ABSTRACT

Title of Document: COMPOSITE CONSTRUCTION OF AN UNMANNED AERIAL VEHICLE

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Directed By: Professor Norman Wereley
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The purpose of this thesis is to develop an understanding of composite construction while building a systematic manufacturing and assembly process for the construction of an all-composite Unmanned Aerial Vehicle. This thesis in intended for both beginners and advanced composite builders and documents the entire construction of a molded composite aircraft from CAD to Runway.

Several processes are discussed including CNC Plug Milling and Foam Cutting, Wet Lay-up, Tooling Manufacturing and Vacuum Assisted Resin Transfer Molding (VARTM – Infusion). Materials extensively used such as polyester resin/MEKP, gel coat, random directional matting, and carbon reinforcement are presented in an illustrated "how-to" approach to building.

COMPOSITE CONSTRUCTION OF AN UNMANNED AERIAL VEHICLE

By

Evandro Gurgel do Amaral Valente

Thesis submitted to the Faculty of the Graduate School of the
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Professor Norman Wereley, Chair
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Professor Jewel Barlow

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2006

Acknowledgements

"Tell me who you walk with and I'll tell you who you are…" Well, these are my friends…..

There have been many hands involved in the creation of this composite aircraft. The undergraduate students whom I have had the pleasure of working with have repeatedly shown a level of commitment that exceeded my expectations many times over. All of you have worked tirelessly and have created many positive memories for all of us to share. Some of the undergraduate team members are shown in the group photo in Chapter 8.

Their names, starting from top left, are:
Gene Cook, Jolyon Zook, Joe Lisee, Nick Wilson, Ben Hoffman
Bottom row, starting from left:
Jon Graff, Evandro Valente (myself), Matt Kless
Other friends have helped and participated in this project. These too deserve mention and my vote of gratitude.
Chris Benic, Mike Chinn, Scott Jacobi, Lucas Parker, Brian Donelly and Holly Shurter

One particular individual in this all-composite UAV project has given 1,000,000% (or maybe more). My amount of admiration and profound respect for you, Gene Cook, can only be partially captured with the following adjective, "leviathanesque". Gene is credited with all of the superb CAD renditions used in this document. Gene, I wish you the best at MIT…your intelligence and talents are mirrored by your <u>humility</u> and professionalism, this is extremely rare.

Thank you all for a job very very well done!

As far as my graduate school days, other friends have been there through innumerous all-nighters and have given it their best along side myself. To my grad friends and classmates, through thick and thin, from 9pm to 9am, from sweat to tears, from laughs to more laughs, we will be forever "The Myers Crew" (Nathan Moulton, Assaf Barnoy, Allan Kruppa and Nick Tuozzo).

I am happy to have all of you as my friends and look forward to a fruitful and rewarding career as your peer and friend.

As for my parents and siblings, you have been supportive of my efforts since day one. There is only one four letter word that sums up the eternal bond that we have shared since we were born. I am blessed in having you as my family. Times have been tough, but we have been tougher.

Lastly, I would like to thank the folks at the Aerospace Engineering Department at UMD. You, the faculty and the staff, are no doubt number one.

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Chapter 1: Introduction

1.1 Motivation

The motivation for this thesis is to document the construction methods required for the manufacture of an all-composite aircraft. The goal is to create a recipe-like manuscript that not only develops the systematic procedures, but also passes invaluable experience to the reader.

The methods used for composite manufacturing promise substantial results, yet, heavily rely on one's ability to both carefully and patiently follow the described instructions. To increase first-time success rate, the author is particularly motivated towards sharing both good and bad experiences in the Advice Section of each Chapter. The beginner will benefit from this document by understanding and following the step-by-step construction. Meanwhile, advanced builders can use this document as a point of reference to refresh or refine their own composite construction background.

1.2 Introduction to Composite Material and Construction

1.2.1 Definition of Composite Materials

A composite material is made up of two constituents: the reinforcement and a binder called the matrix. The reinforcement and the matrix, when combined, work in concert to offer mechanical properties far superior than the components by themselves. The matrix has two roles in the composite material: 1) transfer loads to the structure, i.e. reinforcement and 2) shield the reinforcement from external and environmental hazards.

The reinforcement is the structural component of the composite often responsible for its anisotropic property. This means that a composite material is purposely designed to transmit loads along a preferred fiber direction. As a result, while properties along the fiber are superior, load-carrying ability in the transverse direction is minimal. Therefore, a composite structure can be specifically designed to carry loads in a particular or multidirectional path(s). Furthermore, a composite laminate may employ different materials for each layer; glass fiber – e-glass, s-glass, c-glass; carbon fiber – graphite and organic fiber – aramid.

Composites contain materials that are not only chemically different, but also generally mechanically separable. This additional definition further narrows the types of materials that qualify to be a composite. The composite materials discussed and used in this project fall under the polymer matrix and fiber reinforcement class of composites. One other term can be applied to composites as defined above. Since a composite, made of fiber and matrix, is made up of two or more materials, it is considered inhomogeneous. The material properties like density and internal structure are varied from point to point within a given sample.

1.2.2 Why Composite Construction

Since the first modern application of composites, a glass-reinforced fishing pole constructed in 1945, this new class of materials have revolutionized the way products are made. Although well established and backed by hundreds of years of usage, metals have been slowly replaced by composites in several industries. Advancements in technology have pushed the physical limits and requirements for materials. Metals are in no way being extinct from modern manufacturing methods, but rather sharing the workspace with composites that have unique characteristics.

Although the Aerospace Industry has used aluminum and titanium alloys that outperform steel, requirements like corrosion and fatigue resistance or high specific tensile stiffness have created a niche for composite materials. Early uses for composite were restricted to nonstructural applications since material properties were not completely known and were still under testing. As the decades progressed, the advents of new reinforcement fibers and construction techniques have inspired new applications for composites. These applications have combined both aesthetics appeal and structural properties into one package.

Typical overall advantages to composite materials are:

- High strength to weight ratio
- High stiffness to weight ratio
- Low density
- Environmental resistance
- Design versatility
- Chemical resistance
- Quick part turnaround

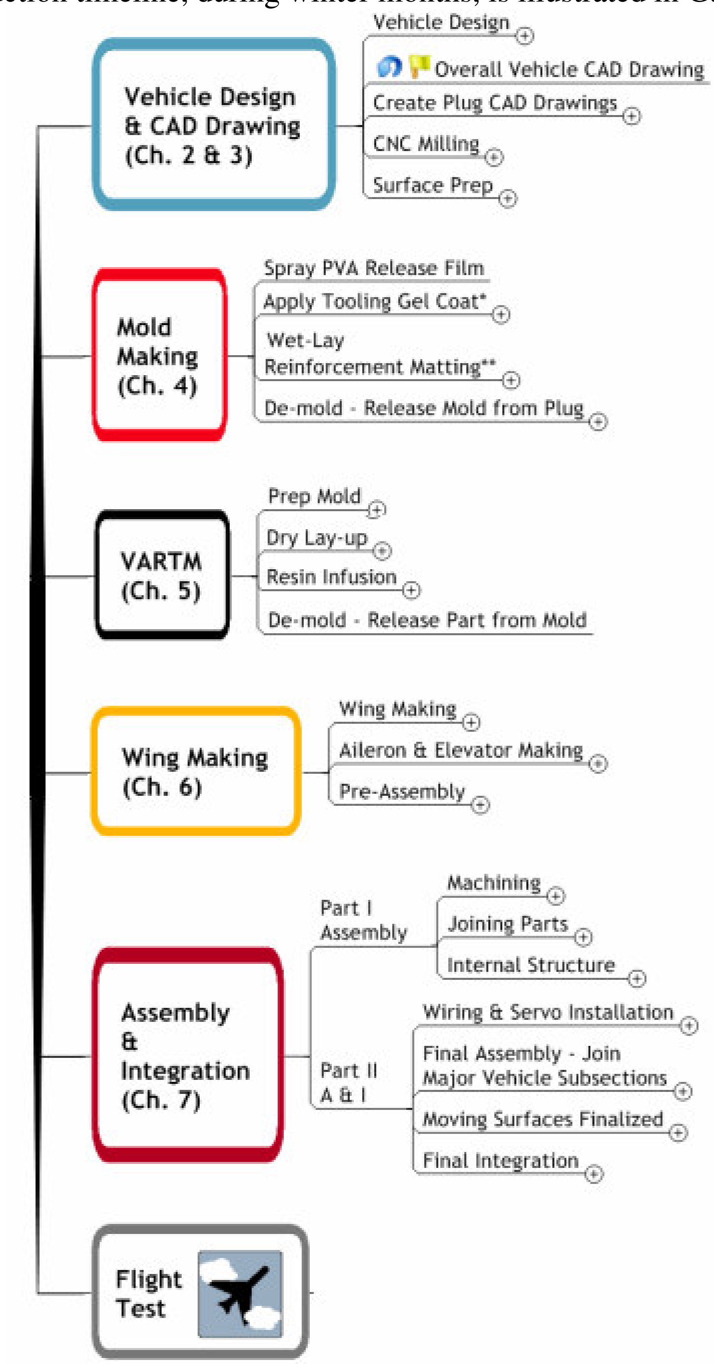
1.2.3 Manufacturing Techniques Overview

Manufacturing techniques for composite construction vary greatly and rely mainly on one key trade-off, target mechanical properties versus manufacturing costs. This trade-off profoundly influences the selection and application of one manufacturing method over another. Desired levels of output in production also drive the decision-making process to favor one method over another. Methods that offer quick turnaround at low costs often fall short in long-term applications, part quality and/or labor efficiency. On the other hand, methods of manufacturing with a higher start-up cost and/or skill requirement tend to be more advantageous for long-term high-quality high-output applications.

Typical manufacturing methods include manual wet lay-up, manual prepreg lay-up (with autoclaving), vacuum bagging, filament winding, pultrusion, vacuum assisted resin transfer molding (VARTM), resin transfer molding (RTM) with matched molds, resin film infusion (RFI) and more. The manufacturing techniques utilized in this project are wet lay-up, vacuum bagging, and VARTM.

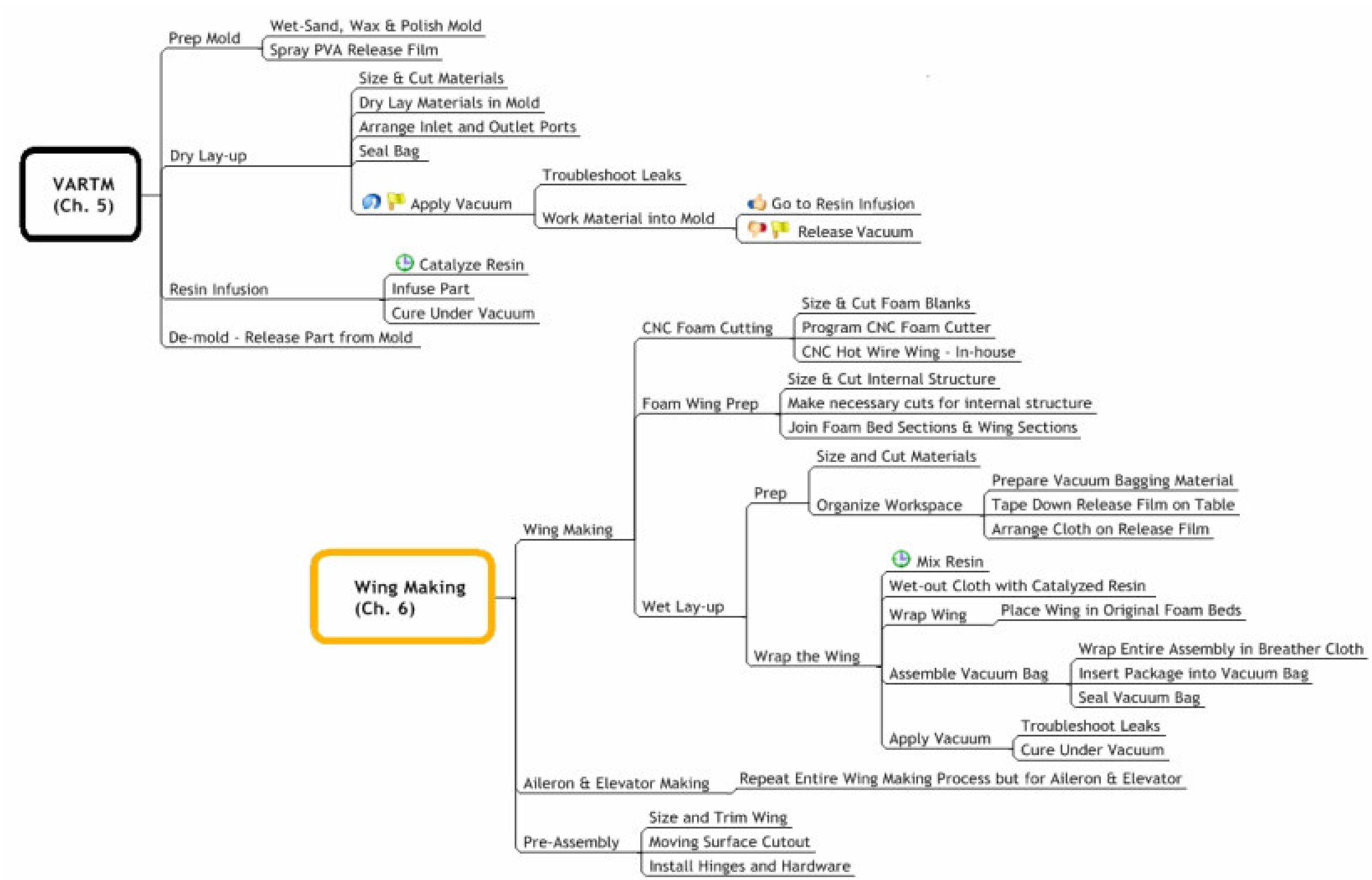
1.3 Aircraft Construction Flowcharts and Gantt Chart

Each chapter develops a major construction phase of the build (Flowchart 1.1). The contents of each chapter are organized into Flowcharts 1.2 to 1.5. A suggested vehicle construction timeline, during winter months, is illustrated in Gantt Chart 1.1.

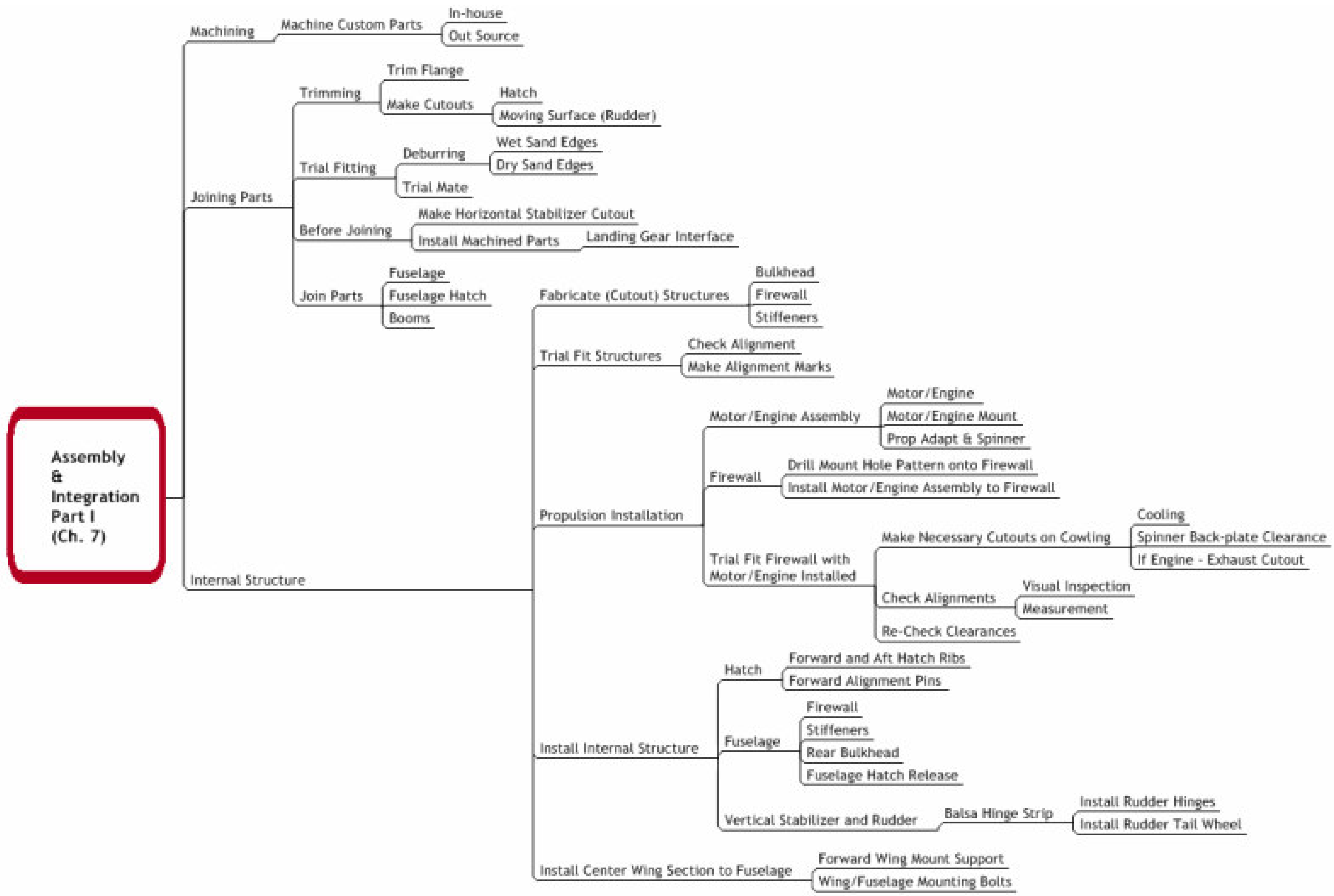


Flowchart 1.1. Overall Vehicle Construction Flowchart – collapsed.

