon fiber off of the mandrel. The larger the CTE difference, the larger the gap and the easier the mandrel is to extract from the cured carbon fiber.
Rigid mandrels are relatively cheap. They will also maintain rigidity during each manufacturing phase. However, removal from the cured part is not guaranteed and may be difficult or impossible if the laminate layup's CTE is not properly designed.

8.2 Mandrel Tests

While the trade study proved worthwhile and provided a conclusive decision to mandrel choice, polypropylene and aluminum mandrels were tested to determine feasibility and quality of spar produced. The mandrel that produces the highest quality spar and separates from the spar easily will be the mandrel used in the full manufacture of all spars.

8.2.1 Polypropylene

A 4-foot long test spar shown in Figure 8-13 was built using a 2-inch diameter polypropylene mandrel. Teflon cloth was used in place of a release agent on the polypropylene mandrel. The layup was cured in a homemade oven at 260°F through the generosity of Kirke Leonard. Oven warm-up, part curing, and part cool-down took approximately three hours. The 4-foot long part was easy to remove from the polypropylene mandrel; the part separated from the mandrel with almost no applied effort. However, through visual inspection, it was determined that the polypropylene mandrel deflected while curing and created a bow in the spar. The part was cured at 260°F, which is 10°F greater than the recommended curing temperature. It was determined that this elevated temperature partially caused the polypropylene mandrel to deflect as there was uneven support on the mandrel when placed in the oven as it was placed on elevated straps.

Bowed spars are unacceptable. They can lead to problems when interfacing with other spars and other helicopter components. It was determined that the full-sized spars will not be manufactured using polypropylene mandrels because of the likelihood of producing bowed spars.
8.2.2 Aluminum

The results of the pre-preg layup tests showed that removing a cured composite from an aluminum tube is difficult. It was hypothesized that the rough surface of the aluminum mandrel caused resin from the carbon fiber to flow and harden in the dents and dings of the surface. A “shaft key” is effectively formed, preventing motion between the cured spar and the aluminum mandrel. To prevent keys from forming, the surface of the aluminum mandrel must be smooth, as shown in Figure 8-14.

![Figure 8-14. Unfinished mandrel (above) and sanded mandrel (below).](image)

Shown in Figure 8-15, a rotisserie-like tool was manufactured to assist in sanding the mandrel and wrapping carbon fiber. The aluminum mandrel is fitted with plugs on both sides of the tube. The plugs are interference-fit with the aluminum mandrel and mounted to metal rods that are able to rotate on the rotisserie. One user inputs a rotary motion through a handle that causes the aluminum mandrel to rotate. The tool saved hundreds of man-hours of sanding and wrapping and prevented debris from accumulating on the carbon fiber while wrapping. The rotisserie also allowed for a more even finish of the unidirectional layers of carbon fiber.

![Figure 8-15. Rotisserie jig for sanding and wrapping carbon fiber.](image)
To sand the aluminum mandrel, a single user inputted a rotary motion to the handle while other users held emery cloth to the surface of the mandrel. The relative motion between the aluminum surface and the emery cloth resulted in a sanded surface. Figure 8-16 shows the sanding process.

![Figure 8-16. Wet-sanding an aluminum mandrel.](image)

The sanding occurred in three stages. First, a coarse-grit emery cloth was applied to the mandrel. The users holding the emery cloth to the aluminum surface traversed the length of the aluminum mandrel in the course of 15 minutes. The surface of the mandrel was inspected for any deep dents or cuts that required brief and intense local sanding. Next, 320-grit wet sandpaper was applied to the aluminum surface. An additional user was required to supply water to the surface of the mandrel. The water kept the aluminum surface and sandpaper wet while removing aluminum chips. Again, users traversed the length of the aluminum tube. Finally, 600-grit wet sandpaper was used to finish the aluminum surface. Between two users, a single mandrel requires two hours to completely finish.

The aluminum mandrel separated easily after curing a 14-foot section of carbon fiber with seven layers of unidirectional cloth. The resulting carbon fiber spar was straight with no bow. It was determined that aluminum mandrels were to be used for spar manufacturing.
# Appendix B - Drawings

## Itemized List

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**NOTE:**

1. DIMENSIONS ARE IN FEET.
NOTES:

1. GENERAL CARBON FIBER LAY-UP IS [0°/±45°]_2
2. ADDITIONAL CARBON FIBER ON ENDS IS [90°]_2
3. CARBON FIBER IS NCT 301 34-700 35% RC UNIDIRECTIONAL TAPE WITH .006 INCH CURE THICKNESS
4. MANDREL USED IS ALUMINUM 6061-T6 15 FEET LONG AND 3 INCH OD Sanded WITH 600 GRIT SANDPAPER
5. CARBON FIBER CURES AT 250°F FOR 60 MIN
NOTES:
1. GENERAL CARBON FIBER LAY-UP IS [0°/±45°/90°]
2. ADDITIONAL CARBON FIBER ON ENDS IS [90°]
3. CARBON FIBER IS NCT 301 34-700 25% RC UNIDIRECTIONAL TAPE WITH .006 INCH CURE THICKNESS
4. MANDREL USED IS ALUMINUM 6061-T6 15 FEET LONG AND RINSED IN SANTOPUR W/ 3M SILICON CARBIDE PAPER
5. CARBON FIBER CURES AT 250°F FOR 60 MIN
NOTES:
1. GENERAL CARBON FIBER LAY-UP IS [0°/(+45°)]
2. ADDITIONAL CARBON FIBER ON ENDS IS [90°]
3. CARBON FIBER IS NCT 301 34-700 38% RC UNIDIRECTIONAL TAPE WITH 0.006 INCH CURE THICKNESS
4. MANDREL USED IS ALUMINUM 6061-T6 1.5 FEET LONG AND 3 INCH OD Sanded WITH 1000 GRIT SANDPAPER
5. CARBON FIBER CURES AT 250°F FOR 60 MIN

SECTION A-A SCALE 1:4

CARBON FIBER LAYER CUTTING SCHEDULE

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DWG SPAR R3
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2. ADDITIONAL CARBON FIBER ON ENDS IS [90°]
3. CARBON FIBER IS NCT 201 34-700 25% RC UNIDIRECTIONAL TAPE WITH .006 INCH CURE THICKNESS
4. MANDREL USED IS ALUMINUM 6061-T6 15 FEET LONG AND 3 INCH OD Sanded WITH 600 Grit Sandpaper
5. CARBON FIBER CURES AT 250°F FOR 60 MIN
NOTES:
1. GENERAL CARBON FIBER LAY-UP IS [0°/±45°].
2. ADDITIONAL CARBON FIBER ON ENDS IS [90°].
3. CARBON FIBER IS NOT 301-34-700-355.0 RC UNIDIRECTIONAL TAPE WITH 0.005 INCH CURE THICKNESS.
4. MANDREL USED IS ALUMINUM 6061-T6, 15 FEET LONG, AND 3 INCH OD Sanded WITH 600 GRIT SANDPAPER.
5. CARBON FIBER CURES AT 250°F FOR 60 MIN.

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CARBON FIBER LAYER CUTTING SCHEDULE

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NOTES:

1. GENERAL CARBON FIBER LAY-UP IS [0°,/(±45°)],
2. ADDITIONAL CARBON FIBER ON ENDS IS [90°]
3. CARBON FIBER IS NOT 301 34-700 35% RC UNIDIRECTIONAL TAPE WITH .006 INCH CURE THICKNESS
4. MANDREL USED IS ALUMINUM 6061-T6 15 FEET LONG AND 3 INCH OD Sanded WITH 600 GRIT SANDPAPER
5. CARBON FIBER CURVES AT 250°F FOR 60 MIN

ISOGRAPHIC SCALE 1:32

SECTION A-A
SCALE 1:4

DETAIL B
SCALE 1:1

CARBON FIBER CUTTING SCHEDULE

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NOTES:
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2. CARBON FIBER IS NCT 301 34-700 35% RC UNIDIRECTIONAL TAPE WITH .006 INCH CURE THICKNESS
3. PART 822-1 IS MADE USING MANDREL PART 842-2
4. CARBON FIBER CURES AT 250°F FOR 60 MIN

SECTION A-A
SCALE 1:4

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NOTE:
1. SLIT IN DETAIL A ALLOWS FOR HOSECLAMP CRIMPING

DETAIL A
SCALE 1:2

Ø2.500 ± .005

Ø2.375 ± .010

.063 ± .010

.50 ± .10

24.00 ± .10
NOTES:
1. INSIDE AND OUTSIDE DIAMETERS MAY HAVE TO BE SANKED AFTER MACHINING TO FIT APPROPRIATELY ON SPAR

\[ \varnothing 2.350 \pm 0.005 \]
\[ \varnothing 2.170 \pm 0.005 \]
\[ .75 \pm 0.10 \]

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NOTES:

1. INSIDE AND OUTSIDE DIAMETERS MAY HAVE TO BE Sanded AFTER MACHINING TO FIT Appropriately ON SPAR

2. PART DR41-1 IS ADHERED TO PART DR823-1 USING A TWO-PART EPOXY

---

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INTERPRET GEOMETRIC TOLERANCES AS:

- G.A.
- COMMENTS:

MATERIAL:

POLYPROPYLENE

NEXT ASSY | USED ON
---|---

PROGRAM | DO NOT SCALE DRAWING

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10 Appendix C – Detailed Supporting Analysis

The analysis of the spar properties was organized into three levels of complexity: basic, intermediate, and advanced. Each level of complexity reflects the amount of detail in the calculations, the understanding of the mechanical properties, and how closely the model follows the actual spar behavior.

As a first iteration, beam theory from mechanics of materials was applied to the spars. The spars were modeled as cantilever beams. Shear and bending forces resulted from vertical loads caused by the distributed mass of the spars and rotors and the lift force. The lift and drag forces applied by the rotors create a torque on the spar if the aerodynamic center was not aligned with the axis of the spar.

The first model was based on several simplifying assumptions. Guy-wire forces acting on the spars were neglected. By ignoring these forces, the number of unknowns in calculations was decreased. It was assumed that the spars have no carbon fiber sleeves. In its current design, the green and yellow rotors on the helicopter did not generate appreciable lift forces. Therefore, the lift is generated by the red and blue rotors. Figure 10-1 shows a free body diagram of a red or blue spar. It was assumed that the total lift force $L$ is equal to the total weight of the helicopter and rider, $W$, with an assumed rider weight of 130 lb. The total weight of the helicopter and rider was 220 lb, and if only the blue and red rotors generated lift, each rotor generated lift equal to half of the combined weight of the helicopter and rider.

The spar assembly was rotating at 10 rpm. It was assumed that the helicopter was at steady-state, which meant that the total lift force is equal to the total weight force. It was assumed that the helicopter was hovering just above the ground, so there was no normal force acting on the cockpit of the helicopter. Finally, it was assumed that the loading of the spar occurs in two dimensions, which meant there were no forces perpendicular to the plane of the free body diagram; drag forces are disregarded. In the first basic model, only the red and blue spars were considered; but for analysis concerning the green and yellow spars, additional dynamic forces due to the rotating propellers would be neglected.
The figure above shows a detailed free body diagram that was more accurate to the actual forces acting on the spars compared to the free body diagram in Figure 10-1. The spar was rotating about the y-axis at steady state. \( L_1 \) through \( L_4 \) denote the lengths of the spar sections. \( \omega_1 \) through \( \omega_4 \) are the distributed weight loads of the spars and rotors. These weight loads were assumed to be uniform. For the spars, this assumption was valid because each section of spar had a uniform outside diameter, a single thickness, and was constructed from Aluminum 6061-T6, an isotropic material. However, for the rotors, it was not likely that the uniform load assumption was valid. The rotors changed in cross-sectional area along the x-axis of the spars. Because the rotors changed in cross-sectional area, they also change in chord length and planform area, which meant that the lift load, \( \omega_L \), was not uniform. Despite these discrepancies in the model, analysis of the spars was carried out.

The purpose of the free body diagram was to solve for the bending moment \( M \) and the shearing force \( P \) within the beam. The maximum bending moment occurred at the rotational axis and the maximum shear force occurred at the end of the length of the first spar, \( L_1 \). Shown in section 10.1 are the results of an EES code written to calculate the bending moment \( M \) and shearing force \( P \) at the rotational axis. The calculations yielded a maximum bending moment of approximately 6100 lb-ft and a maximum shearing force of 100 lb. An additional calculation was made to determine the bending stress at the rotational axis of the hub, which was 133 ksi. Since the ultimate tensile strength of aluminum is only 35 ksi, it was apparent that the calculated bending stress was unrealistic and that too many simplifying assumptions were made. Neglecting the guy-wires and the carbon fiber sleeves were what caused the model to fail--the guy-wire forces are significant and the carbon fiber sleeves provide stiffness and strength. According to Neal Saiki, the guy-wires supported a tension load of 600 lb. It was also probable that the carbon fiber sleeves supported a portion of the loading.

Because the results of the first model were unreliable, Dr. Joseph Mello was consulted to help carry out the calculations. To begin, it was assumed that if the factor of safety in the aluminum spars is 1.0, the aluminum was about to yield because of the loading on the spar. It was assumed that the shearing forces in the beam were small and can be neglected. The maximum allowable bending moment is approximately 8.7 kip-in.
At this point, it was decided that the bending stiffness and torsion stiffness of the new carbon fiber spars must match or exceed the stiffness of the aluminum spars. The bending stiffness must be matched because the helicopter cannot experience excess coning (blade bending upwards due to centripetal and lift forces); the lifting force should not diminish because of coning. The torsional stiffness must be matched because it is possible that the aerodynamic centers of the rotors are offset of the axis of the spar. If this is the case, the rotors would impart a torque onto the spar, which would change the angle of attack of the rotors and diminish the lifting force. Also, the torsional stiffness must be matched because excessive torque could cause the controls system of the helicopter to become unstable. For these reasons, it was important that both of the stiffnesses matched or exceeded the stiffness of the aluminum spars.

Dr. Mello wrote two programs in MATLAB using lamination theory that compute the bending and torsional stiffness as well as the coefficient of thermal expansion of a given layup based on the outer diameter of the spar. The MATLAB codes and results are shown in section 10.2.

### 10.1 EES Code and Results

File:C:\Users\Sterling\Desktop\SparFBDs.EES 6/7/2013 19:14:14 Page 1

EES Ver. 9.210: #552: For use by Mech. Engin. Students and Faculty at Cal Poly

"Spar Bending Analysis - One Side of Red-Blue Spar"

"gc = 386.088 [in/s^2]
Conv_lbmlbf = 386.088 [lb_m-in/lb_f-s^2]
E = 10E+6 [lb_f/in^2] "Elastic Modulus of aluminum"
rho = 0.0975 [lb_m/in^3] "Density of 6061 Aluminum"
W_rider = 135 [lb_f] "assumed weight of human powering the helicopter"
W_cockpit = 12.75 [lb_f] "weight of cockpit"
W_propspar = 7.816 [lb_f] "weight of spar and rotor with propeller. This spar/rotor does not generate any lift force"
W_load = 1/2*(W_rider + W_cockpit) + W_propspar "weight of load taken by 1/2 wing"
OMEGA= 10.4*1/60*2*pi "Rotor rotation speed"

"Spar Geometry and Weight"
L_1 = 144 [in] "Length of spar closest to rotational axis"
L_2 = 144 [in] "Length of spar with largest piece of foam"
L_3 = 144 [in] "Length of spar with medium piece of foam"
L_4 = 90 [in] "Length of spar with smallest piece of foam"
t_1 = 0.035 [in] "Thickness of spar closest to rotational axis"
t_2 = 0.028 [in] "Thickness of spar with largest piece of foam"
t_3 = 0.028 [in] "Thickness of spar with medium piece of foam"
t_4 = 0.028 [in] "Thickness of spar with smallest piece of foam"
D_o_1 = 3 [in] "Outer diameter of spar closest to rotational axis"
D_o_2 = D_o_1 "Outer diameter of spar with largest piece of foam"
D_o_3 = 2.5 [in] "Outer diameter of spar with medium piece of foam"
D_o_4 = 2 [in] "Outer diameter of spar with smallest piece of foam"
D_i_1 = D_o_1 - 2*t_1 "Inner diameter of spar closest to rotational axis"
D_i_2 = D_o_2 - 2*t_2 "Inner diameter of spar with largest piece of foam"
D_i_3 = D_o_3 - 2*t_3 "Inner diameter of spar with medium piece of foam"
D_i_4 = D_o_4 - 2*t_4 "Inner diameter of spar with smallest piece of foam"
MOI_1= pi/64*(D_o_1^4 - D_i_1^4) "Area moment of inertia of bare tube"
MOI_2= pi/64*(D_o_2^4 - D_i_2^4) "Area moment of inertia of spar, large foam"
MOI_3= pi/64*(D_o_3^4 - D_i_3^4) "Area moment of inertia of spar, medium foam"
MOI_4= pi/64*(D_o_4^4 - D_i_4^4) "Area moment of inertia of spar small foam"
\[ \text{Vol}_1 = \frac{\pi}{4}(D_{o_1}^2 - D_{i_1}^2) \cdot L_1 \] "Volume of spar closest to rotational axis. Does not include holes."

\[ \text{Vol}_2 = \frac{\pi}{4}(D_{o_2}^2 - D_{i_2}^2) \cdot L_2 \] "Volume of spar with largest piece of foam"

\[ \text{Vol}_3 = \frac{\pi}{4}(D_{o_3}^2 - D_{i_3}^2) \cdot L_3 \] "Volume of spar with medium piece of foam"

\[ \text{Vol}_4 = \frac{\pi}{4}(D_{o_4}^2 - D_{i_4}^2) \cdot L_4 \] "Volume of spar with smallest piece of foam"

\[ W_1 = \text{Vol}_1 \cdot \rho \cdot g \cdot c \cdot \text{Conv}_{lbmlbf} \] "Weight of spar closest to rotational axis"

\[ W_2 = \text{Vol}_2 \cdot \rho \cdot g \cdot c \cdot \text{Conv}_{lbmlbf} \] "Weight of spar with largest piece of foam"

\[ W_3 = \text{Vol}_3 \cdot \rho \cdot g \cdot c \cdot \text{Conv}_{lbmlbf} \] "Weight of spar with medium piece of foam"

\[ W_4 = \text{Vol}_4 \cdot \rho \cdot g \cdot c \cdot \text{Conv}_{lbmlbf} \] "Weight of spar with smallest piece of foam"

\[ W_{\text{spar}} = W_1 + W_2 + W_3 + W_4 \] "Total weight of spar"

\[ W_{f_2} = 5.33 \ [lb_f] \] "Weight of foam and sleeve on spar with largest foam piece."

\[ W_{f_3} = 4.52 \ [lb_f] \] "Weight of foam and sleeve on spar with medium foam piece."

\[ W_{f_4} = 1.80 \ [lb_f] \] "Weight of foam and sleeve on spar with smallest foam piece."

\[ W_{\text{rotor spar}} = W_1 + W_2 + W_3 + W_4 + W_{f_2} + W_{f_3} + W_{f_4} \] "Weight of rotor and spar under analysis"

"Inertias"

\[ \omega_{s_1} = \frac{W_1}{L_1} \] "Weight of spar per unit length. Closest to rotational axis"

\[ \omega_{s_2} = \frac{W_2}{L_2} \] "Weight of spar per unit length. Large foam"

\[ \omega_{s_3} = \frac{W_3}{L_3} \] "Weight of spar per unit length. Medium foam"

\[ \omega_{s_4} = \frac{W_4}{L_4} \] "Weight of spar per unit length. Small foam"

\[ I_{s_1} = \frac{1}{12}W_1/gc \cdot \text{Conv}_{lb} \cdot L_1^2 \] "Moment of inertia of first spar about its center of mass"

\[ I_{s_2} = \frac{1}{12}W_2/gc \cdot \text{Conv}_{lb} \cdot L_2^2 \] "Moment of inertia of second spar about its center of mass"

\[ I_{s_3} = \frac{1}{12}W_3/gc \cdot \text{Conv}_{lb} \cdot L_3^2 \] "Moment of inertia of third spar about its center of mass"

\[ I_{s_4} = \frac{1}{12}W_4/gc \cdot \text{Conv}_{lb} \cdot L_4^2 \] "Moment of inertia of fourth spar about its center of mass"

\[ \omega_{f_2} = \frac{W_{f_2}}{L_2} \] "Weight of foam per unit length. Large foam. FIRST GUESS. Assumes uniform distribution, covers entire spar."

\[ \omega_{f_3} = \frac{W_{f_3}}{L_3} \] "Weight of foam per unit length. Medium foam. FIRST GUESS."

\[ \omega_{f_4} = \frac{W_{f_4}}{L_4} \] "Weight of foam per unit length. Small foam. FIRST GUESS. Does not account for tapered ends."

\[ \omega_{\text{lift} 2} = \frac{W_{\text{load}}}{3/L_2} \] "Lifting force on large foam spar"

\[ \omega_{\text{lift} 3} = \frac{W_{\text{load}}}{3/L_3} \] "Lifting force on medium foam spar"

\[ \omega_{\text{lift} 4} = \frac{W_{\text{load}}}{3/L_4} \] "Lifting force on small foam spar"

"Guy wire forces and angles"

"FBD - MAD - cut taken about rotational axis and statics performed on each spar section"

\[ W_{\text{lg}_1} = 0.55 \] "Weight of large landing gear"

\[ W_{\text{lg}_2} = 0.5 \] "Weight of small landing gear"

\[ F_{g_w} = 80 \] "Tension in white guy wire"

\[ F_{g_o} = 200 \] "Tension in orange guy wire"

\[ F_{g_r} = 200 \] "Tension in red guy wire"

\[ \theta_1 = 22^{\circ} \] "Angle between white guy wire and first spar"

\[ \theta_2 = 24^{\circ} \] "Angle between orange guy wire and first spar"

\[ \theta_3 = 18.5^{\circ} \] "Angle between red guy wire and second spar"

\[ \theta_4 = 23^{\circ} \] "Angle between white guy wire and second spar"

\[ \theta_5 = 23^{\circ} \] "Angle between red guy wire and third spar"

\[ \theta_A = 68^{\circ} \] "Angle between white guy wire and first landing gear"

\[ \theta_C = 72.5^{\circ} \] "Angle between red guy wire and second landing gear"

"Base Spar"

\[ y_0 + F_{s_1} - F_{g_w} \cdot \sin(\theta_1) - F_{g_o} \cdot \sin(\theta_2) - \omega_{s_1} \cdot L_1 = 0 \] "Sum forces in y direction"

\[ x_0 + F_{g_w} \cdot \cos(\theta_1) - F_{g_o} \cdot \cos(\theta_2) + x_1 = 0 \] "Sum forces in x direction"

\[ M_0 + M_{s_1} + F_{s_1} \cdot L_1 - F_{g_o} \cdot \sin(\theta_2) \cdot L_1 - \omega_{s_1} \cdot L_1^2 = 0 \] "Sum moments about origin"

"Large Foam Spar"

\[ F_{r_{lg_1}} + F_{s_2} - F_{s_1} - W_{lg_1} - F_{g_r} \cdot \sin(\theta_3) - \omega_{s_2} \cdot L_2 - \omega_{f_2} \cdot L_2 + (\omega_{\text{lift} 2} \cdot L_2) = 0 \] "Sum
forces in y direction"
\( F_{g \_r \_cos(\theta_3)} - F_{g \_w \_cos(\theta_4)} \times \_1 + \_2 = (W_2+W_f \_2)\_\text{Conv\_lbmlbf/gc} \times (L_1 + L_2/2)\_\text{OMEGA}\_2/ \)
\text{Conv\_lbmlbf}

"sum forces in x direction"
\(-M \_s \_1 + M \_s \_2 - F \_g \_w \_sin(\theta_4) \_L \_2 + F \_s \_2 \_L \_2 - \_omega \_s \_2 \_L \_2^\_2 \_L \_2/2 - \omega \_f \_2 \_L \_2^\_2 \_L \_2/2 + (\omega \_lift \_2 \_L \_2/2) \
\_L \_2\_L \_2/2 = 0 "sum moments about origin"

"Medium Foam Spar"
\(-F \_r \_lg \_2 + F \_s \_3 - W \_lg \_2 - F \_s \_2 - F \_g \_r \_sin(\theta_5) - \_omega \_s \_3 \_L \_3 - \_omega \_f \_3 \_L \_3 + (\omega \_lift \_3 \_L \_3) = 0 "sum forces in y direction"
\(-x \_2 + x \_3 - F \_g \_r \_cos(\theta_5) = (W_3+W_f \_3)\_\text{Conv\_lbmlbf/gc} \times (L_1 + L_2 + L_3/2)\_\text{OMEGA}\_3/ \text{Conv\_lbmlbf}

"Small Foam Spar"
\(-x \_4 = 0 "sum forces in y direction"
\(-F \_s \_3 - \_omega \_s \_4 \_L \_4 = -F \_g \_r \_cos(\theta_5) - \omega \_s \_4 \_L \_4 + (\omega \_lift \_4 \_L \_4) = 0 "sum moments about origin"

"Large Landing Gear"
\(-2 \times F \_g \_w \_cos(\theta_A) - F \_r \_lg \_1 = 0 "sum forces in y direction"

"Small Landing Gear"
\(-2 \times F \_g \_r \_cos(\theta_C) - F \_r \_lg \_2 = 0 "sum forces in y direction"

"Mechanics of Materials"
\( \Sigma \_\text{allowable} = \frac{\Sigma \_\text{allowable} \times \text{MOI}_1}{(D_o \_1/2)} \)
\( \Sigma \_1 = M \_0 \times (D_o \_1/2)/(\text{MOI}_1) \)

"Deflections - Shigley's Mechanical Engineering Design"

"Deflection of Bare Spar tip"
\( \delta \_11 = -(-F \_s \_1 + F \_g \_o \_sin(\theta_2))/(3 \times E \times \text{MOI}_1) \)
\( \delta \_12 = \_omega \_s \_1/(8 \times E \times \text{MOI}_1) \)
\( \delta \_13 = M \_s \_1/(2 \times E \times \text{MOI}_1) \)
\( \theta \_s \_1 = -(-F \_s \_1 + F \_g \_o \_sin(\theta_2)) \times (L_1)^2/(6 \times E \times \text{MOI}_1) - 8 \times (- \omega \_s \_1)^3/(12 \times E \times \text{MOI}_1) + M \_s \_1 \times (E \times \text{MOI}_1) \)
\( \delta \_s \_1 = \delta \_11 + \delta \_12 + \delta \_13 \)