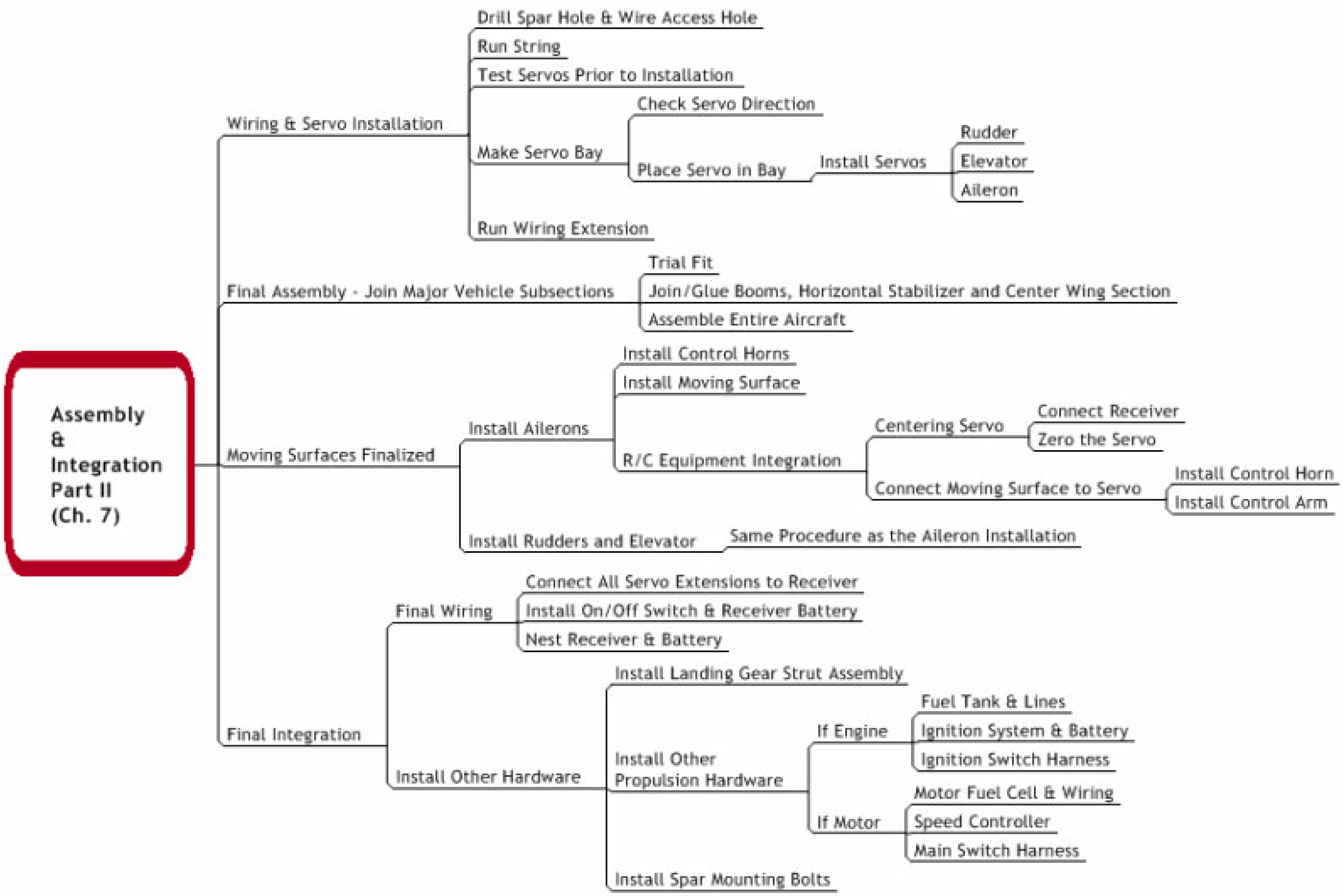
Flowchart 1.2. Chapters 2, 3 & 4 – expanded.



Flowchart 1.3. Chapters 5 & 6 – expanded.



Flowchart 1.4. Chapter 7 Part I (Low-Level Assembly) – expanded.



Flowchart 1.5. Chapter 7 Part II (High-Level Assembly) – expanded.

UAV Composite Construction	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Dates	Total Days
Chapter 2 - Vehicle Design	START								
Design Vehicle	30 Days							9/4 to 10/3	60 Days
CAD Drawing		30 Days						10/4 to 11/2	
Chapter 3 - Plug Fabrication									
CNC Mill Plugs			14 Days					11/3 to 11/16	24 Days
Surface Prep			10 Days					11/17 to 11/26	
Chapter 4 - Mold Fabrication									
Apply Release & Spray Gelcoat			7 Days					11/27 to 12/3	25 Days
Apply Reinforce Matting & Demold				18 Days				12/4 to 12/21	
Chapter 5 - Part Fabrication									
Prep Mold				4 Days				12/26 to 12/29	24 Days
Dry Lay-up, Infusion & Demold					20 Days			1/3 to 1/22	
Chapter 6 - Wing Fabrication									
Wing Making					16 Days			1/3 to 1/18	20 Days
Moving Surface and Pre-Assembly					4 Days			1/19 to 1/22	
Chapter 7 - Low Level Assembly									
Machine Custom Parts					1 Days			1/24 to 1/24	15 Days
Join Vehicle Parts					4 Days			1/25 to 1/28	
Fabricate Internal Structures & Trial Fit					4 Days			1/29 to 2/1	
Propulsion Intallation						2 Days		2/3 to 2/4	
Install Internal Structure						3 Days		2/5 to 2/7	
Install Wing-to-Fuselage Mounting Hardware						1 Days		2/8 to 2/8	
Chapter 7 - High Level Assembly									
Wiring & Servo Installation						3 Days		2/9 to 2/11	10 Days
Final Assembly						3 Days		2/13 to 2/15	
Moving Surfaces Final Installation						2 Days		2/17 to 2/18	
Final Integration						2 Days		2/19 to 2/20	
Flight Test						END		Total	178 Days

Gantt Chart 1.1 Suggested Vehicle Construction Timeline – wintertime construction.

1.4 Content of This Thesis

This thesis concentrates on developing the expertise necessary for fabrication, manufacture, assembly and integration of an all-composite aircraft. The sequentially ordered chapters represent the different stages of construction.

Chapter 2 introduces the CAD drawings generated during the design phase of this aircraft. From the overall design of the aircraft, the design of the plugs is realized.

Chapter 3 takes the CAD drawings of the plugs and turns them into real objects. The plugs are milled then prepped for mold making.

Chapter 4 develops the steps necessary to create molds from the plugs. The high quality molds are used to create the various composite parts of the aircraft.

Chapter 5 contains a systematic procedure for manufacturing aircraft parts using Vacuum Assisted Resin Transfer Molding. The high quality parts are the result of a vastly efficient molding technique that benefits from the vacuum infusion process.

Chapter 6 introduces the wet lay-up method of construction for wing making. The wings and horizontal stabilizer of the aircraft have a foam core wrapped in a single ply of carbon reinforcement.

Chapter 7 encompasses the entire assembly and integration phases of the build. The parts manufactured in previous chapters are joined piece by piece to create a fully integrated product. The first half of the chapter details the low-level assembly of parts. The second half of the chapter finalizes the assembly and vehicle integration.

Chapter 8 presents the completed aircraft.

Chapter 2: CAD Drawing

2.1 Overall Aircraft Drawings

2.1.1 Mission and Design Competition Parameters

The mission profile and aircraft requirements, in accordance with the ONR/AIAA Design/Build/Fly Competition Rules, defined the design criteria for successful entries. The vehicle discussed in this report was built to satisfy two of the three missions listed in the competition rules. The payload configuration and storage inside the aircraft is shown in Figure 2.8. Each mission involved flying the pattern shown in Figure 2.1.

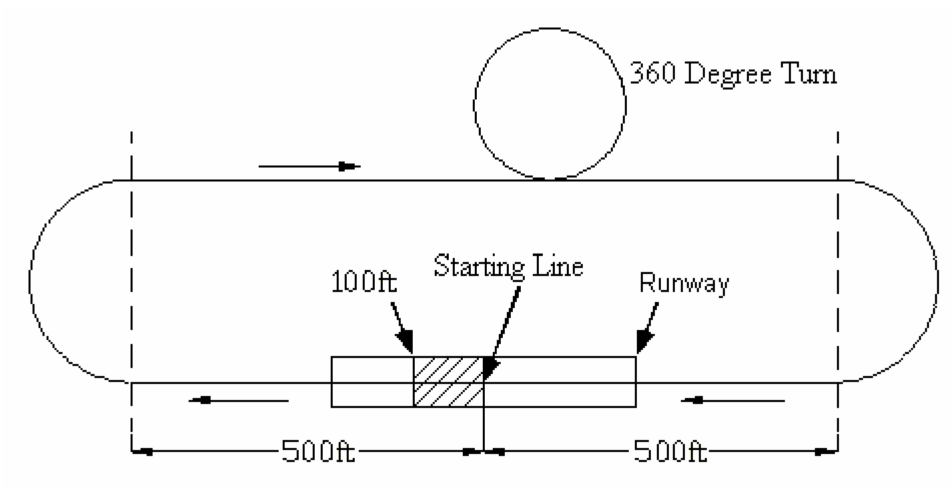


Figure 2.1. Competition Flight Pattern.

The first mission required 96 tennis balls to be flown for at least two minutes. The 96 balls could be flown at once or in multiple sorties. This aircraft was designed to carry 48 tennis balls in its cargo compartment, thus, required to fly two separate flights of two minutes each to score points successfully.

The second mission required three flights with three different payloads. Each payload was flown once around the course without an airborne flight duration requirement. The payload was flown once then changed, after landing, by the ground crew. The payloads were 48 tennisballs, two 2-Liter Soda bottles filled with water and, lastly, a wood block whose dimensions were specified in the competition rules.

The overall rules required all entries to have a propulsion system that used either a brushless or a brushed motor with a NiCad or NiMh battery pack weighing no more than three pounds.

2.1.2 Aircraft Dimensions, Specs and CAD Drawings

The vehicle parameters and dimensions are given in Table 2.1 and Figure 2.2, respectively. The airfoils used for the wing and horizontal stabilizer are NACA$63_3$618 and NACA0012, respectively. Figures 2.3 to 2.8 contain detailed CAD drawings of the aircraft.

Outboard Wing Section	
Outboard Span	46 in
Section Reference Area	455.4 in^2
Section Mean Aerodynamic Chord	9.9 in
Root Chord	12 in
Tip Chord	7.8 in
Taper Ratio	0.65
Entire Wing	
Wing Span	113.75 in
Wing Reference Area	1171 in^2
Wing Mean Aerodynamic Chord	10.3 in
Aspect Ratio	11.05
Empennage	
Horizontal Tail Area	196 in^2
Vertical Tail Area	144 in^2
Horizontal Tail Volume	5.11 ft^2
Vertical Tail Volume	3.57 ft^2
Performance Parameters	
CL_{max}	1.3
L/D_{max}	22.17
Takeoff Distance	90 ft (max weight)
	50 ft (empty weight)
Stall Speed	42 ft/s (max weight)
	32 ft/s (empty weight)
Aircraft Empty Weight	13 lbs
Electronic Systems	
Motor & Gear Ratio	NeuMotor 1515/2Y/6.7/F, 6.7:1
Speed Controller	77 Amp Jeti Opto
Propeller	APC 24 x 12
Battery Pack	21 Cells, CPB3300SC
Receiver	Futaba FP-R148DP
Aileron Servos	Hitec HS-85MG+ Mighty Micro
Rudder Servos	Hitec HS-225MG+ Mighty Mini
Elevator Servos	Hitec HS-645MG Ultra Torque

Table 2.1. Vehicle Parameters and Specifications.

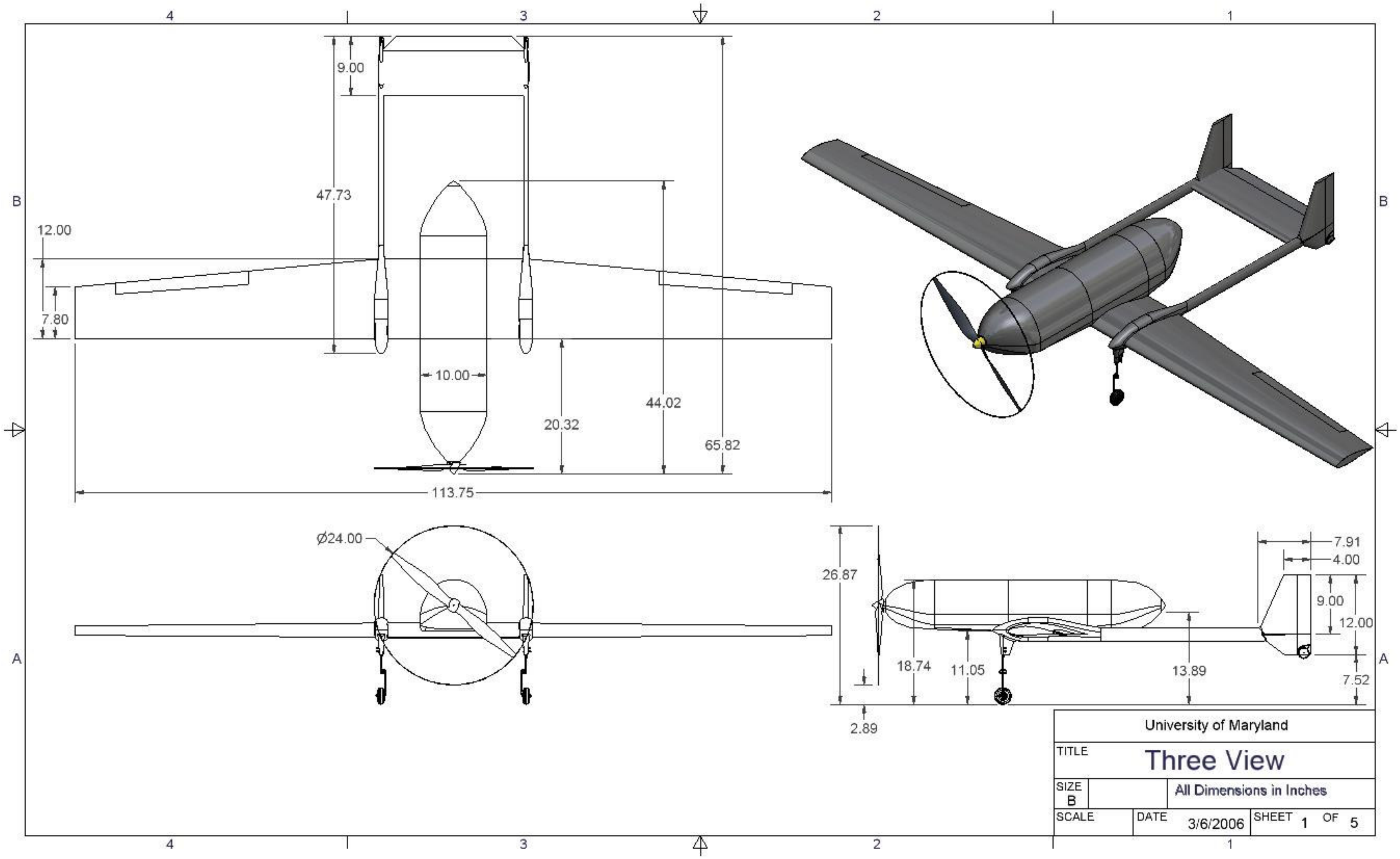
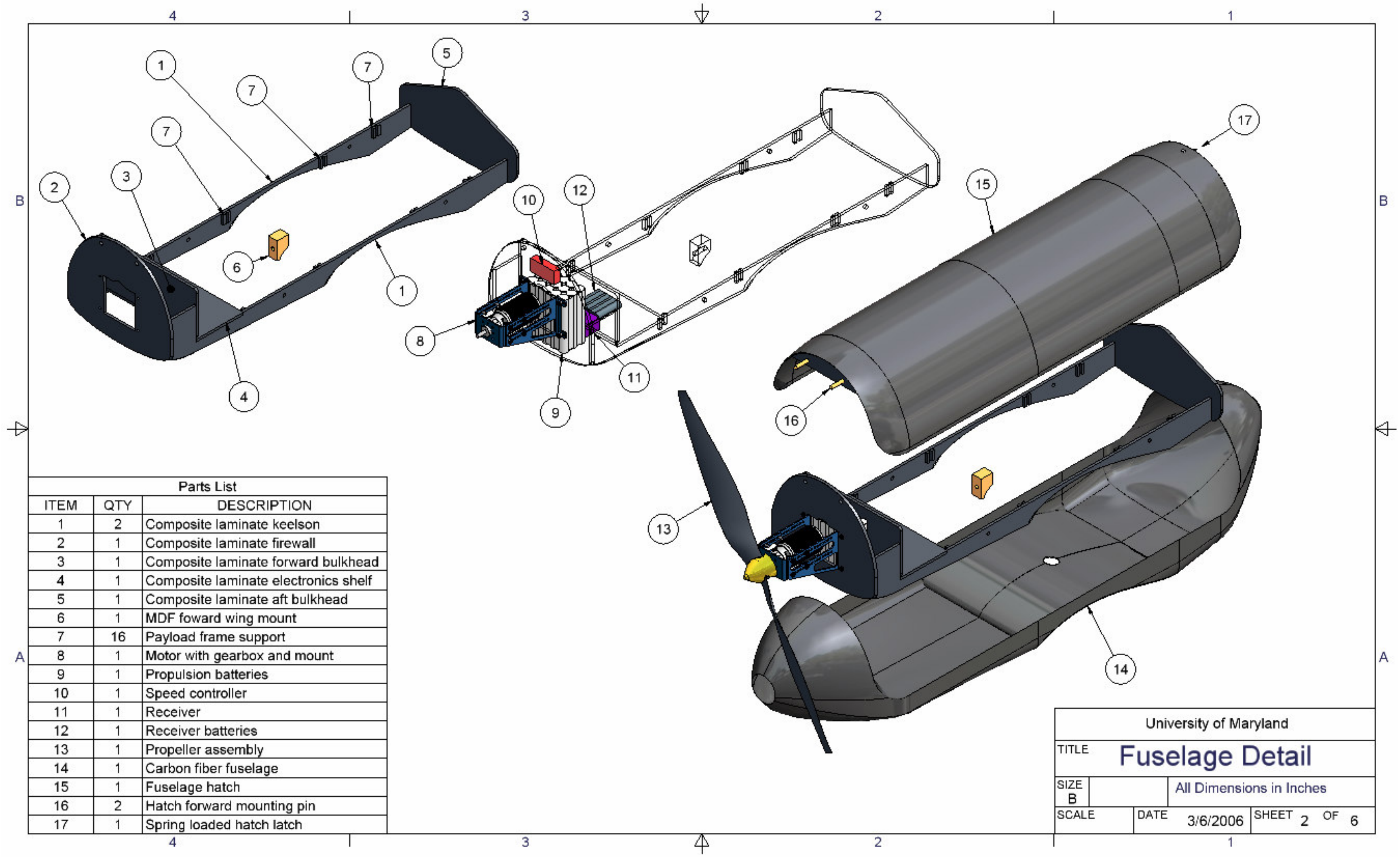


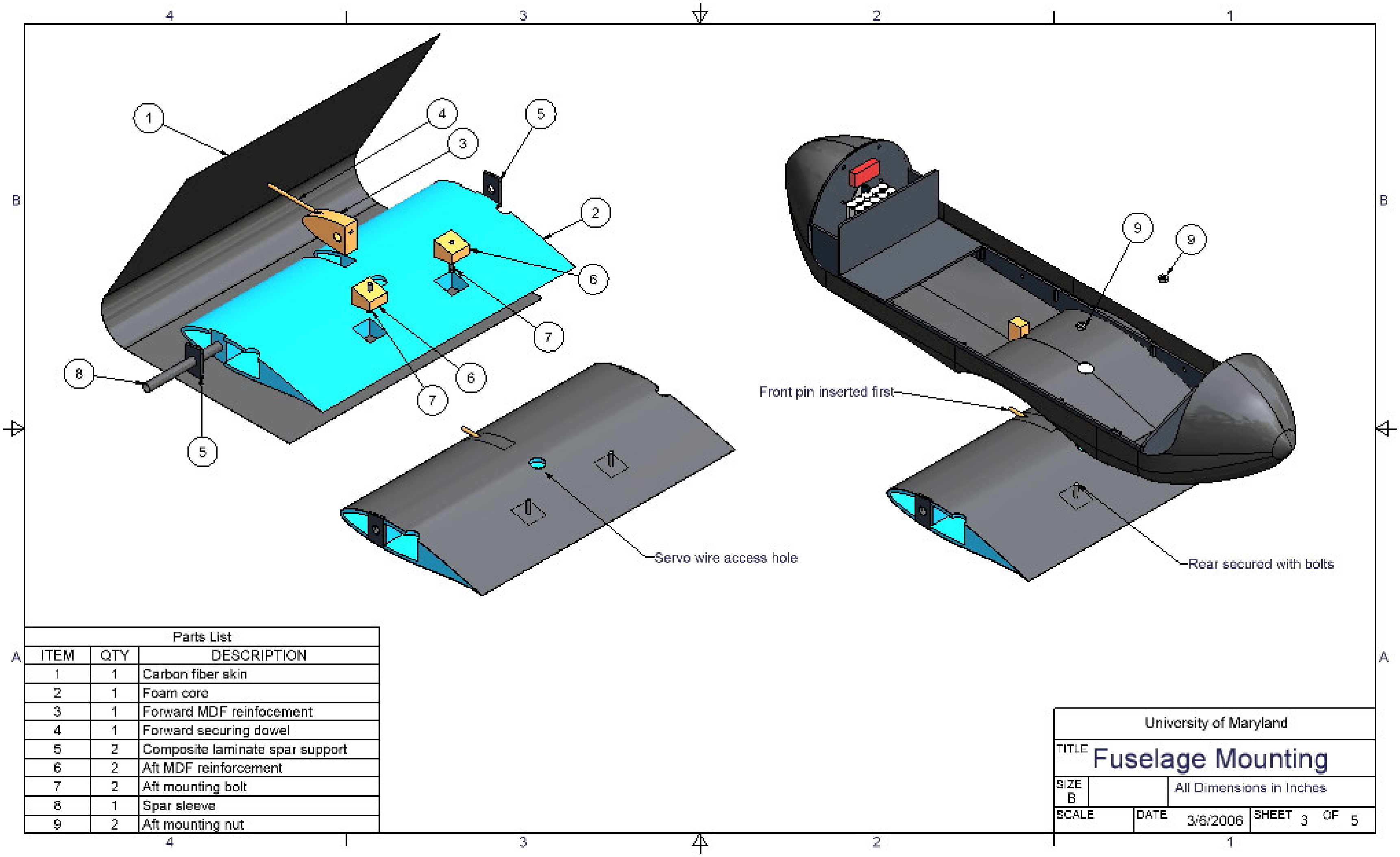
Figure 2.2. Aircraft Dimensions.



Parts List

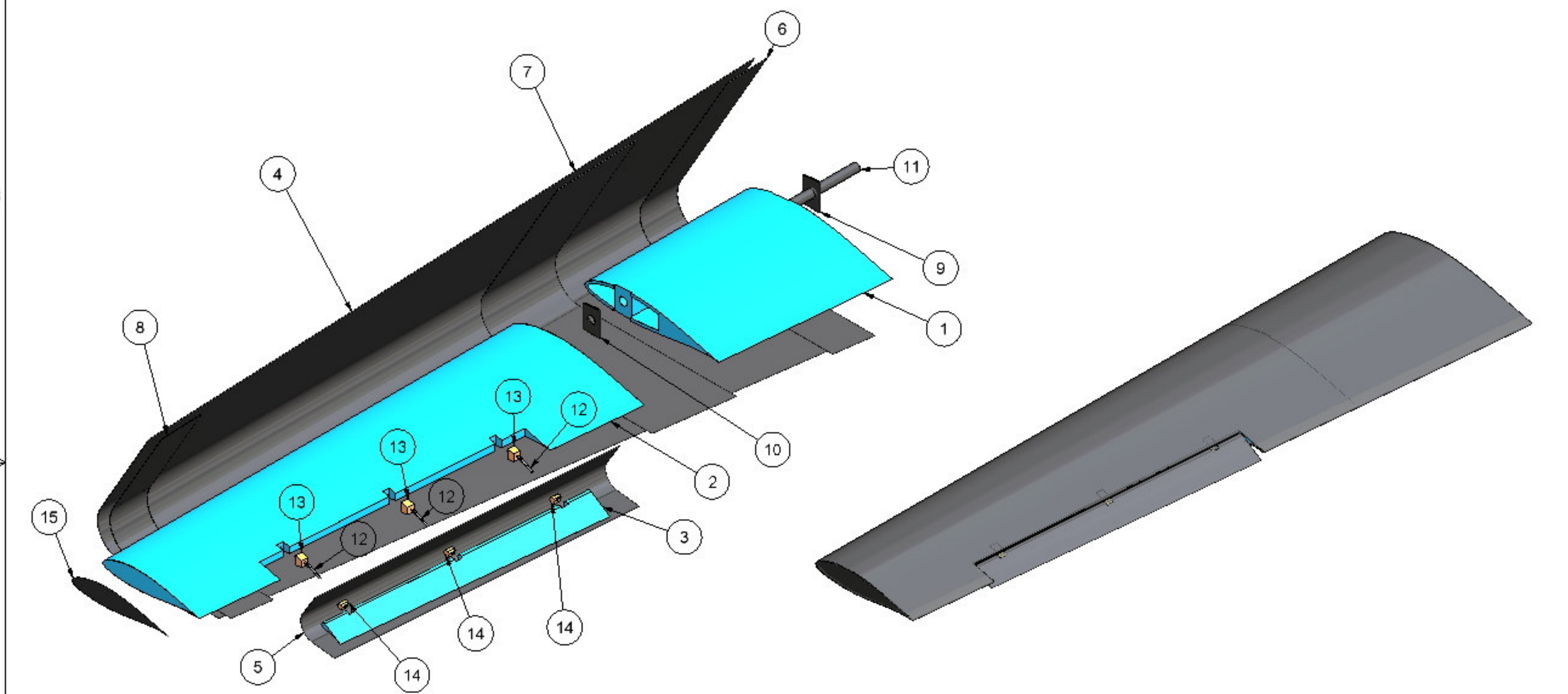
ITEM	QTY	DESCRIPTION
1	2	Composite laminate keelson
2	1	Composite laminate firewall
3	1	Composite laminate forward bulkhead
4	1	Composite laminate electronics shelf
5	1	Composite laminate aft bulkhead
6	1	MDF foward wing mount
7	16	Payload frame support
8	1	Motor with gearbox and mount
9	1	Propulsion batteries
10	1	Speed controller
11	1	Receiver
12	1	Receiver batteries
13	1	Propeller assembly
14	1	Carbon fiber fuselage
15	1	Fuselage hatch
16	2	Hatch forward mounting pin
17	1	Spring loaded hatch latch

Figure 2.3. Detailed CAD Drawing – fuselage structure.



Parts List		
ITEM	QTY	DESCRIPTION
1	1	Carbon fiber skin
2	1	Foam core
3	1	Forward MDF reinfocement
4	1	Forward securing dowel
5	2	Composite laminate spar support
6	2	Aft MDF reinforcement
7	2	Aft mounting bolt
8	1	Spar sleeve
9	2	Aft mounting nut

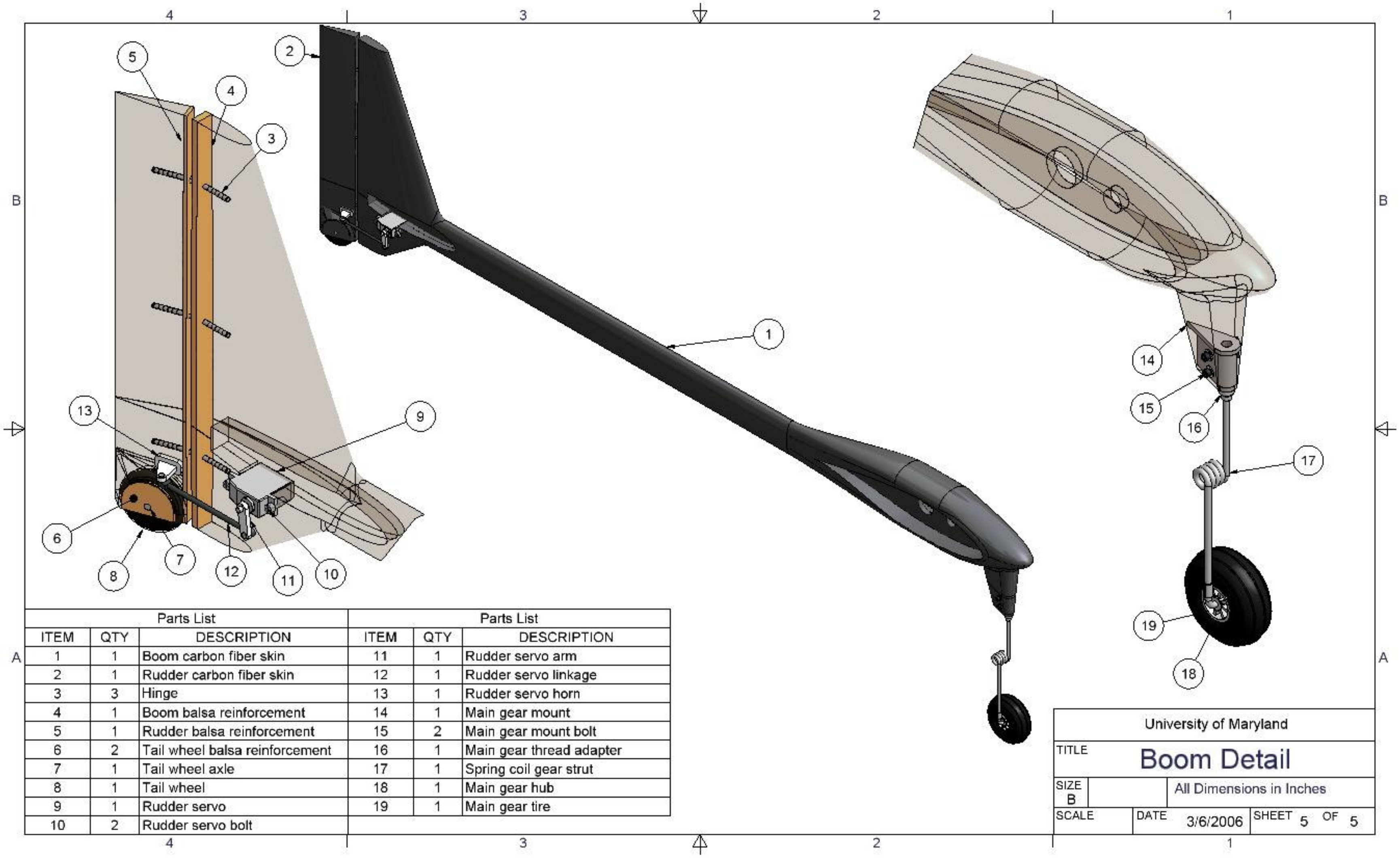
Figure 2.4. Detailed CAD Drawing – wing center-section assembly and mounting.



ITEM	QTY	DESCRIPTION	ITEM	QTY	DESCRIPTION
1	1	Inboard foam core	9	1	Inner composite laminate spar support
2	1	Outboard foam core	10	1	Outer composite laminate spar support
3	1	Aileron foam core	11	1	Spar sleeve
4	1	Carbon fiber skin	12	3	Hinge
5	1	Carbon fiber aileron skin	13	3	Wing hinge reinforcement
6	1	Inboard reinforcing strip	14	3	Aileron hinge reinforcement
7	1	Joint reinforcing strip	15	1	Carbon fiber tip cover
8	1	Outboard reinforcing strip			

University of Maryland
TITLE Wing Detail
SIZE B — All Dimensions in Inches
SCALE — DATE 3/6/2006 — SHEET 4 OF 5

Figure 2.5. Detailed CAD Drawing – wing outboard-section assembly.



ITEM	QTY	DESCRIPTION	ITEM	QTY	DESCRIPTION
1	1	Boom carbon fiber skin	11	1	Rudder servo arm
2	1	Rudder carbon fiber skin	12	1	Rudder servo linkage
3	3	Hinge	13	1	Rudder servo horn
4	1	Boom balsa reinforcement	14	1	Main gear mount
5	1	Rudder balsa reinforcement	15	2	Main gear mount bolt
6	2	Tail wheel balsa reinforcement	16	1	Main gear thread adapter
7	1	Tail wheel axle	17	1	Spring coil gear strut
8	1	Tail wheel	18	1	Main gear hub
9	1	Rudder servo	19	1	Main gear tire
10	2	Rudder servo bolt			

Figure 2.6. Detailed CAD Drawing – boom and rudder assembly.