"Deflection of Large Foam Spar tip"
\( \delta \_21 = -(-F \_s \_2 + F \_g \_w \_sin(\theta_4)) \times (L_2)^3/(3 \times E \times \text{MOI}_2) \)
\( \delta \_22 = \_omega \_s \_2 \times (L_2)^4/(8 \times E \times \text{MOI}_2) \)
\( \delta \_23 = M \_s \_2 \times (L_2)^2/(2 \times E \times \text{MOI}_2) \)
\( \theta \_s \_2 = -(-F \_s \_2 + F \_g \_w \_sin(\theta_4)) \times (L_2)^2/(6 \times E \times \text{MOI}_2) - 8 \times (- \omega \_s \_2 \_L_2^3)/(12 \times E \times \text{MOI}_2) + M \_s \_2 \_L_2^2/(E \times \text{MOI}_2) \)
\( \delta \_s \_2 = \theta \_s \_2 \times L_2 + \delta \_s \_1 + \delta \_21 + \delta \_22 + \delta \_23 \)

"Deflection of Medium Foam Spar tip"
\( \delta \_31 = -(-F \_s \_3 + F \_g \_r \_sin(\theta_5)) \times (L_3)^3/(3 \times E \times \text{MOI}_3) \)
\( \delta \_32 = \_omega \_s \_3 \_L_3^4/(8 \times E \times \text{MOI}_3) \)
\( \delta \_33 = M \_s \_3 \_L_3^2/(2 \times E \times \text{MOI}_3) \)
\( \theta \_s \_3 = -(-F \_s \_3 + F \_g \_r \_sin(\theta_5)) \times (L_3)^2/(6 \times E \times \text{MOI}_3) - 8 \times (- \omega \_s \_3 \_L_3^3)/(12 \times E \times \text{MOI}_3) + M \_s \_3 \_L_3^2/(E \times \text{MOI}_3) \)
\( \delta \_s \_3 = \theta \_s \_2 \_L_3 + \delta \_s \_2 + \delta \_31 + \delta \_32 + \delta \_33 \)
"Deflection of Small Foam Spar tip"

\[
\begin{align*}
\delta_{41} &= 0 \\
\delta_{42} &= -(\omega_s - \omega_{lift,4})^4 / (8E \cdot \text{MOI}_4) \\
\delta_{43} &= 0 \\
\delta_{s,4} &= \delta_{s,3} + \delta_{41} + \delta_{42} + \delta_{43}
\end{align*}
\]

**SOLUTION**

**Unit Settings: Eng F psia mass deg**

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74
$\omega_{f,1} = 0.03139 \text{ [lb/in]}
\omega_{f,4} = 0.02 \text{ [lb/in]}
\omega_{s,2} = 0.1891 \text{ [lb/in]}
\omega_{s,3} = 0.1891 \text{ [lb/in]}
\omega_{s,4} = 0.3026 \text{ [lb/in]}
\omega_{s,1} = 0.03179 \text{ [lb/in]}
\rho = 0.0975 \text{ [lb/m^3/in]}
\sigma_1 = -25562 \text{ [lb/in^2]}
\sigma_{allowable} = 40000 \text{ [lb/in^2]}
\theta_1 = 22 \text{ [deg]}
\theta_2 = 24 \text{ [deg]}
\theta_3 = 18.5 \text{ [deg]}
\theta_4 = 23 \text{ [deg]}
\theta_5 = 23 \text{ [deg]}
\theta_A = 68 \text{ [deg]}
\theta_c = 72.5 \text{ [deg]}
\theta_{s,1} = 0.1894 \text{ [rad]}
\theta_{s,2} = -0.08389 \text{ [rad]}
\theta_{s,3} = 0.1886 \text{ [rad]}
t_1 = 0.035 \text{ [in]}
t_2 = 0.028 \text{ [in]}
t_3 = 0.028 \text{ [in]}
t_4 = 0.028 \text{ [in]}
Vol_1 = 46.95 \text{ [in^3]}
Vol_2 = 37.65 \text{ [in^3]}
Vol_3 = 31.31 \text{ [in^3]}
Vol_4 = 15.61 \text{ [in^3]}
W_1 = 4.577 \text{ [lb]}
W_2 = 3.67 \text{ [lb]}
W_3 = 3.053 \text{ [lb]}
W_4 = 1.522 \text{ [lb]}
W_{cockpit} = 12.75 \text{ [lb]}
W_{W1} = 5.33 \text{ [lb]}
W_{W1.2} = 4.52 \text{ [lb]}
W_{W1.3} = 1.8 \text{ [lb]}
W_{W2} = 0.55 \text{ [lb]}
W_{W2} = 0.5 \text{ [lb]}
W_{load} = 81.69 \text{ [lb]}
W_{propspar} = 7.816 \text{ [lb]}
W_{thrust} = 135 \text{ [lb]}
W_{rotspar} = 24.47 \text{ [lb]}
W_{spar} = 12.82 \text{ [lb]}
x_0 = 196.8 \text{ [lb]}
x_1 = -87.29 \text{ [lb]}
x_2 = -197.3 \text{ [lb]}
x_3 = -4.868 \text{ [lb]}
x_4 = 0 \text{ [lb]}
y_0 = 16.54 \text{ [lb]}

No unit problems were detected.

10.2 MATLAB Code – Lamination Theory

%%%% HPH 3\textquoteleft OD Hub Spar

%%%% Simple CLT File including hygrothermal

75
clear all
close all

%set up a diary file
diary HPHSpar.dat

%units are US customary (lb, in, E in psi)

% total laminate definition in matrix below
% [ply angles, thicknesses, matl. #]

%Set up for two materials

% Data in there now is
%1-carbon
%2-cloth

%Laminate is defined in this matrix l (one)
% [ angle  thick  matl #]
l=[ 0  1*.006   1;
    0  1*.006   1;
    0  1*.006   1];

%delta temp
DT = -130;

% size command to get number of plies
n = size(l,1);

% Lamina Properties
% matrix for engineering constants
%E1     E2    v12    G12    a11      a22
E = [20.4e6  1.2e6 .304  .64e6  -.5e-6  15e-6;
     9.0e6  9.0e6 .050  .93e6  -.5e-6  15e-6;
     10.0e6 10.0e6 .30  3.84e6  12e-6   12e-6]; % Newport NCT301 tape
% a's are CTE's

%intialize the ply distance and ABD matrices
NT = zeros(3,1);
MT = zeros(3,1);

h = zeros(n+1,1);
A = zeros(3);
B = zeros(3);
D = zeros(3);
% Form R matrix which relates engineering to tensor strain
R = [1  0  0;
     0  1  0;
     0  0  2];
% find the total thickness
total = sum(l,1);
thick = total(1,2);

% locate the bottom of the first ply
h(1) = -thick/2.;
imax = n + 1;

% loop for rest of the ply distances from midsurf
for i = 2 : imax
    h(i) = h(i-1) + l(i-1,2);
end

% loop over each ply to integrate the ABD matrices
for i = 1:n

    % ply material ID
    mi=l(i,3);
v21 = E(mi,2)*E(mi,3)/E(mi,1);
d = 1 - E(mi,3)*v21;

    % Q12 matrix
    Q = [E(mi,1)/d v21*E(mi,1)/d 0;
         E(mi,3)*E(mi,2)/d E(mi,2)/d 0;
         0 0 E(mi,4)];

    % ply angle in radians
    a1=l(i,1)*pi/180;

    % Form transformation matrices T1 for ply
    T1 = [(cos(a1))^2 (sin(a1))^2 2*sin(a1)*cos(a1);  
          (sin(a1))^2 (cos(a1))^2 -2*sin(a1)*cos(a1);  
          -sin(a1)*cos(a1) sin(a1)*cos(a1) (cos(a1))^2-(sin(a1))^2 ];

    % Form Qxy
    Qxy = inv(T1)*Q*R*T1*inv(R);

    % build up the laminate stiffness matrices
    A = A + Qxy*(h(i+1)-h(i));
    B = B + Qxy*(h(i+1)^2 - h(i)^2);
    D = D + Qxy*(h(i+1)^3 - h(i)^3);

    % load alphas into and array
    a=[E(mi,5); E(mi,6); 0.0];

    % transform cte’s mult by DT to get thermal strain exy
    exy = (R*inv(T1)*inv(R)*a)*DT;

    % build up thermal load as well now
    NT = NT + Qxy*exy*(h(i+1)-h(i));
    MT = MT + .5*(Qxy*exy*(h(i+1)^2 - h(i)^2));
%end of stiffness loop
end

%change the display format for compliance matrix
format short e

A = 1.0*A;
B = .5*B
D = (1/3)*D;

K = [A, B;
    B, D];

%design moment. alum equiv = 8660 for aluminum .035" wall thickness
M = 6106;

%max shear load
V=100;

%max torsion load - currently not used by code!
T=600;

%Tube Mean Radius
r_nom = 1.5;
%  r = r_nom;
r= r_nom + thick/2;

%Thickness of Al tube
Al_thick = 0.035;
Nxmax=M/(pi*r^2);
Nxymax=V/(pi*r);

% incude incduec moment to suppress kappy and Kappxy
Nx=Nxmax;
Ny=0.0;
Ns=Nxmax;
Mx=0.0;
My=0.0;
Ms=0.0;

% superimpose mech and thermal loads
load = [ NT(1) + Nx;
NT(2) + Ny;
NT(3) + Ns;
MT(1) + Mx;
MT(2) + My;
MT(3) + Ms];

C = inv(K);

EI_CF = pi*r^3/C(1,1)
EIcrude = pi*r^3*0.01*20e6;
EI_A1 = pi*(r_nom-Al_thick/2)^3*Al_thick*10e6

Gxy=K(3,3)/thick;
Galum=10e6/(2*(1.3));
JG_CF=2*pi*r^3*K(3,3)
JG_A1= 2*pi*(r_nom-Al_thick/2)^3*Al_thick*Galum

%compute the strains = compliance times load
e = C*load;

% axial CTE
alphax = e(1)/DT

% hoop CTE
alphay = e(2)/DT

% Change in Diameter
DD = e(2)*2*r

% reduction factor for ultimate (pseudo A-basis use .80 or .60
% reduce for CALPOLY Made
RF=.60;

% allowable strains reduced to account for ultimate strength after impact
% row1 is carbon
% row2 is E-glass
% transverse properties assumed same
% load allowable strains into array
% load allowable strains into array
%     ELU  ELUP  ETU  ETUP  ELTU
ea = [RF*.010  RF*.010  RF*.010  RF*.010  RF*.025; %UNI (type unknown)
      RF*.02  RF*.018  RF*.0067  RF*.031  RF*.0296; %Clothepoxy

79
RF*.0035 RF*.0035 RF*.0035 RF*.0035 RF*.00175] %Alum Failure strains

%zero out results array
ERES = zeros(2*n,6);
SRES = zeros(2*n,6);

% loop over each ply and calculate strain
for i=1 : n;
    %loop over top and bottom of each ply
    for j=1 : 2;
        % one is bottom two is top for loc
        ply = i;
        loc = j;

        z = h(i-1+j);

        %ply strain from midplane strain
        el= [ e(1)+z*e(4);  e(2)+z*e(5);  e(3)+z*e(6)];

        %ply material ID
        mi=l(i,3);
        v21 = E(mi,2)*E(mi,3)/E(mi,1);
        d = 1 - E(mi,3)*v21;

        %Q12 matrix
        Q = [E(mi,1)/d          v21*E(mi,1)/d      0;
             E(mi,3)*E(mi,2)/d   E(mi,2)/d          0;
             0                 0               E(mi,4)];

        %ply angle in radians
        a1=l(i,1)*pi/180;

        %Form transformation matrices T1 for ply
        T1 = [(cos(a1))^2       (sin(a1))^2          2*sin(a1)*cos(a1);
             (sin(a1))^2        (cos(a1))^2         -2*sin(a1)*cos(a1);
             -sin(a1)*cos(a1)    sin(a1)*cos(a1)  (cos(a1))^2       -(sin(a1))^2 ];

        % load alpha for the ply
        a=[E(mi,5); E(mi,6); 0.0];

        % tranform to 1,2
        ep = R*T1*inv(R)*el - a*DT;

        %calculate stress in 1,2 coords
        sp = Q*ep;

        %failure index now looks at two different materials
        if ep(1) > 0.0;
            FI = ep(1)/ea(mi,1);
            FIF=FI;
        end
end
end
end
elseif ep(1) < 0.0;
    FI = abs( ep(1) )/ea(mi,2);
    FIF=FI;
end

if ep(2) > 0.0;
    F1 = ep(2)/ea(mi,3);
elseif ep(2) < 0.0;
    F1 = abs( ep(2) )/ea(mi,4);
end

if F1 > FI;
    FI = F1;
end

F1 = abs( ep(3) )/ea(mi,5);
if F1 > FI;
    F1e = F1;
elseif F1 < FI;
    F1e = FI;
end

% load the results array
% note top and bottom of every ply!