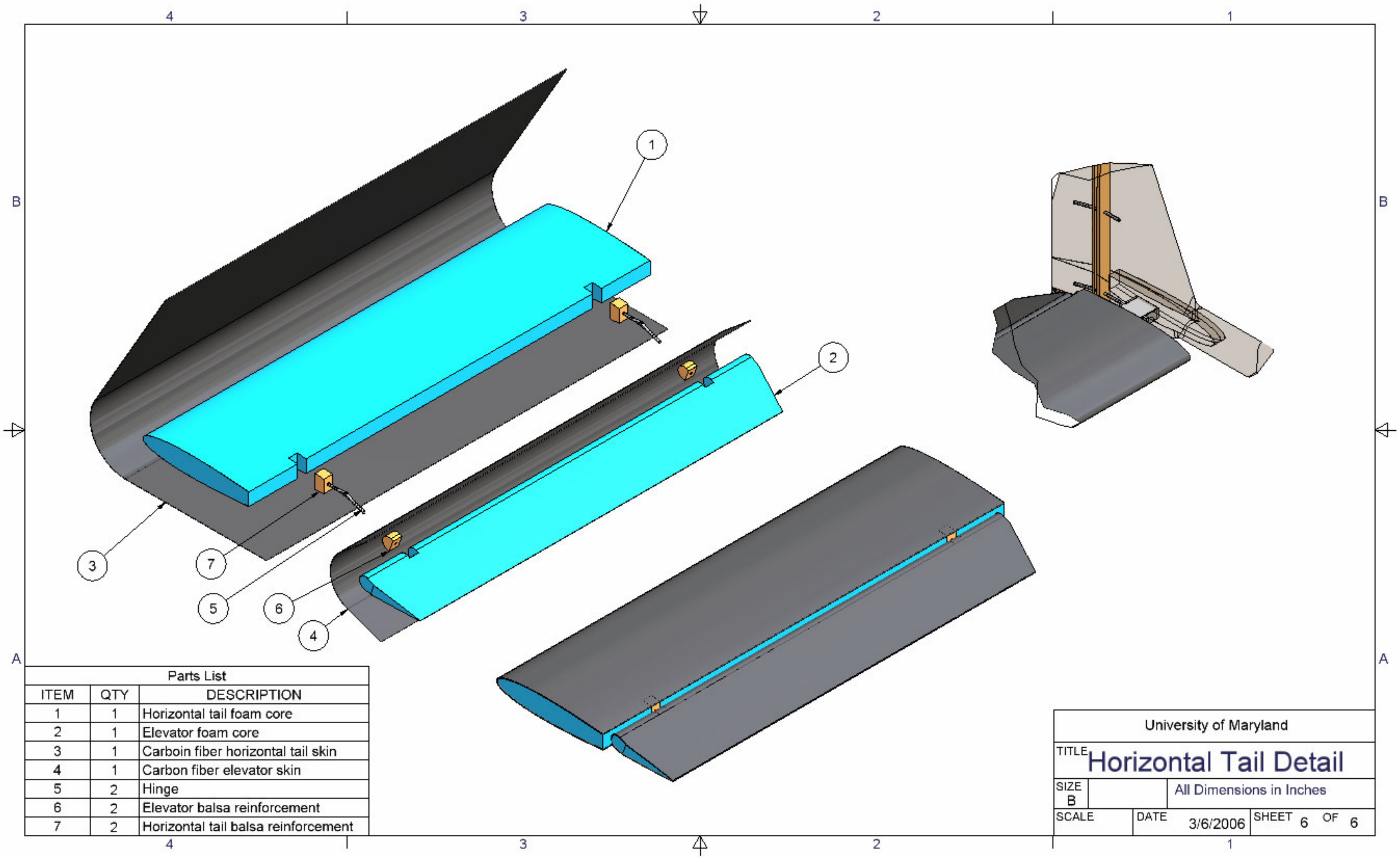
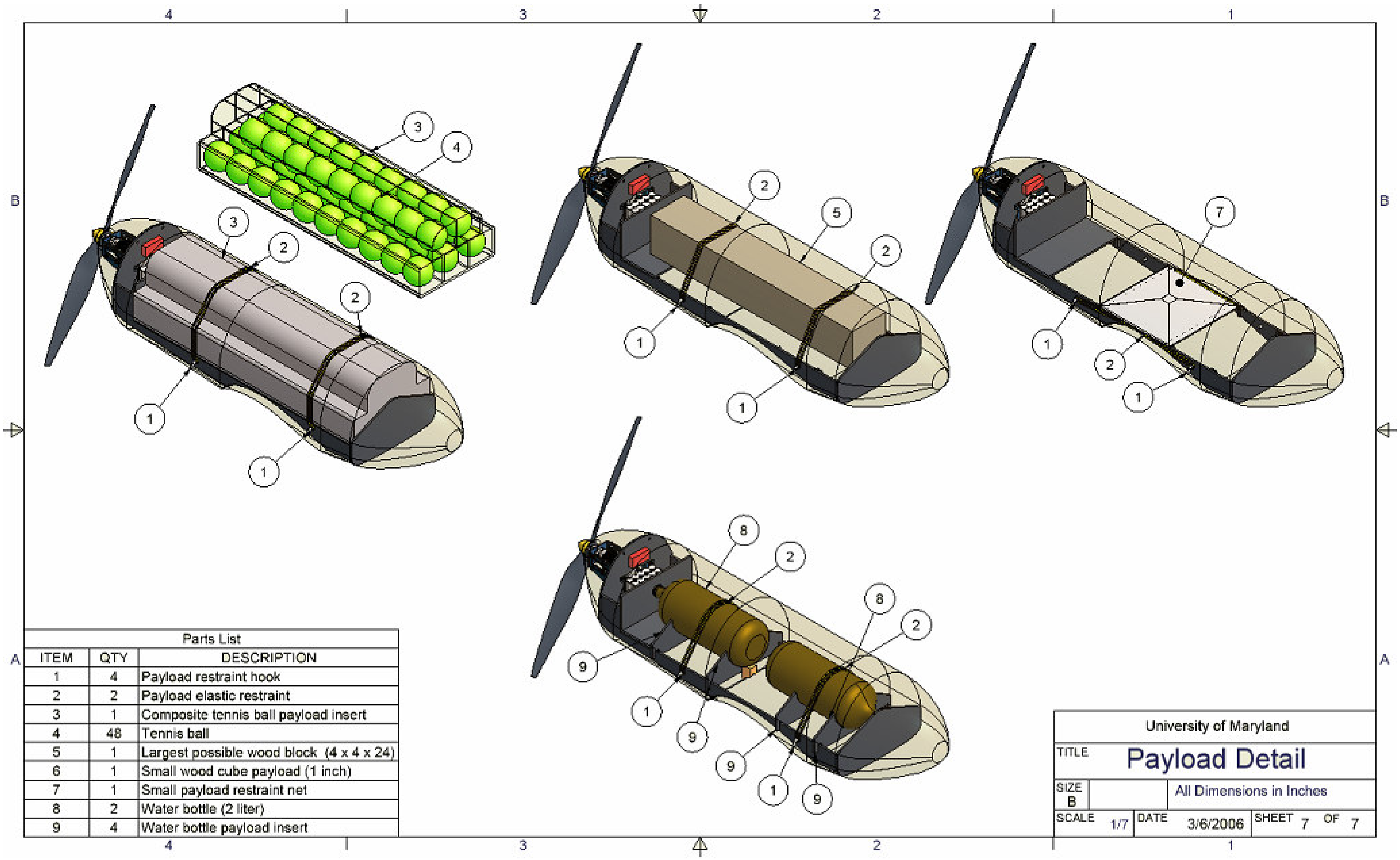


Figure 2.7. Detailed CAD Drawing – elevator assembly and mounting.



Parts List

ITEM	QTY	DESCRIPTION
1	4	Payload restraint hook
2	2	Payload elastic restraint
3	1	Composite tennis ball payload insert
4	48	Tennis ball
5	1	Largest possible wood block (4 x 4 x 24)
6	1	Small wood cube payload (1 inch)
7	1	Small payload restraint net
8	2	Water bottle (2 liter)
9	4	Water bottle payload insert

Figure 2.8. Detailed CAD Drawing – payload configurations.

2.2 Plug (Male Mold) CAD Drawings

2.2.1 Sectioning the Aircraft

There are many patterns available for sectioning the aircraft. The available options directly reflect the complexity of the surface curvature and overall design of the aircraft. The easiest partitioning scheme for a closed shape is to split it into two halves. Most often, a two-section split results in what is intuitively called left/right or top/bottom halves.

The design criteria of sectioning a plug in two halves imposes restrictions on the complexity of the plug in question. This is because there is an overall construction limitation in molded composite manufacturing. A plug whose shape does not allow de-molding is not suitably partitioned. In another words, the restriction says that the plug and mold must be able to separate from each other. If the desired plug shape is highly complex, the plug may have to be sectioned into various pieces that are guaranteed to de-mold. This subject is developed in detail in the Chapter 3.1.3.

The booms and fuselage for this construction were designed for a left/right plug-partitioning scheme. Therefore, no other plug-partitioning scheme sectioned the plugs as efficiently as the vertical cut along the center of the fuselage and boom.

2.2.2 Plug CAD Drawing

The aircraft was sectioned into parts that would make up the various plugs. To simplify construction, the aircraft was purposely designed so the fuselage and boom molds consisted of only left and right sections. The drawings were modified accordingly to generate the CAD representation suitable for plug milling. The CAD drawings of the left-hand plugs sent out for CNC milling are found in Figures 2.9 and 2.10. The right halves of the plugs are mirror images of the ones displayed below. Two very important features in plug design are the flange and the offset. Design considerations and CNC milling for the plugs are discussed in detail in the next chapter.

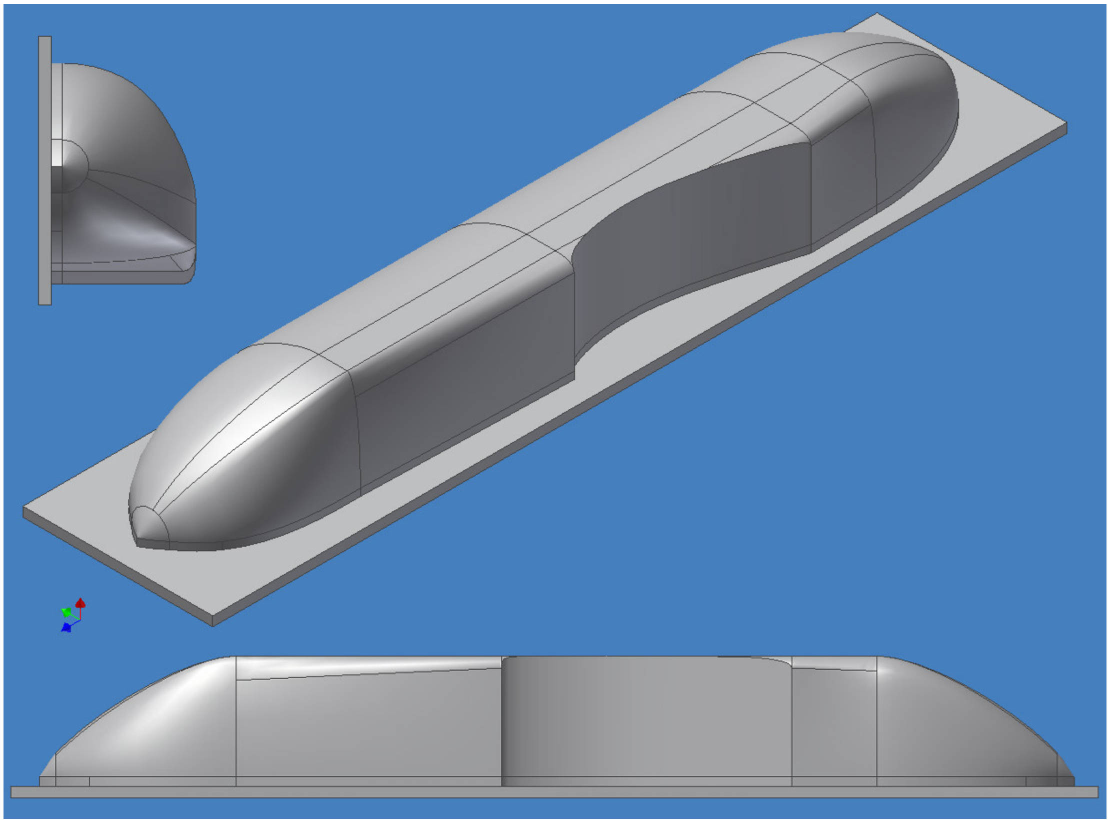


Figure 2.9. Fuselage Plug – left half: front, isometric & side views.

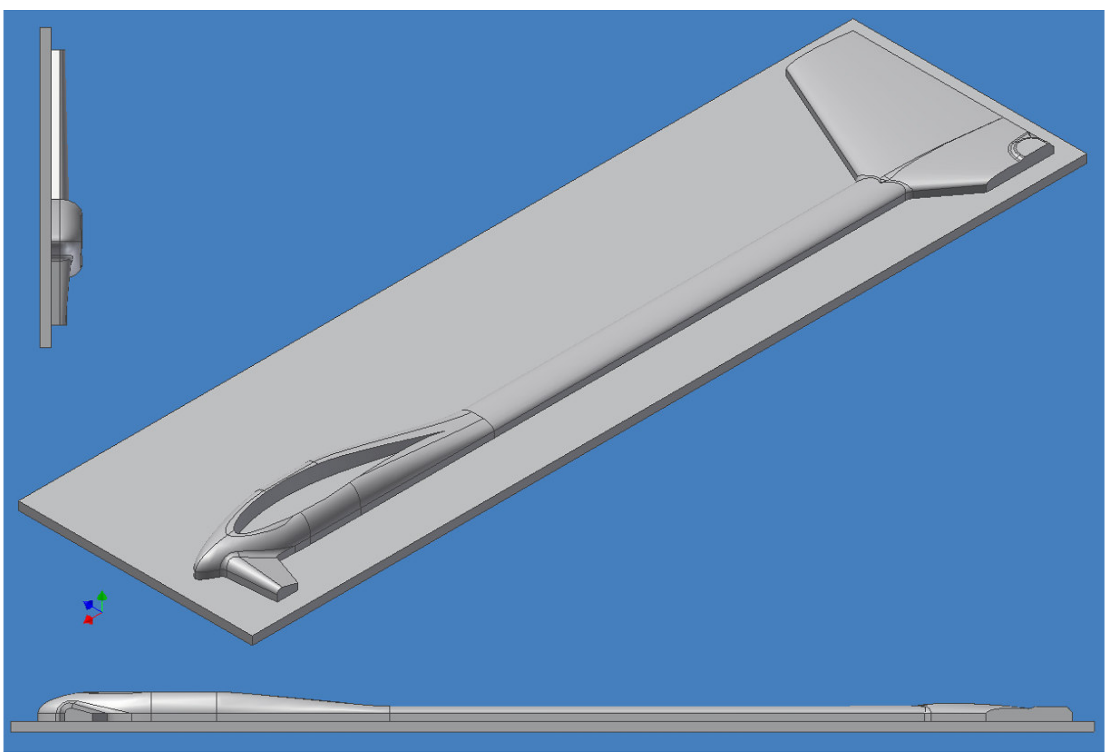


Figure 2.10. Boom Plug – left half: front, isometric & side views.

Chapter 3: Plug Making

3.1 CNC Machining and Plug Design

3.1.1 CNC Process

To create the plugs for the aircraft, Computer Numerical Control (CNC) Milling was extensively utilized. This particular project used a milling machine that had 3 degrees of freedom: X, Y and Z axis translation. More sophisticated CNC milling machines may have 5 degrees of freedom where the cutting tool is manipulated in not only translation but also angular direction.

The CAD drawings discussed in the previous chapter were saved as Initial Graphics Exchange Specification (IGES) files that the CNC milling machine recognizes. The machine shop took the CAD drawings in IGES format and ran a Computer Aided Machining Software (CAM) that calculated the path of the cutting bit. During this process, the machinist was able to further diagnose the integrity of the drawings and estimate the cutting time/cost.

3.1.2 CNC Limitations

It was important to correspond with the machine shop and establish the dimensional limitations of the milling machine in two regards: maximum XYZ cut travel lengths and cutting table size/interior enclosure. The size of the table can be a limitation because most jobs require clamping the blank block of material. The clamps themselves reduce the actual cutting space of the table (Figure 3.1).

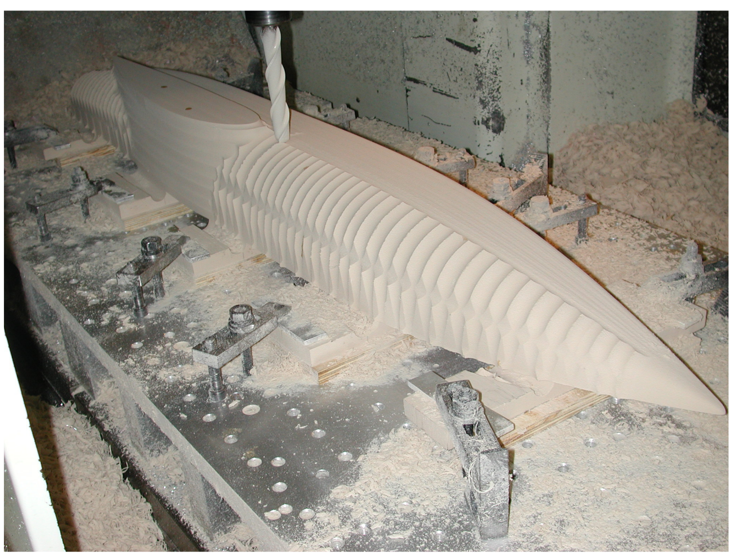


Figure 3.1. Sample Picture of CNC Milling – rough cut.

Since the mill uses rotary bits, a radius is unavoidable when milling inside corners (Figure 3.2 B & F). If a specific radius of an inside cut is required, the mill will have to past over the same area several times with an incrementally smaller radius bit. Thus, increasing both machining time and cost. A sharp internal cut corner is very difficult to achieve unless an end mill can be used for the desired cut (Figure 3.2 B).

Considerations for CNC machining are evident in Figure 3.2 and are described in the following two cases:

1) Examples A, D, E & F require CNC milling machines with capabilities beyond XYZ Degrees of Freedom.
2) Examples B & C require CNC milling machines with XYZ degrees of freedom only.

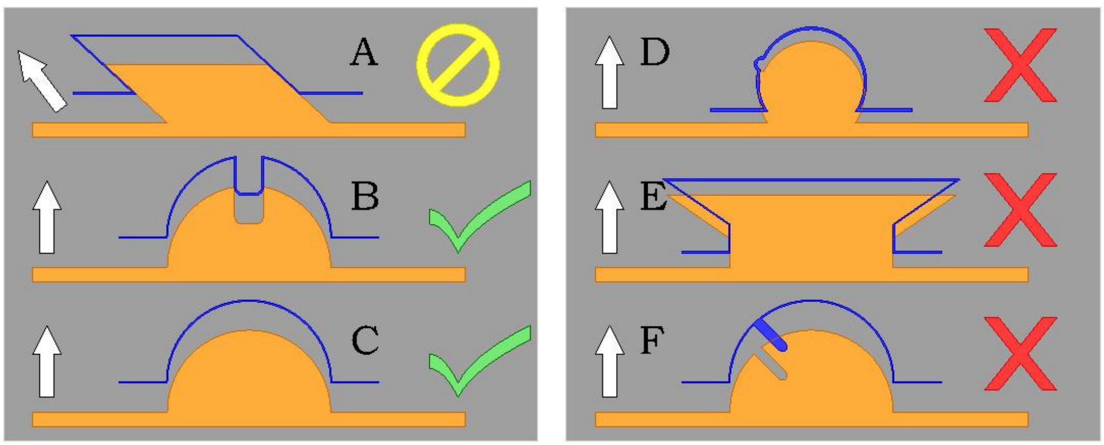


Figure 3.2. CNC Milling and Plug Design Limitations – cutaway front view.

3.1.3 Plug Limitations and Design

As discussed earlier, the plug CAD drawings must contain curves that the CNC machine can handle depending on the degrees of freedom of the machine. Angled depth/insert cuts must be avoided if the CNC milling machine has only translational degrees of freedom. However, even if a five DOF CNC milling machine is available, complex or deep depth cuts should still be avoided because the female mold that will be extracted from the plug must have a straight separation path to de-mold. Deep cuts into the plug, although straight, can pose difficulties during separation of the mold from the plug. The arrows in Figure 3.2 show the direction that the mold must be pulled to be detached from the plug. Also in Figure 3.2, the mold is drawn in blue and the plug is drawn in orange.

Limits on plug design are exemplified in Figure 3.2 and are described in the following cases:

A) A plug may require that the mold be "pulled" at an angle. Although this is possible in theory, in practice this can be much more difficult. The user must understand how to de-mold the part correctly as to avoid damage and unnecessary wear on the mold. A warning sign accompanies this case to indicate that this is possible, yet, requires careful consideration.

B) A well-designed plug should have an intuitive de-molding process. This mold can be separated straight up without being caught in any other feature of the plug. As mentioned earlier, the insert cut should be discussed with the machinist. It is recommended to have a shallow cut depth so the mold can release easily and the part to be generated from the mold can tolerate the complex curvature and right angle. (This is seen in the boom molds where the airfoil cutout is located. This complex inside cut causes bridging, a phenomenon described in Chapter 5). This case receives a check mark.

C) This example does not violate the de-molding process. This case receives a check mark.

D) Two features on the plug render this case unfeasible. Firstly, given the overall shape of the plug, the blister, given its location, on the side makes de-molding impossible. However, there are cases where features similar to the blister can be used. Secondly, the contour of the circular shape "tucks in" at the base. The mold will not separate due to this undesired contour. In this case, the contour is exaggerated for demonstration purposes. In reality, minimal invasion (in the order of $1/64^{th}$ of an inch) of the contour at the base/flange will create de-molding inconvenience or failure.

E) This case fails by inspection. No part can ever be obtained from this plug. This plug requires a different partitioning scheme all together to work.

F) The angled cut imposes a de-molding direction parallel to it. However, the overall shape of the mold requires an upward de-molding direction. This case fails because the mold must be pulled in two directions at the same time (which is not possible).

3.1.4 The Flange

The flange is the flat area around the curved surface of either the plug or the mold. The flange of the plug was transferred to the mold during wet lay up and played an important role in the manufacturing of parts.

It may appear attractive to minimize the flange so there is less material used in the plugs. The material and CNC milling costs are significant, but product quality and ease of manufacturing depend on how much flange is available to work with. For reasons discussed in Chapter 5, a good mold should have wide flanges. A good rule of thumb is to allow no less than 5 inches of flange around the entire perimeter of the contour curve.

In Figure 3.3, the flange of both the plug and the mold is represented in red, the mold contour or mold cavity in blue, and the plug offset in dashed orange and red.

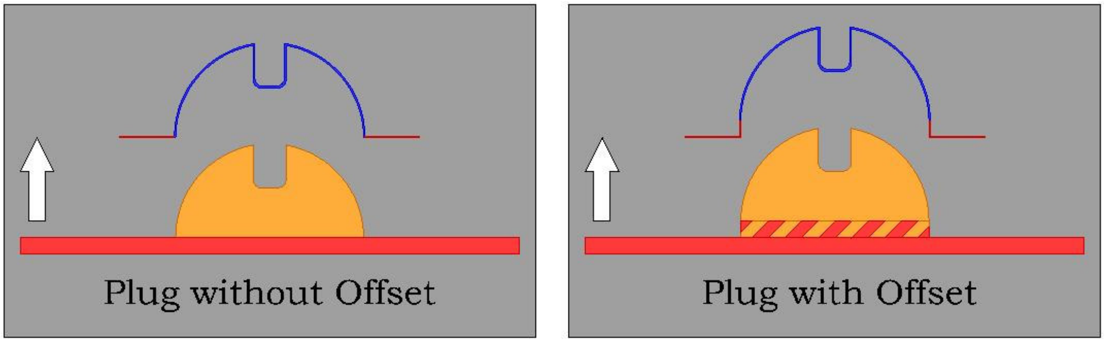


Figure 3.3. Plug Flange and Offset.

3.1.5 The Offset

As observed in Chapter 2.2.2, the complex curves of the plugs have an offset from the surface plane of the flange. In another words, the contoured surface was raised a certain amount above the flange. Thusly, the mold extracted from the plug was deeper by the offset amount, as observed in Figure 3.3. The offset was there because of three choices made during plug design:

1) Creating an offset allowed the machine shop to mill a radius on the corner edge of the perimeter of the contour. Having a radius along the perimeter of the cavity provided some relief on the fiberglass/carbon cloth during dry lay-up of the cloth, and facilitated vacuum bagging/resin transfer. The details of Resin Transfer Molding are discussed in Chapter 5.
2) The offset was necessary based on the method chosen for cutting the flange from the part extracted from the mold. This is discussed in Chapter 7.2.2.
3) To save weight, a manufacturing strategy was chosen that allowed the parts to be of highest quality and finish; thusly, not requiring painting and retaining the original carbon composite "look". As a result, the joining line of two parts would not be hidden by putty and paint. The offset allowed the flange to be trimmed in a systematic and repeatable fashion. Trimming and Joining are developed in Chapter 7.

3.2 Milling the Plug

3.2.1 The Foam Block

Multiple sheets of high-density foam were used as the core material for the plugs. Other materials, like aluminum, could have been used for the plugs. Important factors considered for choosing foam over metal for the plug are discussed in Table 3.1.

	Foam	**Metal/Aluminum**
Material Cost	Reasonable	Expensive
Machining Cost	Reasonable	Very Expensive
Weight	Reasonable	Heavy
Durability	Fair	Very Good
Reparability	Good	Moderate
Reshape/Sanding	Possible	Very Difficult
De-molding Cycles	1 - maybe 2	Multiple

Table 3.1. Material Trade-off for Plug Core.

The material cost, machining cost and weight of aluminum were the main reasons for choosing the foam. However, it was noted that one important factor made aluminum very desirable despite the higher costs. An aluminum plug would be much more resistant to the wear and tear due to cycling the plugs. In another words, if multiple sets of molds had been desired, then aluminum molds would have been the safest choice. Since this project only called for one set of molds, the high-density foam core remained the more justified choice.

3.3 Plug Preparation and Coating

3.3.1 Sanding

Sanding was required in mostly all preparatory phases of manufacturing. The use of the power sander made the job quicker. However, the power sander quickly sanded away too much of the foam. Therefore, as a cautionary measure, power sanding was done ONLY on the flange areas. The contoured areas of the plugs were sanded solely by hand with 600grit or finer sand paper (Figures 3.4 & 3.5). The sanding of the bare foam plugs was dry unlike wet sanding utilized later on.

The bare foam was porous and easily damaged. It was important to keep any sharp or heavy objects clear from the vicinity of the plugs. Objects like pencils, pens, wristwatch, keys, screwdrivers and even cell phones could ding or stab the foam plug. This kind of senseless damage created more work. Any unwanted features due to damage had to be puttied and re-sanded. Higher density foam would have been more resistant to surface rashes due to accidents. However, the use of higher density foam tooling boards would increase the project costs.

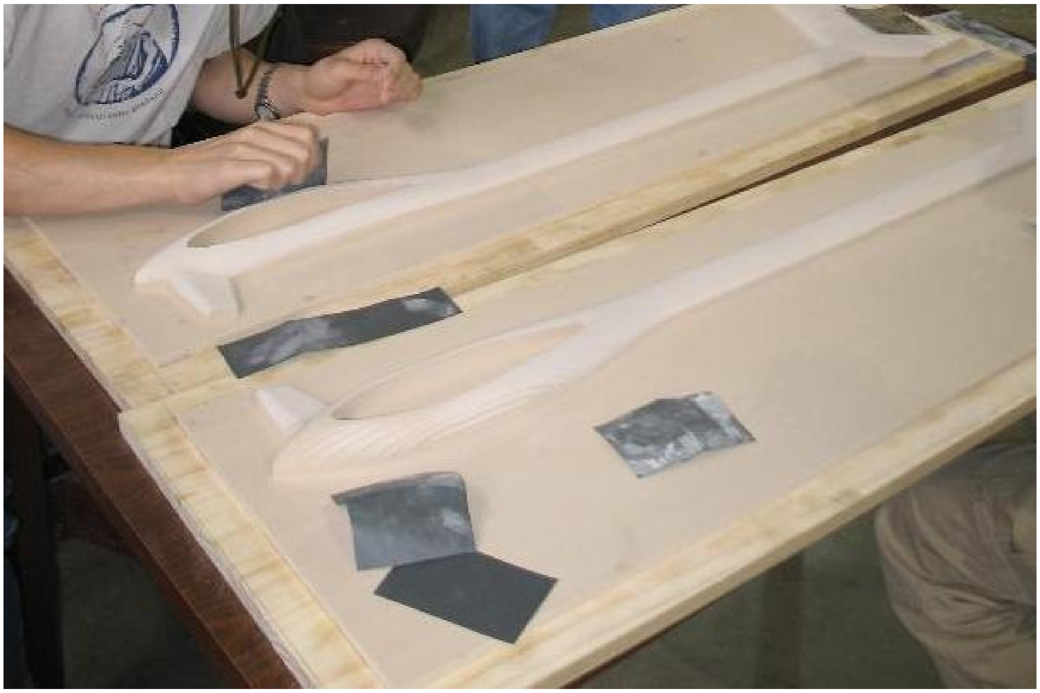


Figure 3.4. Sanding the Boom Molds.

Figure 3.5. Sanding the Fuselage Molds.

Note: The flange of both the fuselage and the boom plugs were insufficient, a lesson learned the hard way, as discussed in the Advice Section of this Chapter and Chapter 5. Also, note the lines on the foam plugs. These lines are also discussed in the Advice Section of this Chapter.

3.3.2 Primer Coating

The primer coating provided a surface seal for the plug. The primer was sprayed on the plug and hardened to a semi-glossy finish (Figure 3.6). The spraying of the primer coating required patience and skill with the spray gun. A careful spray job required hardly any sanding once the primer dried. Conversely, any accumulation or sags in the primer created the necessity for wet sanding. From this point forward in the construction, wet sanding was used with either water or liquid polishing wax.

Figure 3.6. Primer Coated Plugs.

The sanding process was repeated several times, but with recursively finer grit. In most cases, wet sanding paper between 1000 and 2000 Grit was used. Two key "don'ts" were always kept in mind while wet sanding; do not sand down to bare foam and renew the water on the both plug and sand paper often. Sanding the primer coat off completely created the necessity for patchwork. The purpose for changing the water often was to remove the sanded primer dust mixed with the water from the surface of the plug. The entire reason for sanding with finer grit was to remove the sanding scratches made from the previous grit. Not changing the contaminated water negated the purpose of using the finer grit, to reduce the "scratched surface look".

3.3.3 Polishing

Since some areas of the primer coated plug were sanded, the scratches made by the sand paper had to be eliminated as much as possible. The polishing process was divided into 3 stages: 1) Fine Grit Sanding, 2) Liquid Wax Buffing and 3) Hand Wax Coating.

The fine-grit sanding step called for wet sanding with 3000 and 4000 Grit sanding pads. This process used a pneumatic sanding gun and a "thin" liquid wax instead of water.

The buffing step used a pneumatic polishing gun and a thick liquid carnauba wax to polish the plug. Since this liquid wax dried after application, it was necessary to apply and buff the plug in stages. Once the entire plug was buffed, the dried liquid wax was removed with a clean terry cloth. In some cases, this step was repeated if the results were not achieved. It was very important to keep clean both the buffing pads and the terry cloth. Any dust or dirt on either the buffing pad or the terry cloth resulted in scratches being made on the surface.

Lastly, a final coat of carnauba liquid wax was applied; however, this time a terry cloth was used instead of the pneumatic polishing gun. An even coat of wax was spread by hand over the plug surface and allowed to dry. This step removed some of the minutest scratches left from the buffing pad. The resulting surface was mirror-like and had little to no scratches.

It is important to note that the sanding and buffing instructions in this chapter also apply for the molds as well. Once the molds were made from the plugs, the same sanding procedure described above was utilized as necessary depending on how the molds looked. The superior quality of the surface of the plug transferred to the mold being cast from the plug.

3.4 Materials & Tools Summary

3.4.1 Materials & Tools Used

The materials used during the plug making process are listed in Table 3.2. Basic supplies like latex gloves, stir sticks, tyvek suits, eye protection, mixing cups, water bucket, acetone bucket, etc. are not explicitly discussed. The author assumes that the reader is aware of such necessities.

Materials	Description
General Materials	Mixing cups, stir sticks, latex gloves, eye protection, masks, etc
Packing Tape	Tape used for masking areas
Contact Adhesive	Spray adhesive used to bond foam block to base plate
Primer	Polyester coating used for sealing and priming the plug surface
MEKP Catalyst	Hardener used for polyester based systems: gel coat and resin
High Density Foam	Closed cell high density tooling board foam
Liquid Shine	Gel coat clean and shine compound
Machine Glaze	Polishing Compound
Liquid Wax	Surface Wax in liquid form

Table 3.2. Plug Materials Used.

Several tools were necessary to prepare the plugs for casting the female molds. The tools are listed in Table 3.3. These tools along with others were repeatedly used in various phases of the construction as developed in later chapters. Nevertheless, one tool not listed below that was of overwhelming importance was patience.

Tools	Description
Sand Paper/Pad	Abrasive sheet/pad used for adjusting surface quality and features
Buffing Pads	Polishing Pad used for removal of surface scratches due to sanding
Digital Scale	Instrument used for weighing polyester primer
HVLP Spray Gun	High Volume Low Pressure Siphon Gun used for spraying primer
Pneumatic Sander	Pneumatic Device used for efficient sanding of large areas
Pneumatic Polisher	Pneumatic Device used for efficient polishing of large areas
Paint Booth	Closed ventilated area reserved for spraying
Compressed Air	High pressure air line

Table 3.3. Description of Tools.

3.4.2 Tools Clean-up

Aside the buffing pads, which were cleaned with warm water, all other tools were cleaned with acetone as necessary. Any tool that had contact with polyester or/and MEKP hardener was thoroughly cleaned immediately with acetone. The acetone was poured in the siphon of the spray gun and sprayed until the acetone sprayed clear. Often, the spray gun was taken apart and cleaned as well. Clean up was done quickly since polyester materials mixed with hardener had a finite working time before setting. Tools were squirted with acetone or dipped in an acetone bath before being wiped.

3.5 Advice

3.5.1 De-molding Criteria

Sections 3.2 and 3.3 discuss several limitations and considerations for plug design and CNC milling. The cases shown in Figure 3.2 are cutaway views and represent specific body stations of a given plug along its span. If a plug fails the de-molding criterion at any given body location along the plug then most likely the mold will not separate from the plug.

The de-molding direction should be as intuitive as possible even if this means sectioning the body into more then 2 pieces. It is desirable to have as few molds as possible; however, some shapes cannot be split into left and right halves unless designed/drawn that way. Creating multiple plugs and molds for a complex shape is sometimes the best alternative. After all, a mold and plug that does not separate from each other results in total loss.

In summary, the main criterion for plug design is its ability to generate a mold that separates successfully and retains the desired features of the plug. This sounds simple, but be mindful not to overlook it. Furthermore, the parts for the aircraft will come from the molds. In the end, the ease of manufacturing of parts directly tracks back to choices made or overlooked during the plug design.

3.5.2 Plug Surface Quality Trade-off

The process of preparing/polishing the plugs can be tedious and repetitive. However, every effort at increasing the quality of the plugs results in a superior surface quality of the mold. Often, the difference between fair and superior surface quality translates to two or three more passes with the pneumatic polisher and carnauba liquid wax. If the scratches are not vanishing during polishing than most likely, the plug was not sanded with fine enough grit or there is dirt on the buffing pad.

If the quality of the mold is poor, every part pulled from this particular mold will require attention. This “attention” often results in hours of sanding. Evidently, it is beneficial to spend the time creating plugs that provide superior quality to the molds and, consequently, to every part thereof.

3.5.3 More Thoughts about the Plug Flange

As mentioned earlier, taking measures to reduce material (high-density foam board) and machining costs was not advantageous. In this project, due to a limited supply of foam, the plugs were machined with very small flanges. Not only was the surface area of the flange small but also its thickness was insufficient (Figure 3.4 & 3.5). The foam plug was mounted on a baseboard for support and additional flange area.

Since the thickness of the flange was insufficient, the bare-foam flange was fragile. The surface tension created by the primer caused the thin flange to lift off from the base plate in both boom and fuselage plugs. The contact cement used to glue the foam to the board was not strong enough to keep the plug flange from lifting off. The first attempt at fixing the problem was to use Plexiglas rather than ply wood for the baseboard. Although the contact spray glue worked better on Plexiglas, it still did not solve the problem (Figure 3.7).

To solve the problem, new molds with adequately sized flange would have had to be machined. However, the problem was bypassed by laying down plenty of packing tape along the flange edges. The resulting mold lost some aesthetics along the flange area and posed problems during de-molding. The uneven flange and the step along the flange made de-molding the boom mold fairly trying.

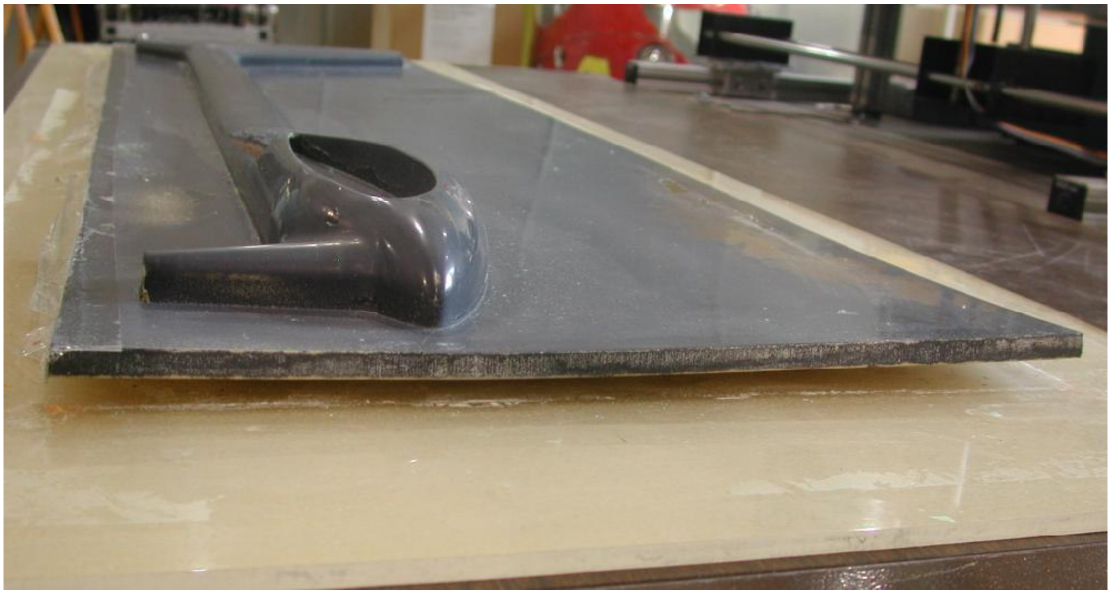


Figure 3.7. Boom Plug on Plexiglas Base Plate.