% strain results, FI based on Max Strain
% angle, eps1, eps2, gamma12, FI, FIfiber
ERES(2*i+j-2,1)=1(i);
ERES(2*i+j-2,2)=ep(1);
ERES(2*i+j-2,3)=ep(2);
ERES(2*i+j-2,4)=ep(3);
ERES(2*i+j-2,5)=F1e;
ERES(2*i+j-2,6)=FIF;

% stress results, F1 based on max strain
% angle, Sigma1, Sigma2, Tau12, FI, FIfiber
SRES(2*i+j-2,1)=1(i);
SRES(2*i+j-2,2)=sp(1);
SRES(2*i+j-2,3)=sp(2);
SRES(2*i+j-2,4)=sp(3);
SRES(2*i+j-2,5)=F1e;
SRES(2*i+j-2,6)=FIF;

end
%
end
ERES=ERES*1
SRES=SRES*1

diary off
10.2.1 Strength and Stiffness Results

thick =
0.0180

B =
\begin{bmatrix}
-3.4106e-013 & -7.1054e-015 & 0 \\
-7.1054e-015 & -2.1316e-014 & 0 \\
0 & 0 & -1.4211e-014
\end{bmatrix}

EI_CF =
3.9639e+006

EI_A1 =
3.5826e+006

JG_CF =
2.4871e+005

JG_A1 =
2.7559e+006

ea =
\begin{bmatrix}
6.0000e-003 & 6.0000e-003 & 6.0000e-003 & 6.0000e-003 & 1.5000e-002 \\
2.1000e-003 & 2.1000e-003 & 2.1000e-003 & 2.1000e-003 & 1.0500e-003
\end{bmatrix}

ERES =
Columns 1 through 5
\begin{bmatrix}
0 & 2.3245e-003 & -7.0664e-004 & 1.8311e-003 & 3.8741e-001 \\
0 & 2.3245e-003 & -7.0664e-004 & 1.8311e-003 & 3.8741e-001 \\
0 & 2.3245e-003 & -7.0664e-004 & 1.8311e-003 & 3.8741e-001 \\
0 & 2.3245e-003 & -7.0664e-004 & 1.8311e-003 & 3.8741e-001
\end{bmatrix}
\[
\begin{array}{cccc}
0 & 2.3245e-003 & -7.0664e-004 & 1.8311e-003 & 3.8741e-001 \\
0 & 2.3245e-003 & -7.0664e-004 & 1.8311e-003 & 3.8741e-001 \\
\end{array}
\]

Column 6

\[
\begin{array}{c}
3.8741e-001 \\
3.8741e-001 \\
3.8741e-001 \\
3.8741e-001 \\
3.8741e-001 \\
3.8741e-001 \\
\end{array}
\]

\[
SRES =
\]

Columns 1 through 5

\[
\begin{array}{cccc}
0 & 4.7419e+004 & 2.2737e-013 & 1.1719e+003 & 3.8741e-001 \\
0 & 4.7419e+004 & 3.4106e-013 & 1.1719e+003 & 3.8741e-001 \\
0 & 4.7419e+004 & 3.4106e-013 & 1.1719e+003 & 3.8741e-001 \\
0 & 4.7419e+004 & 4.5475e-013 & 1.1719e+003 & 3.8741e-001 \\
0 & 4.7419e+004 & 4.5475e-013 & 1.1719e+003 & 3.8741e-001 \\
0 & 4.7419e+004 & 3.4106e-013 & 1.1719e+003 & 3.8741e-001 \\
\end{array}
\]

Column 6

\[
\begin{array}{c}
3.8741e-001 \\
3.8741e-001 \\
3.8741e-001 \\
3.8741e-001 \\
3.8741e-001 \\
3.8741e-001 \\
\end{array}
\]

\[
\textbf{10.2.2 CTE Results}
\]

\[
\text{alphax} =
\]

\[-1.8381e-005
\]

\[
\text{alphay} =
\]

\[2.0436e-005
\]

\[
\text{DD} =
\]

\[-8.0177e-003
\]
The entirety of this section is a report by Graham Garvin for ME 404.

FEA Spar and Sleeve Analysis

ABSTRACT

Two ABAQUS/Explicit models were constructed. The first modeled the spars of the long wing under flight loads using 4063 3-D beam elements. The four individual sections of spar were attached using tie constraints. Guy wires were added to the system to provide accurate loading. The loads from that model were extracted and applied to a separate model of the sleeve connecting the first two spar sections. This model consisted of two shortened spar sections connected by the sleeve. The model was comprised of 15502 shell elements. A thickness of 0.040” was obtained for that to prevent yielding by a safety factor of 2. However, due to the linear modeling of the system and other simplifications, even with a yielding safety factor of 2 this thickness is questionable.

INTRODUCTION

The human powered helicopter (HPH) club on campus received a functional but not optimized HPH. The helicopter currently has aluminum tubes acting as spars with external carbon fiber sleeves. The club would like to recreate the sleeves but is unsure of the carbon fiber laminate layup and therefore cannot recreate the sleeves. The club obtained a Matlab file that can give the carbon fiber laminate layup for a tube that has equivalent strength and stiffness of an aluminum tube given the aluminum thickness. The purpose of this analysis was to find the required thickness of the sleeve connecting the first two sections of spar so that the club can input this thickness into the Matlab code to discover the appropriate carbon fiber laminate layup. However, to model the sleeve, the forces at the sleeve must be determined. To determine these forces, a model of the the HPH was constructed. See pictured below.

BACKGROUND

This analysis only obtained a thickness for one of the 10 sleeves on the HPH. The sleeve considered joins the bare spar and the spar under the section of foam marked “Large Foam” in Figure 2. All other joints and the two shorter wings were not considered in this analysis. Note, the wing is 42 feet long from hub to tip.

MODEL DEVELOPMENT: SPARS

Because the forces acting at the sleeve are needed for the sleeve analysis and those loads come from the model of the spars, the spar model was constructed before the sleeve model.
First, the 4 spar sections making up the long wing were modeled in Abaqus using 3-D beams and connected using tie constraints to represent the sleeves. An encastre boundary constraint was imposed on the end of the bare spar where it intersects the hub to represent the hub sleeve. The Bare spar section currently has an OD of 3” and a wall thickness of .035. The large foam section has an OD of 3”, the medium foam section has an OD of 2.5” and the small foam section has an OD of 2”. All three of those sections have a wall thickness of .028”. The material for all spar sections is aluminum 6061-TS which has the following material properties:

The wings of the helicopter sag when they are not rotating. To keep them from contacting the ground, two landing gears are placed on each of the longer wings. The landing gears are carbon fiber rods with small wheel at one end. They are attached to the spars through a pin and slot connection. Each sleeve is epoxied to one spar and slip fit onto the other spar. A 5/16” diameter hole goes through the side of the sleeve that is not epoxied to a spar. A 5/16” hole is also drilled at the end of the spar section that slip-fits into the sleeve. When the two spars are fit together in the sleeve and touch, the hole in the sleeve and the hole in the non-epoxied spar line up. A pin at the end of the landing gear fits into that hole to keep the non-epoxied spar from exiting the sleeve during flight. These holes in the spars were neglected in analysis to reduce complexity. Although the holes will create stress concentrations in the spars, causing them to be less stiff and altering the deflection of the spars, the holes are only 5/16” in diameter and were assumed to contribute minimally to spar deflection.

The landing gears (0.75” diameter) were modeled as 3-D beams and given a modulus of elasticity of 30 *10^6 psi. The actual modulus is unknown, but because the landing gears are part carbon fiber and part aluminum, it is most likely in this range. Because the landing gears only see a compressive axial load (due to equalization of guy wires at the base of each landing gear), their properties do not affect the system greatly as long as the part has somewhat substantial stiffness. This is because a ¾” diameter rod will not bend very much, at least in comparison to the dimensions of this helicopter.

The landing gears were tie constrained to the nodes of the intersecting spar sections.

Next, the guy wires were added to the model. The guy wires are key to the system because they provide a downward force on the wing to keep it from coning upward due to the upwards lift. The guy wires were the crux of the analysis. When the helicopter is in flight, all wings are essentially horizontal. From watching a video of the helicopter in a test flight I determined that the tip deflection for one of the longer wings is no more than 2 feet upwards. Without the aid of the guy wires, the tip deflection would be MUCH greater.

The guy wires are connected to the bottom of the landing gears and the top of the spars. To simplify the analysis, the guy wires were attached to the middle of the spar sections. The guy wires are attached to the helicopter while the wing is under static loading (drooping downwards) and have little to no pretension. Figure 3 shows the unloaded guy wires attached to the statically loaded long wing.

<table>
<thead>
<tr>
<th>Aluminum 6061-TS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Density (lb/in^3)</strong></td>
</tr>
<tr>
<td>0.098</td>
</tr>
</tbody>
</table>

Figure 10-5. Long Spar Under Static Loading, No Guy Wire Loads
As the wings begin to spin, the airfoils begin to provide lift which bends the wing upward. Upward spar deflection requires the guy wires to elongate. The stiffness in the guy wires mandates how much force they exert on the system. The more deflection, the more force they provide. The stiffness of the guy wires was experimentally found to be 8500 (lb/in) per undeformed length, linear in the region of load testing (up to 30 pounds) and assumed to be linear for all loading magnitudes. The stiffness of a section of guy wire is obtained by dividing 8500 lb/in by the undeformed length of that section of guy wire.

The guy wires were modeled as beams. The stiffness was converted to a modulus of elasticity to be assigned to the circular profile. See Appendix A for these calculations.

The spars were created in the horizontal position, not in the statically loaded position. This means that in the assembly, the guy wires have to match up with the horizontal spars, not the statically loaded spars. However, if the guy wires are created for the geometry of the horizontal wing then they don’t exert any force at that geometry because they have not deflected at all. This was overcome by the application of bolt loads.

In Abaqus, a bolt load essentially acts as a pretension which is exactly what each guy wire needs if it is created as a pre-deformed member. The lengths of each undeformed guy wire section from static loading was obtained using geometry. Then the length of each guy wire section was calculated for the horizontal wing position. The difference between these two multiplied by the stiffness is the bolt load.

**Loading**

A gravity force was applied to the model which accounted for the weight of the aluminum spars. The weight of the rotors was placed on the spars as pressure loads. The rotor weights were multiplied by 1.2 to account for extra weight from the control system and epoxy. The figure below shows the profile of the lift load.
The lift load profile is described with the following equation:

\[-2.83 \times 10^{-6}x^3 + 2.05 \times 10^{-3}x^2 + 1.41 \times 10^{-2}x - 14.7\]

Where \(x\) is the distance away from the hub (in inches). This equation was implemented into the model with a line load. A force function was defined as the above equation and a line load force was created acting on the three sections of spar which have rotor lift. The global coordinate system (origin at the hub) was used to define the distance \(x\). The line load was divided by the total length it acts over in order to achieve units of force/length required for a line load. The lift load distribution was validated by comparing the moment it creates in Abaqus to calculated values. See Appendix A for these calculations.

Unfortunately, with the calculated bolt loads the tip deflection was far too high. This could be an error produced by one of the model shortcomings (see section below) or it could have been produced by inaccurate guy wire stiffness. Because the model shortcomings could not be resolved, it was assumed that the error was in the guy wire stiffness. The change in length of the guy wires from statically loaded to horizontal position was determined by geometry and that does not change regardless of the preload in the guy wires. Therefore, the guy wire preloads were all multiplied by the same factor until the tip deflection was within an acceptable range. It was found that the guy wire loads need to be multiplied by 4.5 to achieve a tip deflection of 37.25" (the maximum allowable upwards tip deflection from visually observing the helicopter in flight).

**Model Shortcomings**

There were two major factors that are believed to contribute substantially to error in the model; the inability to model the system nonlinearly and the use of beam elements for guy wires. Also, the magnitudes of the hand calculated bolt loads were insufficient in keeping the spar from deflecting less than the maximum upward 3 feet at the tip. The bolt loads were all increased proportionally inorder to achieve 3 feet up upward tip deflection.

The deflection of the spars is small, which means that the system will behave nonlinearly. Abaqus can account for this by turning on nonlinear geometry. The model was run without nonlinear geometry and then again with nonlinear geometry turned on with the calculated guy wire loads. The tip deflection almost halved when the model was run with nonlinear geometry (604.5" to 330"). Obviously the system is acting nonlinearly and to achieve accurate results this needs to be accounted for in the model. However, when the guy wire forces exceeded roughly 100lb each, the model gave the error of “Too many attempts made for this increment”. Typically this means that within the model there is an indeterminant deflection. Typically this indicates that a constraint was not properly defined and one component of the assembly is free to rotate or translate. However, the model ran without encountering this issue when run with large bolt loads under linear analysis. From this I concluded that my constraints were not the issue. Despite through investigation into this issue, its cause was not determined meaning that the model was run linearly with large bolt loads.

The guy wires act essentially as truss elements because they cannot resist a moment and are attached to the landing gears with the equivalent of a pin joint. The model was first constructed with truss elements but when the following error message persisted “Too many attempts made for this increment” truss elements were switched to beams. This is the same message encountered when nonlinear geometry was turned on and typically indicates that a constraint has not been properly defined. However, all constrains worked with the beam element and were not changed when the guy wires were changed from beam to truss elements. Because this issue could not be resolved, the guy wires were modeled as beams. The beams act in the same manner as trusses except that they resist bending and are attached to nodes rigidly and are not free to rotate. Because the landing gears move around
stretching the guy wires, angles that the guy wires make with the landing gears changes. In the real system the angle changes with no resistance from the guy wires but the beam elements are rigidly attached to the landing gears at the tip node and not allowed to change in angle. The result of this situation is that the beams produce bending resistance in the system that is not present in the physical system. However, section moments were checked in the landing gears and the guy wires and discovered to be small. The guy wires carried almost no moment and the landing gears were under 100 lb*in. This indicates that beam elements are not as bad of an assumption as initially thought to be.