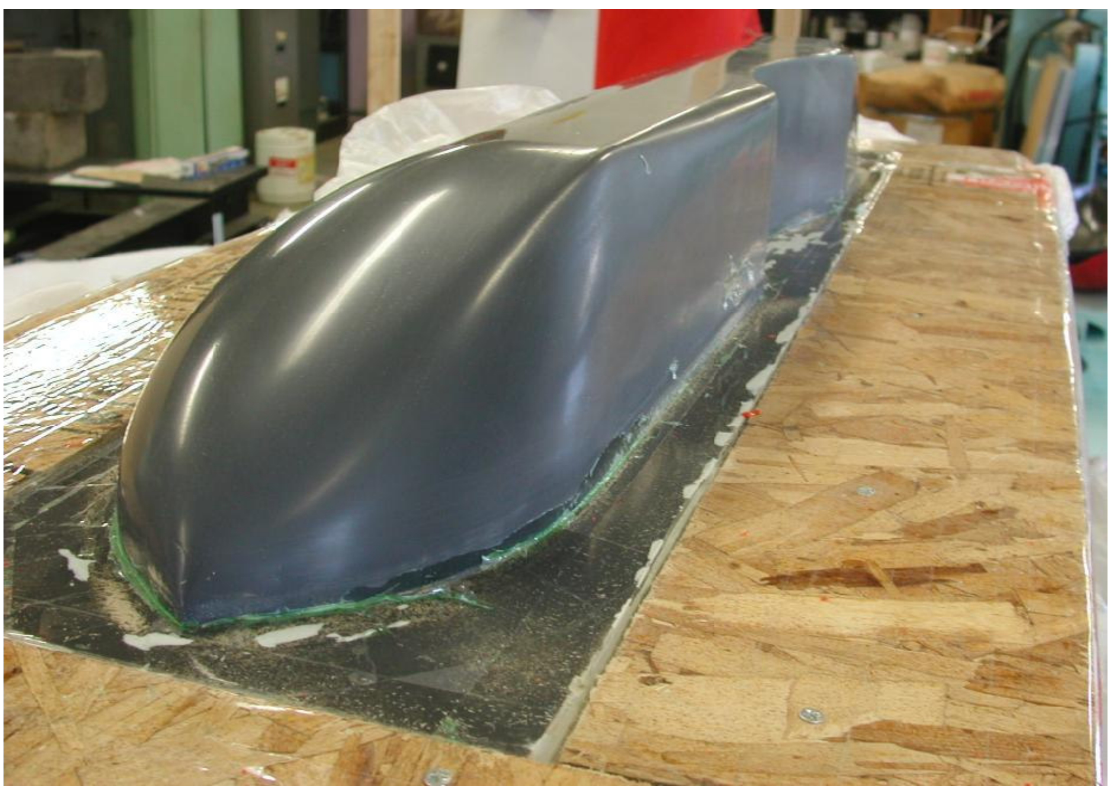


Figure 3.8. Fuselage Plug with Plywood Flange Extension.

After having dealt with the booms and knowing that the fuselage plug flange had similar problems, a different approach was taken. The fuselage plywood baseboard was left in place and additional plywood was added. The additional layer of plywood added flange area in the same plane as the foam flange, thus, the fuselage plugs did not have the "step" that the boom plugs did (Figure 3.8). The additional plywood layer was installed with its own frame for support. Packing tape was used to seal the bare plywood and cover the gap along the foam/plywood edge (Figure 3.8).

These problems took many days to solve and, to some extent, reduced the quality of the flange of the plugs/molds. Despite a few surface imperfections in the flange, the molds extracted from the plugs still performed as expected. Nevertheless, this ordeal highlighted the importance of not cutting cost and corners.

3.5.4 Damage and Storage

After many days working on the plugs, the most frustrating event is to damage or ruin it carelessly. A sunless climate-controlled environment free of overhead objects that can fall on the plug is the ideal storage location. Heavily trafficked areas are highly discouraged for use as storage. Curious hands tend to damage and scratch the surface that took much labor to perfect. Special care must be given to plugs that have not yet had molds extracted. Lastly, the plugs must lie on a flat surface. In time, the entire plug will warp under its own weight if not supported evenly on all corners.

Figure 3.9. Surface Damage on Fuselage Plug.

The damage shown in Figure 3.9 occurred after the molds were made. Therefore, these scratches did not interfere with the progress of the project or the quality of the fuselage mold. The scratches were a result of mishandling the plugs during transport to storage.

3.5.5 Thoughts on Project Management

There are many materials necessary for the construction of the plugs, molds and parts. Running out of items like latex gloves, stir sticks or mixing cups can create delays in production. Similarly, other items like polyester gel coat and resin can only be ground shipped since these are considered hazardous materials. The shipping of these hazardous items alone can take two weeks. Often times, it is best to order the hazardous supplies by themselves. There is no need to have non-hazardous supplies take so long to arrive.

It is very important keep track of supplies and inventory. The longer plugs or molds sit due to a shortage in materials the more prone they are to sustaining careless damage. This is because the plugs/molds/parts sit in the active work area where other unrelated activities may damage them.

3.5.6 Machining Costs VS Manual Labor

As observed in Figures 3.4 & 5, there are visible lines running the length of the milled foam. The lines are created by the step-over rate used by the CNC machine shop. The CNC milling process was done in stages where several “rough” cuts were made followed by “finer” cuts. It was possible to have the machine shop mill the plugs to perfection, but required more milling machine time. To reduce machining cost, the foam plugs were machined to a point where a person could hand sand the small ridgelines. Had the plugs been made of aluminum, there would be no choice other than to mill the metal to perfection. Evidently, hand filing an aluminum plug, although not impossible, poses many problems and risks.

Hand sanding the lines did reduce CNC milling costs, but took a few days to sand. If the foam had been of higher density, it would have taken more time to hand sand. In this case, the choice is clearly between available money and time. Electing to hand sand the step-over lines is the only safe money saving alternative (when using foam). As discussed earlier, saving material and machining costs by reducing size of the blank foam block (minimizing flange area) is highly discouraged.

Chapter 4: Mold Making

4.1 Preparation

4.1.1 Materials and Tools

The materials used for mold making are listed in Table 4.1.

Materials	Description
General Materials	Mixing cups, stir sticks, latex gloves, eye protection, masks, etc
Strand Mat	Random directional chopped strand mat
Gel coat	Glossy polyester mold surface coating
Gel coat Additive	Gel coat thinner and enhancer
Resin	Polyester resin used for reinforcement of matting
MEKP Catalyst	Hardener used for polyester based primers, gel coats and resins
Release	Polyvinyl Alcohol (PVA) release film
Liquid Shine	Gel coat clean and shine compound
Machine Glaze	Polishing compound
Liquid Wax	Surface Wax in liquid form
Wood	2" by 4"

Table 4.1. Mold Making Materials.

The tools used for mold making are listed in Table 4.2.

Tools	Description
Cutting Instruments	Shears and/or sharp bladed tools for cutting cloth
Buffing Pads	Polishing Pad used for removal of surface scratches due to sanding
Digital Scale	Instrument used for weighing polyester primer
HVLP Spray Gun	High Volume Low Pressure Siphon Spray Gun
Dump Gun	Cup gun used to spray polyester gel coat and resin
Pneumatic Polisher	Pneumatic Device used for efficient polishing of large areas
Paint Booth	Closed ventilated area reserved for spraying
Compressed Air	High pressure air line, adequate fitting, nozzle, etc.

Table 4.2. Mold Making Tools.

4.1.2 Labor and Task

The mold making process was a coordinated group effort organized in two parts. The first phase of this process required only three individuals. For the second phase of the process, it was found that the ideal number of individuals was six. Although it was possible to include more pairs of hands in either phase, management of too many people was cumbersome as the room became crowded. Once proficient, it was possible to perform phase two tasks with just four individuals; however, this required a highly experienced group, thorough preparation and, most importantly, knowledge of the various quantities to mix.

The subdivisions of tasks for Phases I and II are listed in Tables 4.3 and 4.4, respectively.

Labor	Task Description
Sprayer	Sprays gel coat and issues commands to other members
Mixer	Mixes pre-measured gel coat batch and supplies sprayer as queued
Observer	Aids spray effort, prevents mishaps and points out bare areas

Table 4.3. Gel Coating (Phase I) Labor Distribution.

Labor	Task Description
Sprayer	Sprays resin, issues commands
Rollers (2)	Places mat and rolls reinforcement mat
Cutter	Cuts strand mat
Mixer	Mixes pre-measured gel coat and supplies sprayer as queued
Observer	Aids spray and mat placement efforts

Table 4.4. Reinforcement Application (Phase II) Labor Distribution.

The Advice Section of this Chapter contains further information on Labor and Tasks.

4.1.3 Further Plug Preparation – Release

Once the plug was polished and waxed as described in Chapter 3, the PVA release was applied to the plug. The release was sprayed on with a high volume low-pressure siphon gun. The release was applied with either repeated light coats or one "just right" coat. In due course, different sprayers developed their own preferred methodology: one "thick", two "medium" or three "light" coats. The sprayed release was allowed a couple of hours to dry. The result was a glossy film barrier that protected the plug from the, yet to be sprayed, gel coat. The Advice Section of this Chapter contains several important thoughts on this matter.

4.2 Making the Molds

4.2.1 Mold Making – Breakdown and Comments

The molds were made following the sequence described in Flowchart 4.1.

Flowchart 4.1. Mold Making – breakdown and comments.

4.2.2 Phase I – Gel Coating

Once the PVA release was sprayed and dried, the gel coat was applied evenly with the HVLP spray gun. Although of same make and model, this HVLP was reserved for gel coating only. An additive was mixed into the gel coat before canalization. The purpose of the additive was to: 1) thin the gel coat so the HVLP gun could spray it, and 2) enhanced the luster and surface quality of the gel coat once dried.

4.2.3 Phase II – Reinforcement Application

The random directional strand mat served as a support structure for the gel coat and, overall, the mold. The first strand mat layer was of lighter weight than the following layers. The ¾oz strand mat was desirable as the first layer because it was easier to roll out the trapped air bubbles. The first layer of matting had to support the gel coat completely. Any portion of the gel coat that was not in direct contact with the initial layer could crack or collapse once the mold was placed under vacuum. A defect of this kind could risk the molds ability to release from the part being made not to mention produce faulty parts. This problem did not occur with this project. Additional layers of reinforcement used 1.5oz weight strand matting.

The plugs were measured and sectioned into three even parts. Sectioning the ply into three separate pieces allowed the rollers to concentrate their effort on a smaller region. It was possible to blanket the mold with one continuous ply; however, this would pressure the rollers to eliminate/roll out trapped air in record time. For this reason, as a cautionary measure, the spraying of resin and placement of matting was done piecewise. The resin was sprayed with a dump gun capable of wetting the surface very quickly. The dump gun used 90PSI; thus, delivered large quantities of resin in each continuous burst.

Figure 4.1. Strand Mat Sheet placed on bare Gel Coat.

In the case of the boom molds, the front section contained the wing mount cutout, the middle section contained the boom extension and the rear section contained the rudder. The mat sheets were cut oversized so each sheet overlapped at least 1 inch. The overlapped mat sheets provided additional stiffness to the mold. The mat sheets were placed in the following order: middle, tail and front. This order was chosen based on difficulty.

The middle portion of the boom was the easiest to cover while the front of the boom required many relief cuts and patches due to the complex curvature. Once an entire layer of reinforcement was placed, the process was repeated four more times. The first layer used the lighter weight matting while the subsequent three layers used the heavier matting as mentioned earlier. Figure 4.1 shows the first strand mat sheet being placed on the bare gel coat cover. The technical drawing in Figure 4.2 shows the sequence that the layers were applied. The green layer represents the PVA release and the red layer represents the tooling gel coat (Figures 4.2 & 4.3).

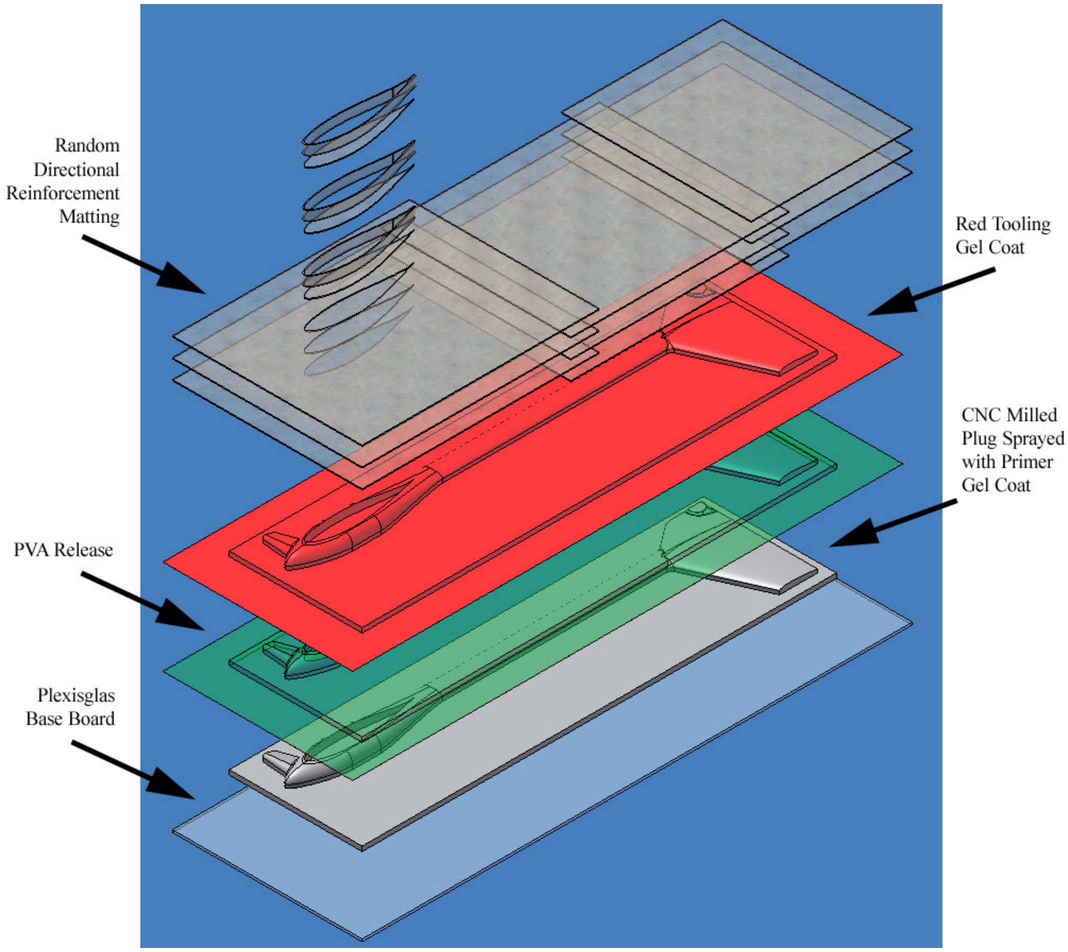


Figure 4.2. Boom Reinforcement Build-up.

In similar fashion, the fuselage mold reinforcement was placed in sections starting at the middle then the ends. The fuselage mold was easier to work with since its curvature did not contain internal cutouts. The technical drawing in Figure 4.3 shows the sequence that the layers were applied. Since the fuselage flange was wide, additional layers were included.

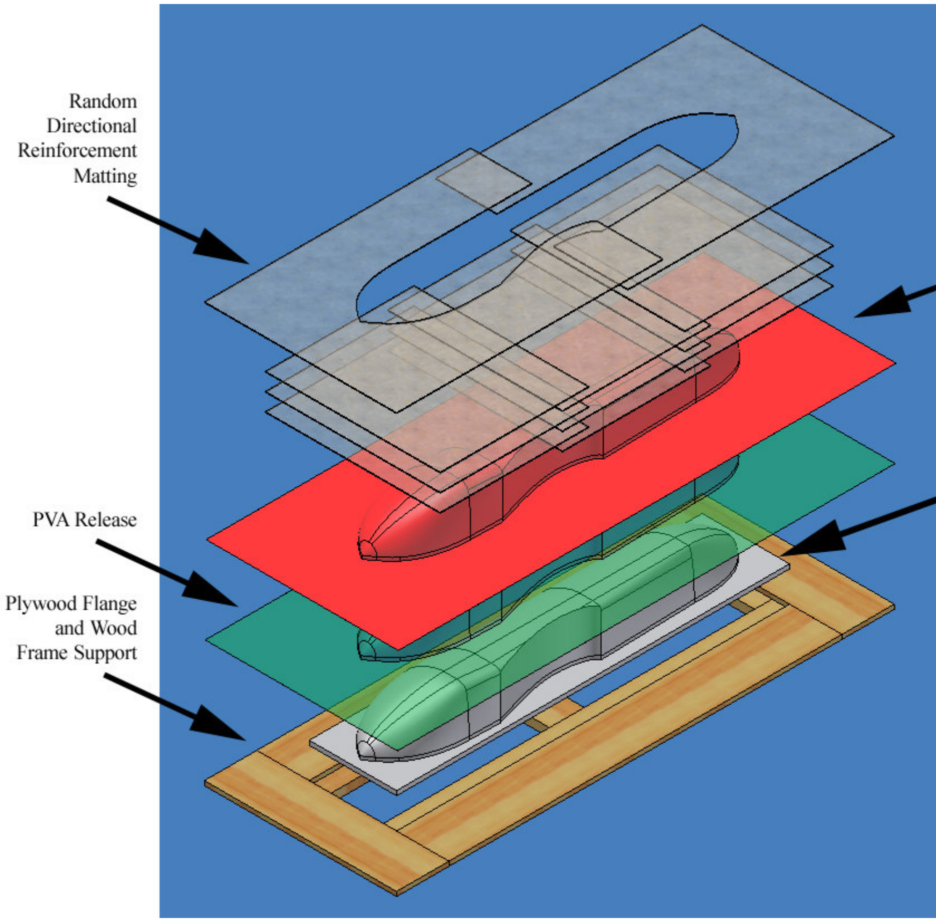


Figure 4.3. Fuselage Reinforcement Build-up.

The reinforcement side of the molds using this process are shown in Figures 4.4. and 4.5. It is possible notice the locations of the overlap in the random directional matting sheets.

The Subsection entitled “More on Labor, Tasks and Process” provides a comprehensive flowchart highlighting the actions and instructions for Phases I and II of mold construction.