An attempt was made to model guy wires as beams with rigid body pin connections which would essentially nullify the bending resistance of the beams. Reference points were attached to the landing gears and the guy wire beams were defined as rigid bodies pinned to the reference points. When this change was made to the model, the following error message persisted: “Nodes may not be used with a multi-point constraint since they are also part of pretension section”. The model was thoroughly checked to ensure that no single point was multi constrained indeterminantly. The error was not overcome and all beam elements were tied to landing gears, not rigidly pinned.

In the real system, the guy wires are allowed to adjust themselves at the connections at the bottom of the two landing gears. In the Abaqus model they are attached to the base of the landing gears and not allowed to equalize. An attempt was made to construct the guy wires out of connector elements which might have the possibility of equalization if specified. However, many difficulties were encountered when attempting to switch over from beams to connector elements, most stemming from the bolt loads.

Mesh Convergence

The landing gears were tied to the spars by constraining their entire length to the node of intersection. This meant that they did not bend at all. Landing gears were assumed no to deform much at all in their lengthwise direction (resulting from compression) and were therefore given very stiff properties. Because the landing gears are essentially rigid, their mesh did not effect the system.

The guy wires were all modeled with two elements each. The high bolt loads in combination with the small cross-sectional area of the guy wires made the guy wires buckle in on themselves when the mesh was fine. One element would have been ideal, however a minimum of two elements were required to assign the bolt loads properly.

There were two output variables that were important to the analysis, the loads at the first sleeve and the tip deflection (to validate the model). A mesh convergence study was preformed on these variables. Quadratic beam elements were used.

<table>
<thead>
<tr>
<th>Spar Seed Size</th>
<th>M1</th>
<th>% Diff</th>
<th>M2</th>
<th>% Diff</th>
<th>Tip Deflection</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>853.155</td>
<td>NA</td>
<td>954.635</td>
<td>NA</td>
<td>36.8787</td>
</tr>
<tr>
<td>0.125</td>
<td>872.963</td>
<td>2.3</td>
<td>947.528</td>
<td>-0.8</td>
<td>36.8786</td>
</tr>
<tr>
<td>0.0625</td>
<td>876.265</td>
<td>0.4</td>
<td>946.34</td>
<td>-0.1</td>
<td>36.8786</td>
</tr>
</tbody>
</table>

Figure 10-7: Spar Mesh Convergence

Figure 10-8: Deflection Mesh Convergence

Convergence for this analysis was defined as having less than 1% change in output value for ever time the seed size was cut in half. Deflection and the moment in the second spar were converged at a seed size of 0.5 but the moment in the spar connected to the hub (spar one, M1) did not converge until a seed size of .125. Because the M1 was the last variable of interest to converge, it was the only one plotted for mesh.
convergence. As can be seen, the smaller the mesh size, the smaller the difference in the moment.

The converged assembly contains 4063 beam elements and has 24629 degrees of freedom.

There were a number of warning messages informing that nodes involved in tie constraints were not being moved the specified maximum amount. This did not affect results and was considered a good sign because the nodes not at all offset from each other.

There was an error message reading “Strain output request le is not valid for some elements in this analysis. This request is switched to the strain measure, e." Because strain was not a variable of interest, this message was ignored. However, the strain is involved in the deflection of the beam and this could have an effect on the tip deflection. I did not discover the cause of this error.

The most peculiar error message indicated that both landing gears were too far from the node they are tied to. This error message did not always occur. The tie constraints were examined and determined to be accurate. The model ran with and without the error message and in both cases the result was that the landing gear was tied to the spar as desired. The cause of this occasionally occurring error message was not discovered.

Model Validation

The validation of the entire model was to compare the tip deflection to the observed tip deflection in flight with the calculated pretension in the guy wires. The model did not pass this validation check. As stated before, either the stiffness was incorrectly measured or the model shortcomings are significantly altering the system.

One concern was that the lift load was input incorrectly. Hand calculations validated that the lift load is correct in the Abaqus model. See Appendix A for lift load verification.

In addition, an EES code was created to determine the deflection of the spars given a guy wire preload. See Appendix B for EES code. The code is complex and long so there is plenty of room for error. Therefore the results cannot be trusted to be accurate to beam theory. For the EES code to produce the same tip deflection as the Abaqus model, the calculated guy wire loads need to be multiplied by 1.95 instead of the 4.5 that is required in Abaqus. When the calculated guy wire loads are multiplied by 4.5 in the EES code, this produces a tip deflection of 285 inches downward as opposed to 37 inches upward that Abaqus yields. The match is not good at all. However they are at least on the same order of magnitude. The discrepancies between the two can most likely be attributed to the differences in system simplification between the EES code and the Abaqus. The biggest assumption that
EES employed was simplified point loading while Abaqus applied distributed loads. This alone could create large differences in results.

**MODEL DEVELOPMENT: SLEEVE CONTACT**

The wall thickness of the spars is very thin and it was initially assumed that the thickness of the sleeve would be thin as well. Therefore to obtain stresses in the sleeve, 3-D shell parts were constructed for the spars and sleeve.

The sleeve length was predefined by the HPH club to be 24” long giving each spar 12” of contact with the sleeve. The only variable that needed to be determined was the sleeve thickness. Also, it was predetermined that the sleeve would be an internal fitting (jointing spars on the inside) instead of an external sleeve which is currently in use on the HPH.

The two spar sections and the sleeve section were created using the same aluminum properties as before. When setting the section assignment it was important to take note of which direction the shell offsets. For the sleeve, the shell offset was defined from the top surface meaning that the thickness would go inward from the part making it easier to change the thickness of the part without creating difficulties with interference. The spars had a shell offset defined from the bottom surface meaning that the thickness protruded outward from the defined sketched circle.

**Constraints and Boundary Conditions**

The two spars and the sleeve were instanced in the assembly and lined up. Both sleeves were partitioned in the middle and so was the sleeve in order to ensure that only the sections of the parts that touch are connected. It was assume that the parts don’t move relative to each other and are in contact. This assumption enabled the use of tie constraints instead of defining a complex interaction. Two tie constraints were created. Half of the sleeve to half of spar one, and the other half of the sleeve to half of spar two.

**Loading**

The forces and moment 24 inches to the right of the node representing the sleeve under analysis were taken from spar model. These were obtained using the section properties probe. The force was applied as a shell edge load to the spar in the shell element model, and the moment was applied using a rigid body tie constraint. A reference point was assigned to the center of the spar and the moment was applied to the reference point.

The guy wire loads and the landing gear load were considered next. In the physical system, the guy wires are attached to the top of the spars (pulling down) and the landing gear pushes up on the spars. This was taken into account in the model. A small section of the spars on the top and bottom was partitioned for a pressure load to be applied. The area was an estimate of the area that the guy wires and landing gear act on. It was estimated that this area is between .5 in² and 1 in² so in the model the area was defined as roughly .76 in².

**Neglected in the Model**

Gravity was neglected (it contributes less than 3 lbs in the system) and considered insignificant in comparison to the large forces and moments acting on the system. The major item that was not considered in
the model was the hole through one of the landing gears and through one side of the sleeve. A small pin (5/16") porturdes from the top of the landing gear and goes through the one spar and through one side of the sleeve. The hole is just slightly offset from the center of the sleeve. The purpose of this hole is to keep the spar that is not epoxied into the sleeve, in place. The hole was neglected due to its small size and the initial assumption that there would be little axial loading.

**Model Shortcomings**

Due to the inaccuracies in the spar model, the forces are most likely inaccurate creating a large source of error for the calculation of thickness of the sleeve.

The model tied both spars to the sleeve but in reality only one of them is epoxied in, the other has a slip fit. The small hole in the sleeve could create high stress concentrations depending on how much of the axial loading it takes from the spar not fixex by the epoxy. The high axial load forces the non fixed spar toward the sleeve, the load gets reacted by the interaction of the two spars and by the pin. The amount that each of these takes is unknown. Also, there was assumed to be no torque in the system. Any torque loads would be carried through the spars by the pin which would create stress concentrations. However, the torque loading is unknown and assumed to be negligible.

**Mesh Convergence**

A mesh convergence study was conducted on the maxmum Mises stress in the sleeve. The sleeve converged at a seed size of .2 and the spar converged at a seed size of 0.15. A quadratic geometric order was used for both.

---

**Table 10-2: Spar Mesh Convergence**

<table>
<thead>
<tr>
<th>Sleeve Seed Size</th>
<th>Spar Seed Size</th>
<th>Maximum Mises Stress (psi)</th>
<th>Percent Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>0.3</td>
<td>21194.3</td>
<td>NA</td>
</tr>
<tr>
<td>0.2</td>
<td>.15</td>
<td>20507.4</td>
<td>-3.24</td>
</tr>
<tr>
<td>0.2</td>
<td>0.075</td>
<td>20459.7</td>
<td>-0.23</td>
</tr>
</tbody>
</table>

**Table 10-3: Sleeve Mesh Convergence**

<table>
<thead>
<tr>
<th>Sleeve Seed Size</th>
<th>Spar Seed Size</th>
<th>Maximum Mises Stress (psi)</th>
<th>Percent Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>.15</td>
<td>19834.4</td>
<td>NA</td>
</tr>
<tr>
<td>0.2</td>
<td>.15</td>
<td>20507.4</td>
<td>3.28</td>
</tr>
<tr>
<td>0.1</td>
<td>.15</td>
<td>20578.1</td>
<td>0.34</td>
</tr>
</tbody>
</table>

Below are two graphical represenations of the mesh convergence.

**Figure 10-10: Spar Mesh Convergence, Sleeve Seed Size Held at 0.2**
This mesh convergence was conducted with a sleeve thickness of 0.40". This is the thinnest off the shelf aluminum tube that will achieve a safety factor of 2. The yielding strength of 6061-TS aluminum is 45 ksi, to achieve a safety factor of 2 the yielding strength needs to be divided by two (22.5 ksi). With a sleeve wall thickness of 0.040" the maximum stress is 20.5 ksi which is just under the maximum value of 22.5 ksi.

Mesh convergence was very simple for this analysis. Had the sleeve or spar not converged at these seed sizes, the number of degrees of freedom would have been too great to run lower seed sizes on the entire model and the parts would have to have been partitioned and edge seeds employed. The following figures show the clean element geometry for the sleeve and spar.

The converged assembly contains 15502 shell elements and has 153930 degrees of freedom.

The worst aspect ratio between both models was 1.47 and the worst face corner angle was 89.05 degrees (skew angle of 0.95 degrees because these are quadrilateral elements). These easily meet the criterion of a maximum aspect ratio of 4 and maximum skew angle of 10 degrees.

**FE Error Messages**

There was only one error message in this model “adjusted nodes with very small adjustments were not printed. Specify… for complete printout”. Because this analysis is determining the sleeve thickness with a
yielding safety factor of 2, small inconsistencies in the results produced by “very small adjustments” are insignificant.

**Model Validation**

The stress in the sleeve was validated by hand (See Appendix A). A simplified loading scenario was set, hand calculations indicated a the stress in the middle of the sleeve to be 1,719.6 psi and Abaqus indicated 1228.5 psi (40% off). The hand calculations involved many simplifications and estimations so an error of 40% is reasonable.

**Results**

With a yielding strength safety factor of 2, the aluminum sleeve thickness was determined to be 0.04”. As anticipated, the maximum stress occurs near the middle of the sleeve. The von Mises stress plots of the full spar and sleeve and isolated sleeve are displayed below.

For a simplified loading scenario, the hand calculations of the maximum stress in the center of the sleeve were 40% larger than what Abaqus produced. However, this is acceptable due to the multiple assumptions and simplifications that were involved in calculating the stress by hand.

The results from the model of the spars, guy wires, and landing gears are not as trusted as those of the sleeve model. The guy wire preloads had to be multiplied by a factor of 4.5 to achieve the maximum tip deflection of 3 feet. The EES code that modeled the system linearly required the guy wire preloads to be multiplied by only 1.95 to achieve the maximum tip deflection of 3 feet. This discrepancy most likely comes from the oversimplification of the EES.
code over the Abaqus model or an error in the complex and long coding of the EES code.

The calculated guy wire pretension loads had to be multiplied by a factor of 4.5 to decrease the tip deflection to the maximum allowable value of 3 feet. This means that either there was an error in the experimentally obtained guy wire stiffness or an error in the model (or both). The fact that the maximum Mises stress in the spars is 55 ksi indicates that there is certainly an error in modeling because the aluminum will yield at 45 ksi and the helicopter has flown multiple times without yielding the spars. Much of this error is speculated to originate from the fact that the system is behaving nonlinearly but is being modeled linearly.

The next step in this analysis would be to model the system nonlinearly. Once the wing is modeled nonlinearly, the guy wires should be modeled as self equalizing. If the resulting deflection is still off from the observed tip deflection during flight then the stiffness of the guy wires should be re-tested. After that, the sleeve model should be modified to incorporate the hole in which the landing gear fits. With all of those modifications, the resulting sleeve thickness will be much more trustworthy.

**Conclusion**

The model of the wing incorporated the spars, landing gears, and guy wires. The rotor lift distribution, guy wire loads, and weight of aluminum were applied to the system which contained 4063 3-D beam elements. The four individual sections of spar were attached using tie constraints. The loads from that wing model were extracted and applied to a separate model of the sleeve connecting the first two spar sections. This model contained two shortened spar sections connected by the sleeve. The converged model contained 15502 shell elements. Iterating the thickness of the sleeve yielded a final thickness of 0.040” with a yielding safety factor of 2. The loading extracted from the wing model is questionable at best. Simplifications such as the assumption that the system behaves linearly created some or all of the issues encountered with the model of the wing. Another strong candidate for error between the model and the physical system is the experimentally calculated guy wire stiffness. Even with a yielding safety factor of 2, the determined sleeve thickness of 0.04” is questionable.

**References**

Wikipedia.com for all aluminum properties seen in Table 1.
10.4 Testing Analysis

The following documents are hand calculations for the bending stiffness of the tested spar section.

Determine $\frac{EI}{E}$ from applied moment and known strains.

Tensile strain gage is on bending axis.
Compressive strain gage is 27° offset from the bending axis.

\[ E_1 = \frac{\sigma}{\varepsilon_1} \]

\[ C = \frac{MC}{E} \]

\[ \frac{EI}{E} = \frac{MC}{E} \]

For tensile strain gage use $C = R_{num} = 1.273''$
For compressive strain gage use $C = R_{num} \cos(27°) = 1.18''$

Also use a composite solution to obtain $E_x$

\[ E_x = \frac{1}{a_{xx}} \]
\[ a_{xx} = \frac{ex}{y_k} \]
\[ N_k = \frac{M \cdot \cos(\theta)}{1 + R_{num}} \]

\[ I = \pi \cdot R_{num}^2 \cdot t \]

\[ \frac{EI}{E} = \frac{M}{E_x} \cdot R_{num} \cdot \cos(\theta) \]

Same as above equation
\[ MC = \frac{EI}{E} \]
\[ \delta_i = \frac{F(L-x)}{2EI} \delta_b \]
\[ \delta_0 = \frac{L^3F}{3EI} + \delta_b \]
\[ \delta_{bb} = L \sin(\theta) \]
\[ \delta_{bb} = L \sin(\theta) \]
\[ \delta_i = \frac{F(L-x)}{2EI} + L \sin(\theta) \]
\[ \delta_0 = \frac{L^3F}{3EI} + L \sin(\theta) \]
\[ \sin(\theta) = \frac{1}{L} \left( \delta_i - \frac{F(L-x)}{2EI} \delta_b \right) = \frac{\delta_i}{L} - \frac{F(L-x)}{2EI} \]
\[ \delta_0 = \frac{L^3F}{3EI} + \frac{1}{L} \delta_i - \frac{F(L-x)}{2EI} \]
\[ \delta_0 = \frac{1}{EI} \left( \frac{L^3F}{3} - \frac{F(L-x)LL}{2} \right) + \frac{1}{L} \delta_i \]
\[ \delta_{test} = 1.8 \]
\[ \delta_{Theo} = 2.9 \]
11 Appendix D – Manufacturing Operations

This manufacturing intense project required custom tooling and clearly defined operations to be performed before and after the carbon fiber was cured. The result of this labor was a set of finished spars.

11.1 Tooling

The geometry of the spars and mandrels required a rotisserie to rotate the spar and/or mandrel to ease machining operations. A v-block was utilized to align holes.

11.1.1 Rotor Jig

The rotor jig was comprised of two complementary wooden stands supporting horizontal steel rods at an even height (see Figure 11-1). The rods positioned and supported plugs (Figure 11-2) which matched the inside diameters of the mandrels.

Figure 11-1. Assembled rotor jig with carbon fiber part.

The first stand, named the front end, had the rod forged into a “z” to act as a handle. The other end had 2” extended out with a washer welded on to act as a back-plate. A second rod was positioned parallel to the first rod to provide a torque so that the part could be turned. On the other stand, named the end stand, the rod acted as a dead center; it extended 2” out the front with a washer welded to it as a back-plate.

Figure 11-2. Finished 2” plug.

The plugs were made out of rend-shape on a HASS CNC Mill using the following code. After the code was complete, two 3/8” holes were drilled manually on the same machine. Note
that the full code produced a 2.0” diameter plug. The first section of code produced a plug for the 3.0” diameter mandrel, and the section produced a plug for the 2.5” diameter mandrel. Use only the appropriate sections of code to produce the desired size.

```
O####
G80 G90 G40 G54
T1 M06
S5000 M03
G43 H01
G00 X3. Y-3.
Z2.
G01 Z0. F20.
G01 G41 X0. Y-2.075 D01 F25.
G02 I0. J2.075 F25
Z0.
G01 G41 Z0. Y-1.375 D01 F25
G02 I0. J1.375 F25
G01 Z3.
G01 G40 X3. Y-3. F20
G01 G41 X0. Y-1.125 D01 F25.
G02 I0. J1.125 F25.
G01 Z3.
G01 G40 X3. Y-3. F20
M30
```

11.1.2 Drilling Fixture

The drilling fixture was provided by Luis Gonzalez and DJ Ikeda. The fixture consisted of an aluminum plate supporting a v-block and two long vertical screws. The screws positioned a clamp which held the work piece down and was secured with screws. The fixture was positioned on a drill press table so that the drill bit lined up with the apex of the work piece. With the v-
block, this fixture worked with any size work piece or drill bit without having to reposition the fixture.

11.2 Pre-Cure Operations
This section deals with all curing operations and all operations leading up to curing. All operations should be done in order and in the manner as described below.

Table 11-1. Summary of Pre-Cure Operations

<table>
<thead>
<tr>
<th>OP #</th>
<th>DESCRIPTION</th>
<th>TOOLING</th>
<th>NOTES</th>
</tr>
</thead>
<tbody>
<tr>
<td>000</td>
<td>Safety</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>Prepare Mandrel</td>
<td>Rotor-Jig</td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>Cut Carbon Fiber</td>
<td></td>
<td>See Carbon Fiber Cutting Dimensions</td>
</tr>
<tr>
<td>300</td>
<td>Wrap Mandrel</td>
<td>Rotor-Jig</td>
<td>See Wrapping Operations</td>
</tr>
<tr>
<td>400</td>
<td>Cure Spar</td>
<td>Oven</td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>Spar Removal</td>
<td>Table Vise</td>
<td></td>
</tr>
</tbody>
</table>

Refer to the drawings in Appendix B – Drawings for each carbon fiber layer cutting schedule.

Table 11-2. Summary of wrapping operations.

<table>
<thead>
<tr>
<th>Operation # (300)</th>
<th>Name</th>
<th>1st Time</th>
<th>Time (min)</th>
<th>Description</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>Set-up</td>
<td>10 min</td>
<td></td>
<td>Suspend mandrel in rotor</td>
<td></td>
</tr>
<tr>
<td>311</td>
<td>Apply Release Agent</td>
<td>10 min</td>
<td></td>
<td>Pour, spread, wipe</td>
<td></td>
</tr>
<tr>
<td>312</td>
<td>Lot Dry</td>
<td>20 min</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>321</td>
<td>1st 45°</td>
<td>30 min</td>
<td></td>
<td>See section # of manual</td>
<td></td>
</tr>
<tr>
<td>322</td>
<td>2nd 45°</td>
<td>20 min</td>
<td></td>
<td>See section # of manual</td>
<td></td>
</tr>
<tr>
<td>323</td>
<td>3rd 45°</td>
<td>20 min</td>
<td></td>
<td>See section # of manual</td>
<td></td>
</tr>
<tr>
<td>324</td>
<td>4th 45°</td>
<td>20 min</td>
<td></td>
<td>See section # of manual</td>
<td></td>
</tr>
<tr>
<td>331</td>
<td>1st Axial</td>
<td>20 min</td>
<td></td>
<td>See section # of manual</td>
<td></td>
</tr>
<tr>
<td>332</td>
<td>2nd Axial</td>
<td>20 min</td>
<td></td>
<td>See section # of manual</td>
<td></td>
</tr>
<tr>
<td>333</td>
<td>3rd Axial</td>
<td>20 min</td>
<td></td>
<td>See section # of manual</td>
<td></td>
</tr>
<tr>
<td>341</td>
<td>Wrap Shrink Tape</td>
<td>25 min</td>
<td></td>
<td>75% - 86% Overlay, High tension</td>
<td></td>
</tr>
<tr>
<td>351</td>
<td>Tear Down</td>
<td>10 min</td>
<td></td>
<td>Disassemble jig, store</td>
<td></td>
</tr>
</tbody>
</table>

*By inputting time, engineer signs off completion of operation

OP #: 000
DESCRIPTION: Safety
NOTES:

The pre-cure operations involve the use of heavy machinery and hazardous materials. Eye protection is required at all times. When cutting, sanding, and drilling carbon fiber, apply vacuum to areas under work and wear facemasks.
Required Personal Safety Equipment: Closed toed shoes, long pants, safety glasses. Processes include the use of sharp and/or heavy objects. Take care when handling all material to reduce bodily harm.

Optional Personal Safety Equipment: Latex gloves. Note: while the pre-preg is not harmful to skin, it can be hazardous to consume. Wash hands before and after contacting pre-preg.

Mandrel Protection: Mandrel must be protected from any harm, including but not limited to: dropping, scratches, and hazardous materials. Any damage may result in inconsistent composite structure and can make removal of cured spar extremely difficult. Store mandrels in protected area away from traffic.

Pre-Preg Protection: Pre-preg is tacky by nature as the resin is already in material. It becomes tackier with increases in temperature. This makes it susceptible to gathering dust or particles, especially if laid on the ground. Avoid dropping carbon fiber. Leave back paper on at all times until appropriate time during layup process. All operators should thoroughly wash their hands before contacting pre-preg. Roll up all long sleeves, tie up long hair, and tuck in any ties or sweater laces to prevent any foreign objects from contacting carbon fiber. Keep pre-preg carbon fiber in freezer when not in use. Pre-preg will pre-cure if left at room temperature, which will affect its material properties, and may cause it to become unfit for production.

Operations:

OP #: 100

DESCRIPTION: Prepare Mandrel

TOOLING: Rotor-Jig, Mandrel Plugs, Sand Paper, Water Hose, Towels

RUN TIME: 3 hours

Operations Required: 3 or more

Operation:

Set up rotor-jig with appropriate size plugs (2", 2.5", or 3") onto the metal rods at each end.

Suspend Mandrel on rotor-jig by fitting the plugs inside the mandrel holes. If plugs are loose in the mandrel to the effect that the mandrel plugs spin free of the mandrel, add strips of adhesive tape until it has a tight fit.

Clamp and/or weight down each rotor-jig base so that the entire set-up is rigid.

One operator operates the rotor crank; maintain a quick rotation of the mandrel

All other operators use sand paper to smooth mandrel surface. Slowly work down the mandrel until entire surface has been covered. Make sure to spend extra time at both ends.
Use rough sand paper for 1\textsuperscript{st} pass, medium for the 2\textsuperscript{nd}.

For 3\textsuperscript{rd} and 4\textsuperscript{th} pass use 350 and 600 grit. These require wet sanding. One operator needs to operate a water hose and maintain consistent wetting of the sand paper to remove all the small particles.

After final pass is complete, spray down mandrel with water to remove all particles from mandrel.

Dry mandrel with towels.

If this operation is being completed after a spar removal, only use 600 grit.

Wrap mandrel in plastic wrap for protection during storage.

Remove mandrel from rotor-jig.

Disassemble rotor-jig.

---

**OP #: 200**

**DESCRIPTION:** Cut Carbon Fiber

**TOOLING:** Rule, Cutting Knife, Cutting Board, Marker, Pre-Preg Uni

**RUN TIME:** 2.5 Hours

**OPERATORS REQUIRED:** 2

**OPERATION:**

Lay out carbon fiber sheet on top of cutting board. All strips are cut from the same pre-preg uni material.

Measure out strips according to “Carbon Fiber Cutting Dimensions” chart, Appendix X.

Cut strips out using cutting knife. Avoid stringing strands on edges and keep cuts straight. Strips should be cut with the strands running down the length. Note that for the 45° sections, cut straight rectangular sections as in the axial, as the 45° angle comes from the wrapping process.

Number each section in order to have them later applied in the correct order.

---

**OP #: 300**

**DESCRIPTION:** Set-up

**TOOLING:** Rotor-Jig, Mandrel Plugs, Clamps
RUN TIME: 10 minutes
OPERATORS REQUIRED: 3

OPERATION:
1. Set up rotor-jig with appropriate size plugs (2", 2.5", or 3") onto the metal rods at each end.
2. Suspend mandrel on rotor-jig by fitting the plugs inside the mandrel holes. If plugs are loose in the mandrel to the effect that the mandrel plugs spin free of the mandrel, add strips of adhesive tape until it has a tight fit.

Clamp and/or weight down each rotor-jig base so that the entire set-up is rigid.

Un-wrap any plastic wrap or similar covering that may be on the mandrel.