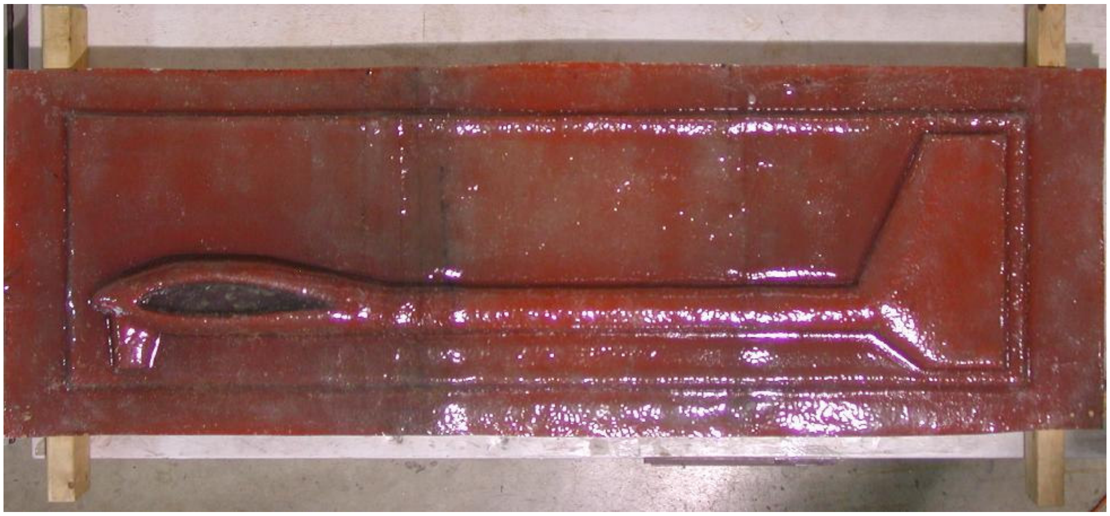


Figure 4.4. Finished Boom Mold – reverse side.

Figure 4.5. Finished Fuselage Mold – reverse side.

4.2.4 Cure Time

Cure times are mentioned in Table 4.5 of this chapter. However, the molds only reached a full cure after 24 hours. In all cases, although the molds were dry to the touch within six hours, the resin had not yet reached the full cure time suggested by the manufacture. To ensure complete cure, the molds were allowed a minimum of three days curing time. The next chapter develops the techniques used for resin infusion and part manufacturing.

4.3 De-molding

4.3.1 Releasing the Mold

After waiting at least eight to ten hours, the mold was separated from the plug. The primary tool used for de-molding was compressed air. Initially, compressed air was burst between the mold and plug without forcing the two apart. The air was injected along the flange of the mold all the way around. By placing one hand on the mold, it was possible to feel the rushing air inside and judge how much of the mold was detached. A good release cover allowed the mold to "pop" loose almost on its own.

The boom molds were more difficult to release because of the features it contained. The airfoil cutout on the boom required patience and methodical air injection. It was important to slowly lift the mold and plug apart straight up as the two detached. Any asymmetrical lifting force on the mold caused the mold to jam and resist de-molding. Furthermore, the ridgeline created by the plug along the flange onto the mold posed problems. The step on the perimeter of the flange made it difficult to focus the compressed air blast in any one desired place. The problems surrounding the flange were discussed in detail in Chapter 3.

The fuselage molds detached with significant ease. The most important point to remember was to inject the compressed air evenly around the entire perimeter of the mold. The fuselage "popped off" after repeated application of the compressed air.

4.3.2 Clean-up and Storage

The de-molding process was somewhat messy since the PVA release film flaked off into many pieces. The PVA release flakes were either swept with a broom or wiped with a damp cloth. The release is water soluble, so a mop was also used for cleaning the floor. The mold was rinsed with a garden hose and dried with a clean cloth without scratching the interior mold surface. The plug was wiped with a damp cloth and set aside for storage.

As described in Chapter 3, the tool clean-up involved some variation of rinsing, wiping or bathing the tool into acetone. The HVLP spray gun used for gel coating (Phase I) and the dump gun used with resin (Phase II) were both cleaned by spraying pure acetone. The HVLP spray gun used with PVA release was rinsed with water. Water was also sprayed to clean the inside of the gun used in the PVA application.


Figure 4.6. Boom Mold – support 2” by 4” frame.

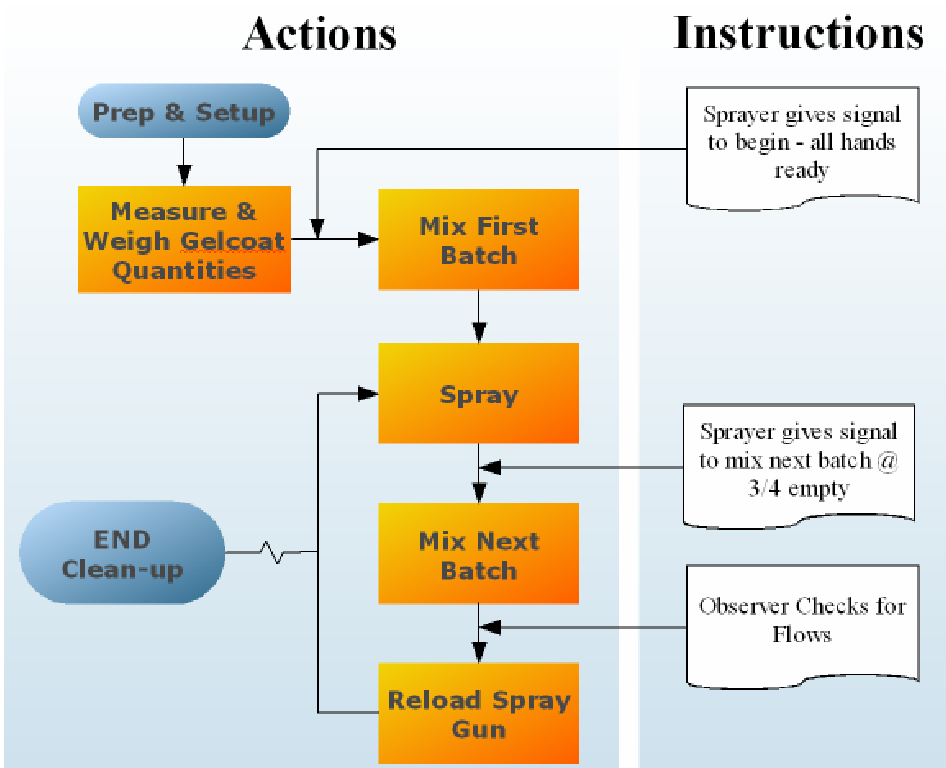
In accordance with Chapter 3 storage instructions, the plugs were relocated shortly after the molds were released. A wood frame was constructed for the molds (Figure 4.6). The frame was important because it provided a stable platform for the mold to rest on. Furthermore, the frame prevented the mold from warping under its own weight over time.

4.4 Advice

4.4.1 More on Labor, Tasks and Process

In both steps to mold making, the person doing the spraying is the group leader. The coordinated effort of the group occurs around the progress of the person spraying. It is not advisable to mix the catalyst to all portions of gel coat or resin at once. Since it takes time to spray, the portions are mixed as the job progresses.

For phase 1, all three of the group members should be able to maintain their hands clean at all times. The first batch of gel coat is mixed and handed to the sprayer. As the sprayer gets down to ¼ of gel coat in the spray-cup, the command is issued to the mixer to prepare the next batch. Once the sprayer runs out, the mixer has a fresh batch on standby. The observer serves as an aid to the spraying effort. The observer constantly looks for bare spots or areas of concern. Furthermore, the observer ensures that nothing touches or drags on the plug while the sprayer concentrates on spraying. The Phase I detailed flowchart is provided in Flowchart 4.2.

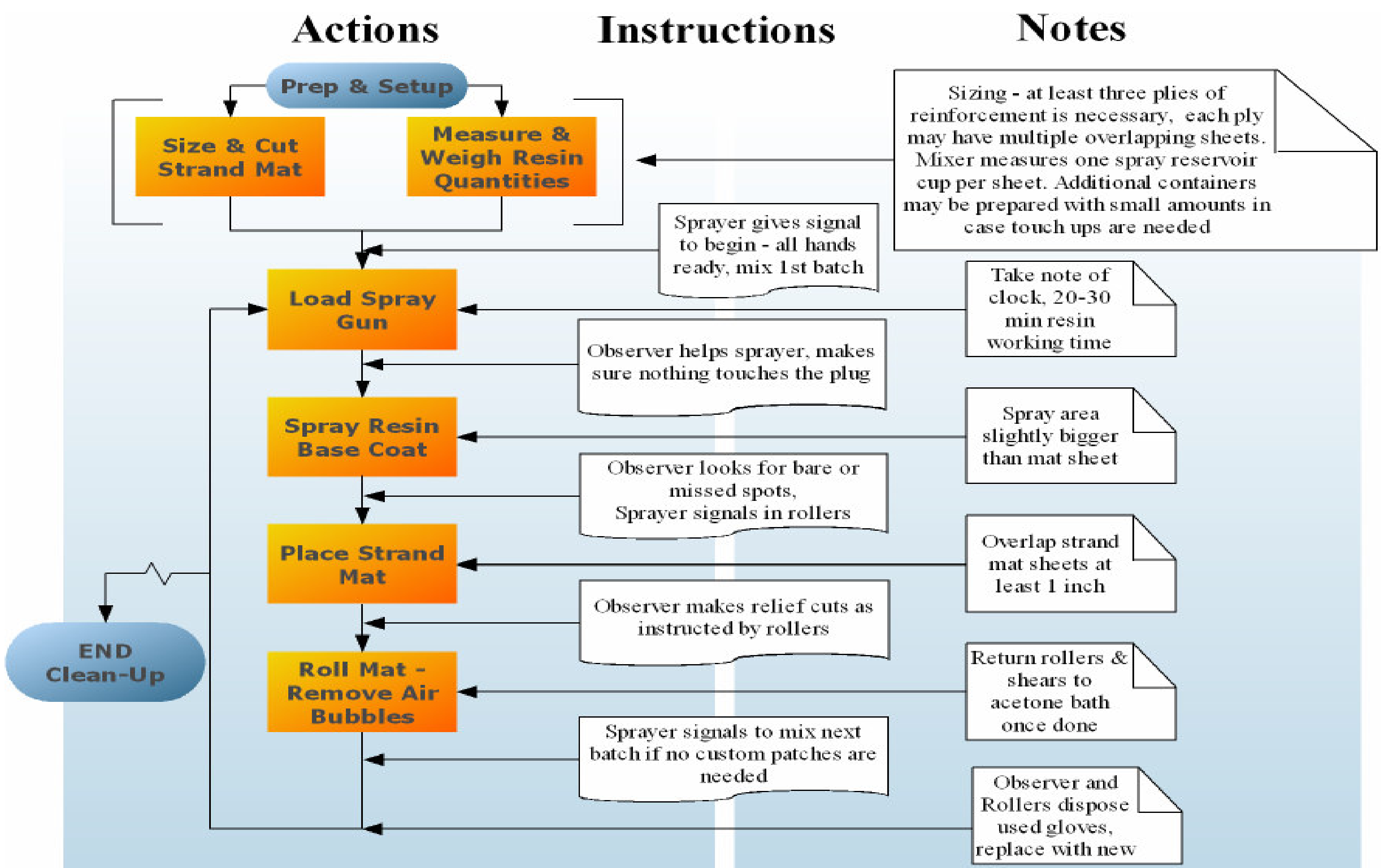


Flowchart 4.2. Mold Making Gel Coating (Phase I) – detailed flowchart.

The hose supplying pressure to the spray gun can easily drag on the plug if both sprayer and observer are not attentive. Another common mishap occurs when clothes, especially the sprayers sleeve, touches the partially sprayed plug. During Phase I, objects touching or dragging on the plug can create two problems: 1) the quality of the gel coat surface is compromised or 2) the PVA release film is detached or frayed. If the release film is damaged, the mold may be permanently attached to the plug.

Phase 2 of the mold making process requires more discipline. The sprayer is still the group leader and has to manage three more helpers. The sprayer should make every effort to keep both hands uncontaminated. More cleanup is required if the sprayer is messy. The observer performs the same duties as in phase 1, but with one additional duty. While the sprayer is reloading, the observer aids the rollers by making relief cuts to the mat as requested by the roller. The mixer performs the same task as described in Phase 1. However, the mixer, in this phase, is working with polyester resin rather than polyester gel coat.

The cutter is responsible for cutting the strand mat. Several pieces of strand mat were pre-cut during setup. However, patches and other pieces may need to be cut on the spot. To minimize cleanup, the cutter works only with dry materials and tools and should not contaminate either hand with resin. The rollers have two duties: placing the strand mat and rolling out bubbles. It takes practice to learn how to perform this function without contaminating either hand. The Phase II detailed flowchart is provided in Flowchart 4.3.



Flowchart 4.3. Mold Making Reinforcement Application (Phase II) – detailed flowchart.

4.4.2 Prepare in Advance

Preparing in advance is a key factor for the successful completion of any composite project. Poor preparation may result in wasted materials, damaged tools, loss of parts and significant stress. Every detail must be satisfied prior to mixing the catalyst with the resin. The work may seem slow during preparation, but goes quickly once the resin working time is counting down.

4.4.3 Thoughts on Mold Release

The spraying of PVA release was found to be more difficult than anticipated. In some cases, the plug had to be sprayed several times. To achieve repeatedly successful applications the PVA release, some level of skill was required on the part of the person doing the spraying. If a PVA spray job was bad, the plug was wiped/rinsed with water, dried and re-sprayed. If the HVLP spray gun is atomizing the PVA while instantly generating "cobwebs", the room temperature is below ideal. This can be important to note during the winter months.

The PVA release is often considered cumbersome to use because it is destroyed with each cycle. Thusly, a new release coat must be applied with each use. However, the film forming PVA release does provide a water-soluble barrier between the mold and the plug. This can provide some degree of fault tolerance as far as detaching two parts since there is a measurable gap, in this case, separating the plug from the mold.

Wax/paste release products are available and commonly used in industry. These waxes vary in chemical content and, when buffed, create a non-stick hard shell on the surface. This kind of product can and will work; however, familiarity with the product and its application is mandatory. A possible drawback to wax or paste based release systems is build up. The wax can accumulate in places both filling in features and/or changing the surface contour. A wax surface coat does require maintenance and will require re-application and buffing after 3 or 4 cycles.

Agent release products are found in liquid form and, most often, wiped on with a clean cloth. These release agents can be very effective, yet, tend to be quite costly. Commonly, the release agent will be highly flammable, have a potent odor and require plenty of ventilation during use. Most often, the "what you pay is what you get" rule does apply to these products.

In general, all external release products follow one rule: more is <u>not</u> always better. For example, spraying too much PVA results in sags and runs while too much wax results in accumulation/build up. Agent release products also have an ideal method of application. Too much release agent can cause crystallization on the surface of the mold. The crystals negate the efforts made during sanding and polishing creating a rough surface. Furthermore, the tiny crystals grab the intended counterpart and render it impossible to de-mold. A heavy application of either PVA film or release agent can suffer from uneven dry-out where the top surface is dry while the undercoat of the product is still liquid.

Further general considerations for external release products are chemical compatibility, temperature range and permanence. Some release products are only chemically compatible with a specific family of epoxies, gel coats and/or resin systems. The temperature range is related to the required cure cycle. Epoxy or resin systems that require autoclaving will also require high-temperature release compounds. Lastly, most waxes and release agents are semi-permanent or permanent and may require a special "strip" agent to recondition the surface to original state. Otherwise, a permanent release agent can only be removed by sanding it away completely.

In summary, the best way to become comfortable with a release system is to practice using it with a trial piece. A good supplier will be willing to share experience and pointers about the various release agents. A trustworthy vendor with good customer service can make the difference between success and frustration. Lastly, any recently made plug or mold does have a break-in period. Often times, it takes repeated release applications or overall cycles for a plug or mold to create the best parts, so, be patient.

4.4.4 De-molding – Troubleshooting

Using compressed air is the least evasive method of separating the mold from the plug or, as explained later, the mold from the part. It was found that using multiple compressed air nozzles worked better than just one. The rushing air entering from opposite locations in the plug generated a lifting cushion. This was so effective that the use of two or more nozzles became standard practice.

Some cases required more effort and called for the use of high-pressure water. The PVA is water-soluble and gets flushed when rinsed. This can create just the necessary room to "wiggle" the pieces loose from one another. Some arm strength was also applied in these stubborn cases. However, there is always some margin of risk when using brute force to separate two pieces. Forceful intervention should only be used in desperate situations, in which case, a decision might have to be made wether to preserve the plug or the mold.

4.4.5 Gel Coating – Troubleshooting

As mentioned before, the gel coat must be applied evenly over the entire plug. Prior to starting Phase I, it was evident that Phase II (Reinforcement Application) of the boom molds would be time consuming. The airfoil cutout in the boom plug would require many relief cuts and custom patchwork as far as the placement of reinforcement matting. Therefore, in an effort to facilitate the Phase II efforts, the airfoil cutout in the boom plug was filled more than halfway with gel coat. At the time, this seemed to be an attractive proposition; however, it did more harm than good.

The gel coat has a shrinkage property sometimes specified by the manufacture. In actuality, the amount of shrinkage may vary from job to job and most companies provide this and other information as reference parameters. The shrinkage of the gel coat as it cures can vary due to storage conditions, age, catalyst to gel coat mixture ratio, room conditions and overall application/methodology employed by the user.

Figure 4.7. Cracked Gel Coat due to Uneven Thickness.

The catalyst initiates an exothermic reaction that releases quite a bit of heat and, thusly, hardening the resin. Filling the airfoil cutout created a concentration of heat in that area of the plug. The gel coat deformed/shrank while curing and caused cracks to occur on the surface (Figure 4.7). This was catastrophic but, fortunately, did not damage the plug itself. The gel coat was carefully peeled off. The PVA release was washed off and re-sprayed. The next time the gel coat was applied, the sprayer was mindful to apply a constant coating no thicker than ⅛th of an inch.

In making the best out of this situation, the solid gel coat with the shape of the airfoil was set aside and later used as a template. The custom cut patches of strand mat used to reinforce the inside of the airfoil cutout was cut using the trace made from the solid gel coat airfoil. This gel coat airfoil was also used as a cutting template in Chapter 5.