OP #: 311 - 312
DESCRIPTION: Apply Release Agent
TOOLING: Paper Towel, Release Agent
RUN TIME: 10 minutes + 20 minute Drying Sequence
OPERATORS REQUIRED: 3
OPERATION:
Have one operator handle the rotor-jig's crank and maintains a quick rotation of the mandrel.
2nd pours the release agent in a very light stream.
3rd operator stands on other side of mandrel and follows closely behind and wipes with paper towels. Use towels to spread out release agent and wipe up excess. Avoid “candy-cane” effect on the mandrel

OP #: 321 - 324
DESCRIPTION: Wrap 45° Layer
TOOLING: 45° Carbon Fiber Strip, Heat Gun
RUN TIME: 30 minutes - 20 minutes
OPERATORS REQUIRED: 3
OPERATION:
Identify correct strip (based on width of carbon fiber strip)

Use a triangle to measure out a 45° angle. Line up end of carbon fiber strip near the end of the mandrel, but do not do over edge or cover any of the holes. The edge of a 45° layer is shown in Figure 11-3.

Spin the mandrel 360° to check the overlap. Overlap should be between 1/4” and 1/16”. For first layer, use high-end overlap as strip will not stick effectively to bare mandrel. Use heat gun if necessary to preheat carbon fiber to make it sticky. Peel off all paper backing before overlap.

One operator operates the rotor crank.

2nd operator lays down carbon fiber. Smooth out strips flat onto mandrel, massaging any wrinkles or crimps out. Communicate with 1st operator on speed of mandrel rotation. Remove paper backing before it gets wrapped under strip, but do not remove beyond point of contact with the mandrel. Without the paper, the mandrel can easily break apart or fray.

3rd operator holds rolled-up strip to keep it off the floor, and feeds strip to 2nd operator. Keep the strip taunt and maintain pressure outwards on both sides of the strip. This reduces potential wrinkles or crimps as fiber is laid down. Maintain watch on overlap.

If overlap gets out of tolerance, carefully remove paper to just beyond point of contact with the mandrel. This allows 2nd operator to manipulate the fiber to the correct angle. Smooth out any wrinkles that result from this. Continue remaining roll as before.

At the end of the roll, cut any excess fiber off if it goes beyond mandrel or covers any rolls. If too short, add additional strips of appropriate length. Start with a slight overlap of previous strip.

Repeat for subsequent layers. Alternate sides of the mandrel after each layer to offset the previous layer. This will create an even 45° and -45° composite structure.

OP #: 331-333

DESCRIPTION: Wrap Axial Layer

TOOLING: Axial Carbon Fiber Strip, Heat Gun

RUN TIME: 20 minutes
OPERATORS REQUIRED: 3

OPERATION:

Identify correct strip (based on width of carbon fiber strip).

2 operators hold one end each of strip over either end of the mandrel. Center strip over center of the mandrel. Keep strip taunt and maintain pressure outwards of both sides of the strip. Hover just above the mandrel.

3rd operator, starting in the middle, smooth down top of strip onto mandrel. Work towards one end of the strip. Cup hands and massage to keep wrinkles moving towards ends of strip.

Now 2 operators can start in the middle and work out towards either end of the strip. Lay down strip all the way down. If there’s an overlap, simply avoid smoothing down the very edges of the strip at this time.

Rotate the mandrel 180°.

Remove about 1” of tape just from the edge of both sides of the strip.

Fold down one edge of the strip (starting in the middle and working outwards towards the ends).

Fold down the other edge of strip (starting in the middle and working outwards towards the ends).

If necessary, apply heat with heat gun down gap or overlap.

Peel off remaining paper.

Repeat for subsequent layers.

Mark each ends of the spar with the appropriate serial number.

OP #: 341

DESCRIPTION: Shrink Tape Wrap

TOOLING:

RUN TIME: 25 minutes

OPERATORS REQUIRED: 2

OPERATION:

Use adhesive tape to tape down shrink tape over edge of mandrel.

1st operator operates the rotor crank. Spin at high speeds.
2nd operator holds shrink tape roll. Maintain strong resistance to ensure tight wrap. Overlap shrink tape over itself 75-80%.

If roll runs out, stop rotation, tape new roll to old role, slowly rotate mandrel until overlap, then proceed as before.

At end of spar, be sure to wrap past carbon fiber, cut shrink tape, then tape end down.

OP #: 351
DESCRIPTION: Tear Down

TOOLING:
RUN TIME: 10 minutes
OPERATORS REQUIRED: 3

OPERATION:
Remove mandrel from rotor-jig.
Carefully store mandrel in designated area.
Disassemble rotor-jig.

11.3 Curing Process
OP #: 400
DESCRIPTION: Cure Spar

TOOLING: Oven
RUN TIME: 2 hours
OPERATORS REQUIRED: 2

OPERATION:
Place spar(s) in oven. Space them evenly so that they are not in contact with each other
Heat up oven to 250° F. This takes about an hour.
Keep oven at 250° F for 60 minutes. Do not open or disturb oven at this time.
Open oven and let the spars air cool for 15 minutes. Caution: spars will be hot. Do not remove until they reach back to room temperature.
Caution: after curing, the carbon fiber is extremely rigid, and thin layers at the ends or single strands can be very harmful. Take care not to get cut or similar bodily harm.

11.4 Post-Cure Operations

OP #: 500

DESCRIPTION: Remove Spar off Mandrel

TOOLING:

RUN TIME: 10 minutes

OPERATORS REQUIRED: 3-5 (or as many as required)

OPERATION:

Un-wrap shrink tape from finished spar.

Insert ¼” rod through both holes at end of mandrel.

Brace end of mandrel inside a vise so that the rod is up against the vise jaws.

Have team of 3-5 pull spar off the mandrel. Resulting cracking sounds is the release agent and resin breaking from mandrel. Be careful to catch mandrel as it falls free of spar. Take care to not damage either.

Re-sand mandrel as in Operation #100 Step 7.

<table>
<thead>
<tr>
<th>Post-Cure operations</th>
<th>DESCRIPTION</th>
<th>TOOLING</th>
<th>NOTES</th>
</tr>
</thead>
<tbody>
<tr>
<td>000</td>
<td>Safety</td>
<td></td>
<td></td>
</tr>
<tr>
<td>600</td>
<td>Cut Spar</td>
<td>Tile Saw</td>
<td></td>
</tr>
<tr>
<td>700</td>
<td>Sand Spar</td>
<td>Rotor-Jig, Belt Sander</td>
<td></td>
</tr>
<tr>
<td>800</td>
<td>Drill Spar</td>
<td>Drilling Fixture, Drill Press</td>
<td></td>
</tr>
</tbody>
</table>

OP #: 000

DESCRIPTION: SAFETY

NOTES:

The post-cure operations involve the use of heavy machinery and hazardous materials. Eye protection is required at all times. When cutting, sanding, and drilling carbon fiber, apply vacuum to areas under work and wear facemasks.

Required Personal Safety Equipment: Closed toed shoes, long pants, safety glasses. Processes include the use of sharp and/or heavy objects. Take care when handling all material to reduce bodily harm.
Optional Personal Safety Equipment: Latex gloves. Note: while the pre-preg is not harmful to skin, it can be hazardous to consume. Wash hands before and after contacting pre-preg.

Mandrel Protection: Mandrel must be protected from any harm, including but not limited to: dropping, scratches, and hazardous materials. Any damage may result in inconsistent composite structure and can make removal of cured spar extremely difficult. Store mandrels in protected area away from traffic.

Pre-Preg Protection: Pre-preg is tacky by nature as the resin is already in material. It becomes tackier with increases in temperature. This makes it susceptible to gathering dust or particles, especially if laid on the ground. Avoid dropping carbon fiber. Leave back paper on at all times until appropriate time during layup process. All operators should thoroughly wash their hands before contacting pre-preg. Roll up all long sleeves, tie up long hair, and tuck in any ties or sweater laces to prevent any foreign objects from contacting carbon fiber. Keep pre-preg carbon fiber in freezer when not in use. Pre-preg will pre-cure if left at room temperature, which will affect its material properties, and may cause it to become unfit for production.

OP #: 600
DESCRIPTION: Cut Spar
TOOLING: Tile Saw
SET-UP TIME: 10 minutes
RUN TIME: 5 minutes
NOTES:
Set-up tile saw. Make sure sufficient water is in the tray to provide adequate cooling throughout entire process.

Refer to part drawings for correct dimensions to cut. Measure cut on Spar. Compensate for the width of the saw blade.

Slowly make cut by pushing spar and rest through saw. A second operator is necessary to hold the extreme end of the spar so it does not sag during cutting.

OP #: 700
DESCRIPTION: Sand Spar
TOOLING: Rotor-Jig, Belt Sander
SET-UP TIME: 15 min
RUN TIME: 2 hours

NOTES:

Set-up up spar between centers on Rotor-Jig. Note that there will no longer be a press fit as the inside diameter of the spars is greater than the inside diameter of the mandrel. To achieve a fit, wrap tape, paper towel, or a similar non-permanent material around the plug.

While one operator rotates the spar, the other operator(s) sand the spar using a belt sander. Apply light pressure and even appliance over complete spar length. The finished carbon fiber will be a constant dull grey color. The shiny black surface is outer layer of resin that bled through during curing. The white specks and coloring is the shrink tape.

OP #: 800

DESCRIPTION: Drill Spar

TOOLING: Drilling Fixture, Drill Press, Drill Index, Grinding Bit

SET-UP TIME: 20 min

RUN TIME: 1 hour

NOTES:

Position drilling fixture so that the drill bit will be over the apex of the part or the center of the v-block.

Clamp drilling fixture to the drill table.

Place a piece of duct-tape over hole location. Measure and mark hole placement.

Clamp spar into drilling fixture at the correct hole position.

One operator will hold vacuum so that it will collect most of the chips and dust. Be wary of the spinning drill bit. They are also responsible for supplying a constant stream of cutting fluid over the hole position. Second operator will operate drill press.

Use center drill to locate and mark hole position.

Start with a ¼” drill bit to drill a through hole through the top of the carbon fiber. The smaller bits may not be long enough to drive through both ends of the tube. When drilling through the fiber, take small quick plunges into the material. Do not force tool through or risk cracking the fiber. Start at 500 RPM.

Use gradually increasing drill sizes to enlarge hole. Be careful when starting the hole on the inside of the spar, as this will usually be with a larger drill bit. Every increase in drill bit size should see a slight reduction in RPM.
If available, use a grinding bit to finish the hole. These leave a better surface finish and cut a rounder hole than drill bits.

Be careful when cutting through the bottom side of the spar to not drill into the fixture. Do not attempt to drill top and flip spar over. Matching up the holes is extremely difficult and inaccurate.

11.5 Transition Sleeves Manufacturing

In addition to spar manufacturing, the bottleneck sleeves and bushings and collars must be manufactured as well.

11.5.1 Bottleneck Sleeve

<table>
<thead>
<tr>
<th>Bottleneck Operations</th>
<th>DESCRIPTION</th>
<th>TOOLING</th>
<th>NOTES</th>
</tr>
</thead>
<tbody>
<tr>
<td>000</td>
<td>Safety</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>Mandrel Manufacturing</td>
<td>HASS CNC Lathe</td>
<td>See G-Code</td>
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<tr>
<td>200</td>
<td>Cut Carbon Fiber</td>
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</tr>
<tr>
<td>300</td>
<td>Wrap Mandrel</td>
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<tr>
<td>400</td>
<td>Shrink Tape</td>
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<tr>
<td>500</td>
<td>Cure Sleeve</td>
<td>Autoclave</td>
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<tr>
<td>600</td>
<td>Sleeve Removal</td>
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<td>700</td>
<td>Cut Sleeve</td>
<td>Tile Saw</td>
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<tr>
<td>800</td>
<td>Sand</td>
<td></td>
<td></td>
</tr>
<tr>
<td>900</td>
<td>Drill Landing Gear Holes</td>
<td>Drill Press, Drill Fixture</td>
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</table>

Sleeve Carbon Fiber Dimensions

<table>
<thead>
<tr>
<th>Type</th>
<th>Size</th>
<th>Number of Layers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial</td>
<td>1”-1.5” by 24”</td>
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</tr>
<tr>
<td>Small Diameter 90°</td>
<td>10” x 2.31”</td>
<td>5</td>
</tr>
<tr>
<td>Large Diameter 90°</td>
<td>11” x 2.81”</td>
<td>5</td>
</tr>
<tr>
<td>Curve Feature 90°</td>
<td>1.25” x 8”</td>
<td>2</td>
</tr>
</tbody>
</table>

OP #: 000

DESCRIPTION: Safety

NOTES:

The bottleneck manufacturing involves the use of heavy machinery and hazardous materials. Eye protection is required at all times. When cutting, sanding, and drilling carbon fiber, apply vacuum to areas under work and wear facemasks.

Required Personal Safety Equipment: Closed toed shoes, long pants, safety glasses. Processes include the use of sharp and/or heavy objects. Take care when handling all material to reduce bodily harm.
Optional Personal Safety Equipment: Latex gloves. Note: while the pre-preg is not harmful to skin, it can be hazardous to consume. Wash hands before and after contacting pre-preg.

Mandrel Protection: Mandrel must be protected from any harm, including but not limited to: dropping, scratches, and hazardous materials. Any damage may result in inconsistent composite structure and can make removal of cured spar extremely difficult. Store mandrels in protected area away from traffic.

Pre-Preg Protection: Pre-preg is tacky by nature as the resin is already in material. It becomes tackier with increases in temperature. This makes it susceptible to gathering dust or particles, especially if laid on the ground. Avoid dropping carbon fiber. Leave back paper on at all times until appropriate time during layup process. All operators should thoroughly wash their hands before contacting pre-preg. Roll up all long sleeves, tie up long hair, and tuck in any ties or sweater laces to prevent any foreign objects from contacting carbon fiber. Keep pre-preg carbon fiber in freezer when not in use. Pre-preg will pre-cure if left at room temperature, which will affect its material properties, and may cause it to become unfit for production.

OP #: 100
DESCRIPTION: Mandrel Manufacturing
TOOLING: HASS CNC Lathe, Carbide Cutting Tool,
SET-UP TIME: 20 minutes
RUN TIME: 2 hours
STARTING MATERIAL: 3" DIA polypropylene round
NOTES:

Cut polypropylene mandrel to 30" in length.

Secure one end into lathe chuck. Given the length of material, secure other end in a live center in the tailstock for stability.

Run the following G-Code. Note that the code matches the final dimensions and involves a single finishing cut. Compensate by adding to the offset the starting material DIA, and subtracting after each pass to get a .050” depth of cut until the final dimensions are met.

O####
G50 S2000
G00 T101 G97 S500 M03
G00 X2.354 Z0.25
G01 X2.354 Z-11. F0.02
G02 X2.602 Z-12. R6
G03 X2.85 Z-13. R6
G01 Z-24.5
G01 X3.
G00 Z0.025
G97
G51
M30
%

Remove from lathe when completed. The final mandrel will have a section of uncut material on the end where the part was held in the chuck. Do not remove this material as it will be used in the sleeve removal process.

OP #: 200
DESCRIPTION: Cut Carbon Fiber
TOOLING: Pre-preg, Cutting Board, Razor
SET-UP TIME: 10 min
RUN TIME: 1 hour
NOTES:
Lay out carbon fiber sheet on top of cutting board. All strips are cut from the same pre-preg uni material.

Measure out strips according to “Sleeve Carbon Fiber Dimensions” chart, Appendix X.

Cut strips out using cutting knife. Avoid stringing strands on edges and keep cuts straight. Strips should be cut with the strands running down the length. Note that for the 45° sections, cut straight rectangular sections as in the axial, as the 45° angle comes from the wrapping process.
Number each section in order to have them later applied in the correct order.

For the beer bottle sleeve the laminate layup consists of 10 layers; 5 layers of unidirectional carbon fiber and 5 layers of 90° carbon fiber is wrapped by alternating layers beginning with a unidirectional layer. The unidirectional layers are cut 1"- 1.5" wide (anywhere in this range is acceptable) and 24" long. The 90° layers are cut in 10" or 11" wide sections depending on whether the section wrapped is on the large or small diameter. Their lengths match the circumferences of the small and large diameters of the mandrel. The taper is handled by taking two 6"-8" long by 1.25" wide strips of carbon fiber and wrapping around the tapered section.

OP #: 300
DESCRIPTION: Wrap Mandrel
TOOLING: Carbon Fiber Strips, Mandrel,
SET-UP TIME: 5 min
RUN TIME: 1 hour
NOTES:
Note: release agent is not required for polypropylene.

Wrap the first layer of unidirectional. The first strip of the layer is placed at the bottom of the bigger diameter section and then laid lengthwise over the mandrel. The next strip is applied in the same manner, minimally overlapping the previous section, yet allowing enough area for the strips to adhere to each other. This procedure is followed until the layer is completed.

After the first unidirectional layer is placed, the first 90° layer is added next. Wrapping the 90° layers is also done in sections. The first sections to be applied are for the non-tapered sections. These are wrapped around the mandrel similar to laying up an axial layer on a spar, except with the fiber direction at 90°. These can be applied in any order.

The taper is handled by taking two 6"-8" long by 1.25" wide strips of carbon fiber and wrapping around the tapered section. Any remaining gaps are filled in with scraps in the 90° direction to complete the layer. The length of the 90° sections increases with each layer to compensate for the increase of the bottle sleeve diameter after every layer.

Continue alternating between unidirectional and 90° layers until 10 layers have been applied.

OP #: 400
DESCRIPTION: Shrink Tape
TOOLING: Shrink Tape
SET-UP TIME: 1 min
RUN TIME: 10 min
NOTES:
Use adhesive tape to tape down shrink tape over edge of mandrel.
Wrap shrink tape using a 75% overlap to ensure complete coverage and apply even pressure over entire mandrel.
At end of spar, be sure to wrap past carbon fiber, cut shrink tape, then tape end down

OP #: 500
DESCRIPTION: Cure Sleeve
TOOLING: Autoclave
SET-UP TIME: 10 min
RUN TIME: 1 hour
NOTES:
Prepare autoclave or oven for cure.
Place sleeve in autoclave. Seal and lock.
Slowly heat sleeve to 250° F over 30 min.
Keep at 250° F for 60 min.
Turn off heat and allow part to return to room temperature.
Remove sleeve from autoclave when cool.

OP #: 600
DESCRIPTION: Sleeve Removal
TOOLING: 1 min
SET-UP TIME: 1 min
To remove the mandrel, hold the wide polypropylene end with one hand and pull the carbon fiber with the other. The sleeve should come off easily since the resin does not bond well to the polypropylene and the part is short.

OP #: 700
DESCRIPTION: Cut Sleeve
TOOLING: Tile Saw
SET-UP TIME:
RUN TIME: 5 min
NOTES:
Set-up tile saw. Make sure sufficient water is in the tray to provide adequate cooling throughout entire process.
Refer to part drawings for correct dimensions to cut to. Measure cut on Spar. Compensate for the width of the saw blade.
Slowly make cut by pushing spar and rest through saw. A second operator is necessary to hold the extreme end of the spar so it does not sag during cutting.

OP #: 800
DESCRIPTION: Sand
TOOLING: Rotor-Jig, Belt Sander
SET-UP TIME: 10 min
RUN TIME: 20 min
NOTES:
Set-up up spar between centers on Rotor-Jig. The wide end will use the 3” diameter plug and the narrow end will use the 2.5” plug. Note that there will no longer be a press fit as the inside diameter of the spars is greater than the inside diameter of the mandrel. To achieve a fit, wrap tape, paper towel, or a similar non-permanent material around the plug.
While one operator rotates the spar, the other operator(s) sand the spar using a belt sander. Apply light pressure and even appliance over complete spar length. The finished carbon fiber will be a constant dull grey color. The shiny black surface is outer layer of resin that bled through during curing. The white specks and coloring is the shrink tape.

OP #: 900
DESCRIPTION: Drill Landing Gear Holes
TOOLING: Drill Press, Drilling Fixture, Drill Index, Grinding Bit

SET-UP TIME:
RUN TIME:
NOTES:

Position drilling fixture so that the drill bit will be over the apex of the part or the center of the v-block.

Clamp drilling fixture to the drill table.

Place a piece of duct-tape over hole location. Measure and mark hole placement.

Clamp spar into drilling fixture at the correct hole position.

One operator will hold vacuum so that it will collect most of the chips and dust. Be wary of the spinning drill bit. They are also responsible for supplying a constant stream of cutting fluid over the hole position. Second operator will operate drill press.

Use center drill to locate and mark hole position.

Start with a ¼” drill bit to drill a through hole through the top of the carbon fiber. The smaller bits may not be long enough to drive through both ends of the tube. When drilling through the fiber, take small quick plunges into the material. Do not force tool through or risk cracking the fiber. Start at 500 RPM.

Use gradually increasing drill sizes to enlarge hole. Be careful when starting the hole on the inside of the spar, as this will usually be with a larger drill bit. Every increase in drill bit size should see a slight reduction in RPM.

If available, use a grinding bit to finish the hole. These leave a better surface finish and cut a rounder hole than drill bits.

Be careful when cutting through the bottom side of the spar to not drill into the fixture. Do not attempt to drill top and flip spar over. Matching up the holes is extremely difficult and inaccurate.
11.5.2 Bushings
Refer to drawing set for full dimensions.

<table>
<thead>
<tr>
<th>OP #</th>
<th>DESCRIPTION</th>
<th>TOOLING</th>
<th>NOTES</th>
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</thead>
<tbody>
<tr>
<td>000</td>
<td>Safety</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>Facing</td>
<td>Lathe</td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>Turning</td>
<td>Lathe</td>
<td></td>
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<tr>
<td>300</td>
<td>Boring</td>
<td>Lathe, Boring Bar</td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>Parting</td>
<td>Lathe, Parting Tool</td>
<td>x4 parts</td>
</tr>
<tr>
<td>500</td>
<td>Deburring</td>
<td>File, Deburring Tool</td>
<td></td>
</tr>
</tbody>
</table>

OP #: 000
DESCRIPTION: Safety

NOTES:
Required Personal Safety Equipment: Closed toed shoes, long pants, safety glasses. Processes include the use of sharp and/or heavy objects. Take care when handling all material to reduce bodily harm.

OP #: 100
DESCRIPTION: Facing

TOOLING: Lathe

SET-UP TIME: 15 min

RUN TIME: 2 min

STARTING MATERIAL: 3” Diameter polypropylene, 12-18” in length

NOTES:
Set polypropylene in lathe chuck so that at least 6” of material is hanging out.

Face end until smooth

V-Speed: 500 RPM

OP #: 200
DESCRIPTION: Turning

TOOLING: Lathe
SET-UP TIME: 1 min
RUN TIME: 20 min

NOTES:

- Turn part down to 2.375" +/- 0.005
- V-Speed: 500 RPM
- Depth of Cut: 0.050"

OP #: 300
DESCRIPTION: Boring
TOOLING: Center Drill, ¼" Drill, ½" Drill, 1" Drill, Boring Bar

SET-UP TIME: 5 min
RUN TIME: 30 min

NOTES:

- Set-up center drill in tailstock and start hole
- Use ¼" and ½" drill bits to progressively increase hole size. Drill as far into part as possible
- Use largest drill bit size available to finish hole enlargement before boring.
- V-speed: 500 RPM
- Set up boring bar in compound rest.
- Use boring bar to bore out hole to 2.164”.
- Depth of cut: 0.050"

OP #: 400
DESCRIPTION: Parting
TOOLING: Parting Tool

SET-UP TIME: 5 min
RUN TIME: 5 min
NOTES:
Set-up parting tool in compound rest
Part off a .75" part
Repeat 4 times
Remove polypropylene from chuck

OP #: 500
DESCRIPTION: Deburring
TOOLING: File, Deburring Tool, File, Sand Paper
SET-UP TIME: 1 min
RUN TIME: 5 min
NOTES:
Use hand tools to clean up part for any rough edges or tabs left from the parting operation.

11.5.3 Collars
Refer to drawing set for full dimensions.

<table>
<thead>
<tr>
<th>Collars Operations</th>
<th>OPERATION</th>
<th>TOOLING</th>
<th>DETAILS</th>
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</thead>
<tbody>
<tr>
<td>000</td>
<td>Safety</td>
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<tr>
<td>100</td>
<td>Facing</td>
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<td>300</td>
<td>Boring</td>
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<td>400</td>
<td>Parting</td>
<td>Lathe, Parting Tool</td>
<td>x8 parts</td>
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<tr>
<td>500</td>
<td>Deburring</td>
<td>Deburring Tool, File</td>
<td></td>
</tr>
</tbody>
</table>

OP #: 000
DESCRIPTION: Safety
NOTES:
Required Personal Safety Equipment: Closed toed shoes, long pants, safety glasses. Processes include the use of sharp and/or heavy objects. Take care when handling all material to reduce bodily harm.
OP #: 100
DESCRIPTION: Facing
TOOLING: Lathe
SET-UP TIME: 15 min
RUN TIME: 2 min
STARTING MATERIAL: 3” Dia polypropylene, 12-18” in length
NOTES:
Set polypropylene in lathe chuck so that at least 6” of material is hanging out.
Face end until smooth
V-Speed: 500 RPM

OP #: 200
DESCRIPTION: Turning
TOOLING: Lathe
SET-UP TIME: 1 min
RUN TIME: 20 min
NOTES:
Turn part down to 2.350”
V-Speed: 500 RPM
Depth of Cut: .050”

OP #: 300
DESCRIPTION: Boring
TOOLING: Center Drill, ¼” Drill, ½” Drill, 1” Drill, Boring Bar
SET-UP TIME: 5 min
RUN TIME: 30 min
NOTES:
Set-up center drill in tailstock and start hole
Use ¼” and ½” drill bits to progressively increase hole size. Drill as far into part as possible
Use largest drill bit size available to finish hole enlargement before boring.
V-speed: 500 RPM
Set up boring bar in compound rest.
Use boring bar to bore out hole to 2.165”.
Depth of cut: .050”

OP #: 400
DESCRIPTION: Parting
TOOLING: Parting Tool
SET-UP TIME: 5 min
RUN TIME: 5 min
NOTES:
Set-up parting tool in compound rest
Part-off a .25” part
Repeat 8 times
Remove polypropylene from chuck

OP #: 500
DESCRIPTION: Deburring
TOOLING: File, Deburring Tool, File, Sand Paper
SET-UP TIME: 1 min
RUN TIME: 5 min
NOTES:
Use hand tools to clean up part for any rough edges or tabs left from the parting operation.