4.4.6 PVA and Gel Coat Spraying Tips

Both PVA and gel coat should be sprayed systematically. The sprayer should maintain the spray nozzle both perpendicular to and 10 inches away from the surface. It is important to spray through the ends/edges of the part. This means that the return pass should be initiated outside the piece being sprayed. Notice Figure 4.1, the gel coat was sprayed on the brown paper covering the table. To ensure that the entire mold piece had a level gel coat, the operator sprayed beyond the edges/flange before coming back. This was particularly important when spraying PVA release. If the corners of the flange are starved of release this can make de-molding very difficult. During preparation, the worktable was covered with either newspaper or brown paper so spraying onto the table was not a problem.

Although more forgiving than the PVA release, the spraying of gel coat does require attention. Troubleshooting guidelines for gel coat application are listed in Table 4.5. Removing and re-applying the entire gel coat cover is the best solution to fixing cracks and/or tackiness problems on the surface. Any doubts as to the quality of the applied gel coat cover needs to be addressed immediately. Risking continuing on to Phase II can be a gamble too costly to take on.

Problem	Cause
Low Gloss	Incorrect catalyst ratio, under cure or poorly mixed gel coat
Uneven Coat Thickness	Excessive surges during spraying – operator error
Tackiness	Insufficient catalyst present, under cure conditions, poor mixture
Sags	Excessive thickness and/or air assist, spray nozzle too close to mold
Cracks	Shrinkage, uneven gel coat thickness applied

Table 4.5. Gel Coat Spray Troubleshooting.

4.4.7 Manage the Workspace

The workspace needs to be clear of all potential obstacles no matter how innocent it appears. All furniture not involved with the process should be cleared. Common hang-ups and accidents involve chairs, extension cords, and/or the compressed air hoses.

The working time can be 20 or 30 minutes, but all it takes is 10 seconds for the gel coat or resin to set. Not having the correct tools and materials handy commonly adds stress to the workplace, especially when the resin working time is nearly expired. It is wisest to use these precious working time minutes doing meaningful work rather than running around after a new box of latex gloves or negotiating objects that are constantly in the way.

4.4.8 Advice Summary

Processes described both above and below promise many desirable outcomes. However, the integrity or lack thereof ones maintains with the work is the decisive factor as to its outcome. It is difficult to predict if something will come out great or superb; yet, easy to predict if it will result poorly or unsatisfactorily. It is always best to error in the side of caution than to remediate the consequences.

Chapter 5: VARTM

5.1 Preparation

5.1.1 Materials and Tools

The materials used for Vacuum Assisted Resin Transfer Molding (VARTM) are listed in Table 5.1.

Materials	Description
General Materials	Mixing cups, stir sticks, latex gloves, eye protection, masks, etc
Spiral Tubing	Tubing used to vacuum air and resin from part, ¼in. or ½in.
T & Y Connectors	Connector fitting for tubing, ½in diameter
Vacuum Hose	Vacuum rated tubing, ½in. diameter
Hose Clamp	Clamp used to secure hose and connectors
Tacky Tape	Vacuum tape used for sealing vacuum bag to mold
Vacuum Bag	Impermeable film cover used to seal mold during vacuum application
Peel Ply	Barrier film/fabric that is removable post cure
Resin	Polyester resin used for reinforcement of matting
MEKP Catalyst	Hardener used for polyester based primers, gel coats and resins
Carbon Cloth	3K 2x2 Twill 5.7oz/sq Carbon Reinforcement
Infusion Media	Honeycomb infusion mat and diamond shape infusion mesh
Release	Polyvinyl Alcohol (PVA) release film
Liquid Shine	Gel coat clean and shine compound
Machine Glaze	Polishing compound
Liquid Wax	Surface Wax in liquid form

Table 5.1. VARTM Materials.

The tools used for VARTM are listed in Table 5.2.

Tools	Description
Cutting Instruments	Shears and/or sharp bladed tools for cutting cloth
Measuring Equipment	Measuring tape (preferred) and/or yard stick
Buffing Pads	Polishing Pad used for removal of surface scratches due to sanding
Digital Scale	Instrument used for weighing polyester resin
HVLP Spray Gun	High Volume Low Pressure Siphon Spray Gun for PVA
Resin Trap	Container that prevents resin from going into vacuum pump
Pneumatic Polisher	Pneumatic Device used for efficient polishing of large areas
Paint Booth	Closed ventilated area reserved for spraying
Air Injection Wedge	Wedge shaped air injection nozzle
Compressed Air	High pressure air line, adequate fitting, nozzle, etc
Vacuum Pump	Vacuum pump with adequate fittings, hose, etc

VARTM Tools.

5.1.2 Labor and Task

The vacuum infusion process (VIP) required several people. To management of the available personnel was made efficient by dividing the process into two parts: preparation/dry lay-up and infusion. The labor and task descriptions are provided in Tables 5.3 and 5.4.

Labor	Task Description
Sprayer	Pre-PVA prep, handles molds, and sprays PVA
Sprayer Helper	Handles molds, aids in PVA preparation and spraying
Dry Lay-up Crew	Cuts materials, reinforcement cloth and infusion dissipation core Locates cut materials into mold and assembles vacuum bag (2 to 3)
Workspace Support	Clean-up & Prep Workspace, organize tools

Preparation & Dry Lay-up (Phase I) Labor Distribution.

Labor	Task Description
Mixer	Mixes pre-measured resin batch
Vacuum Operator	Manage vacuum pump
Infusion Support	Assists infusion process (4 to 6 people)

Resin Infusion (Phase II) Labor Distribution.

Although both phases could be carried out with as little as three people, it was found that multiple hands working together increased the chances of making a successful part. During the preparation phase, typically four to five individuals were sufficient. However, the infusion phase required more helpers on-site. The Advice Section of this Chapter contains further information on Labor and Task.

5.1.3 Further Mold Preparation

The molds were prepped as necessary depending on their quality once de-molded from the plug. In this stage, the mold was polished and waxed as described in Chapter 4. Any polishing work done to the molds followed the same steps and procedures used for the plugs.

The PVA release was sprayed in similar fashion as previously done on the plugs. However, one additional step was required. The border of the flange was masked with clear packing tape. Once the mold was sprayed and the sprayer approved the job, the packing tape was peeled off. It was important to peel off the packing tape before the PVA fully dried. If the packing tape is not removed readily, the dried PVA will peel off with the packing tape as it is removed. Thusly, the spray job may be ruined and require re-application. The spraying of PVA followed the same procedure as described in Chapter 4.

The sprayer and helper performed the following actions in sequence: moved the mold to the spray booth, wiped off any surface dust, masked the flange edges, sprayed PVA release, inspected spray job, and removed the packing tape. If the spray job was unsuccessful, the existing film was washed off with water. The mold was then dried and prepped for another PVA application. A successful PVA application resulted in a shiny film free of sags, bare spots and pools (Figures 5.1 and 5.2).

Figure 5.1. Fuselage Mold (Right Half) Sprayed with PVA – tape along flange border removed.

The fuselage mold was further prepped with a pinstripe line. The white line was located inside the mold with a template. The PVA was sprayed on top of the pinstripe. The line created a slight impression on the fuselage part. The hatch cutout was made following the line imprint (Chapter 7). Once successfully sprayed, the packing tape was removed and the fuselage mold was allowed 2 hours to dry completely (Figure 5.1).

Figure 5.2. Boom Mold (Right Half) Being Sprayed with PVA – with tape along flange border.

5.2 Infusion

5.2.1 Process Description

The Vacuum Infusion Process (VIP) uses lower than atmospheric conditions on the laminate to propel the catalyzed resin. The liquid resin, while under vacuum, wets the dry reinforcement inside the sealed mold. In the case of VARTM, the resin is infused by vacuum while creating a single-sided finished part.

The single sided Vacuum Assisted Resin Transfer Molding used in this project utilized both resin injection molding and vacuum bagging processes (Figure5.3). The laminate retained the exact contour and surface quality of the mold on the finished side. The vacuum bag side of the laminate did not retain a repeatable finish since it did not have direct contact to a counter mold.

The single sided resin infusion molding process allowed the reverse side to be finished such that it was suited for gluing other laminates post-infusion. The use of a porous fabric, called Peel Ply, allowed the reverse side to be constantly rough; therefore, surface –ready for later assembly (Chapter 7).

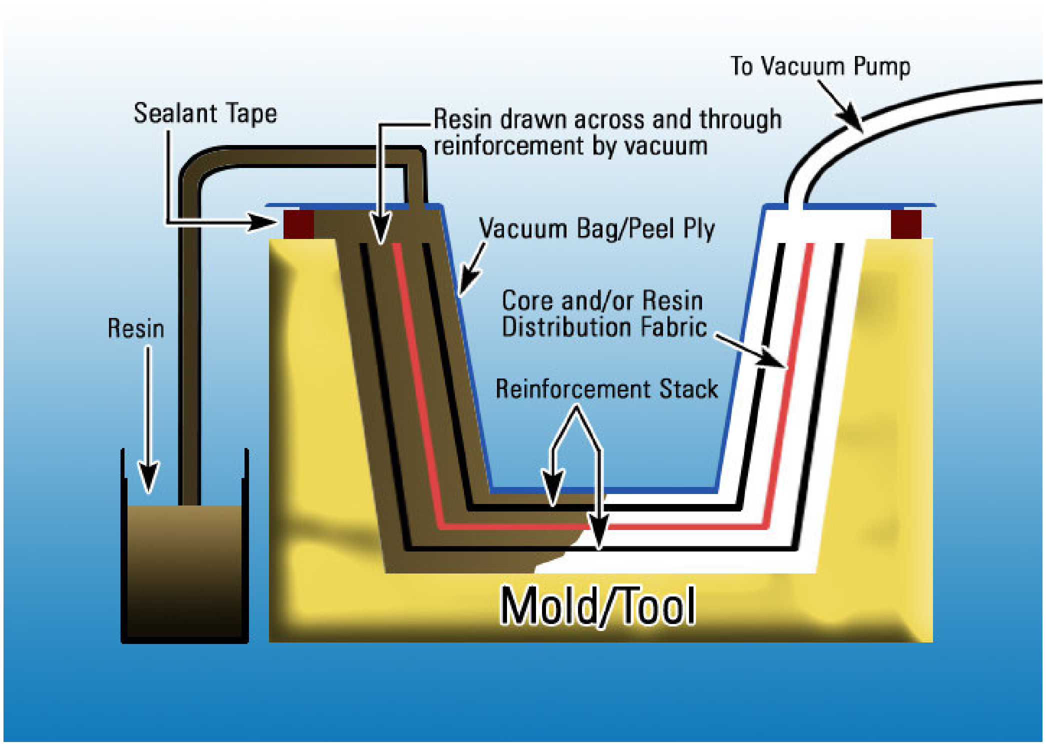


Figure 5.3. Vacuum Infusion Process.

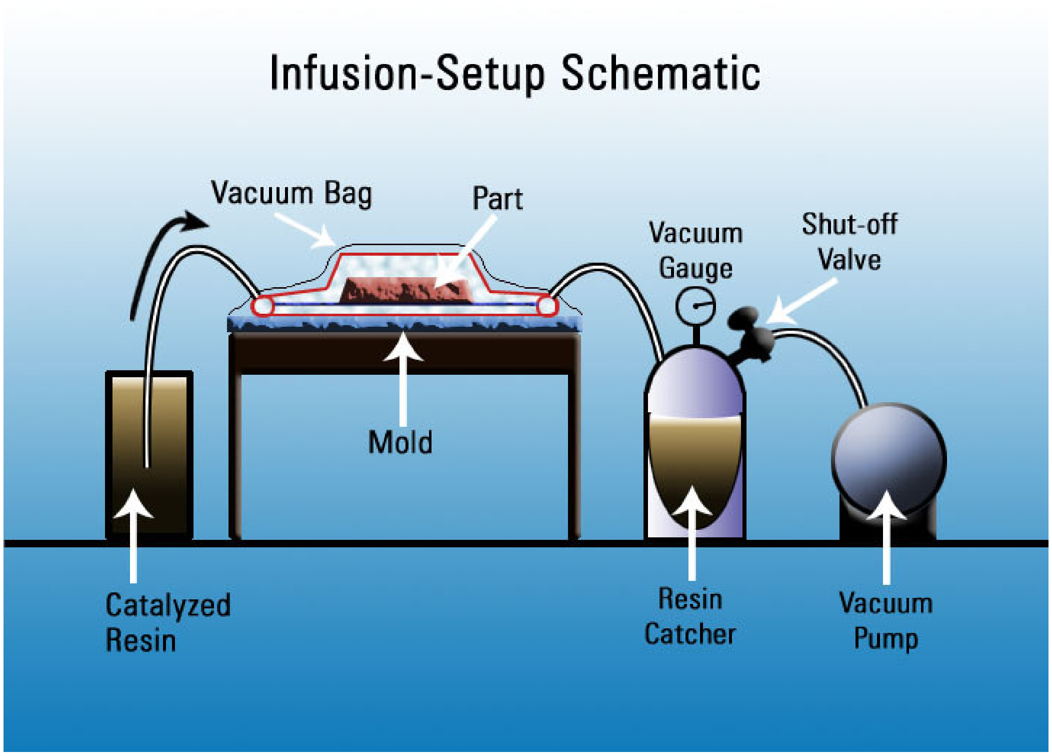


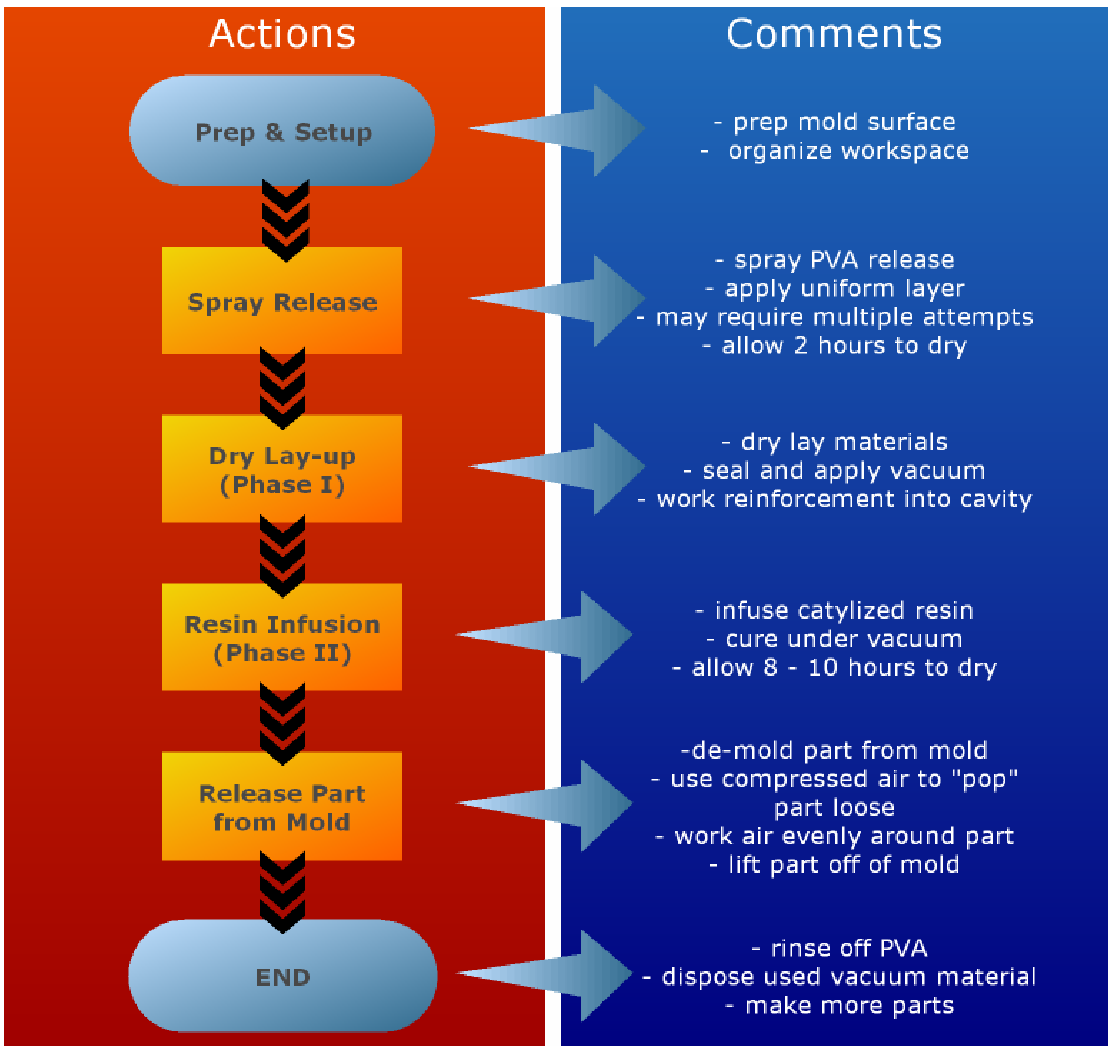
Figure 5.4. VIP Setup.

The Infusion Setup is illustrated in Figure 5.4. The resin is drawn into the part by means of suction provided by the vacuum pump. The resin trap protects the vacuum pump by allowing out flowing resin to drip into the bucket. The gage on the resin trap is used to monitor the vacuum pressure in the system.

Other Resin Transfer Molding (RTM) methods use molds on both sides to provide consistent finish in both the exterior and interior faces of the part. Furthermore, parts that are required to have a specific thickness everywhere may also need to have molds on both sides. However, the creation of matched male and female molds double the time to production time and cost.

5.2.2 VARTM – Breakdown and Comments

The parts were made following the sequence described in Flowcharts 5.1 and 1.3.



Flowchart 5.1. VARTM – breakdown and comments.

5.2.3 Phase I - Dry Lay-up

The dry lay-up phase, as the name implies, represents all portions of the process prior to the infusion of the catalyzed resin. There are many important steps between the spraying of PVA release and the infusion of resin. Any skipped or abbreviated actions in this phase may result in loss of part and/or mold.

While the PVA release film dried, two plies of carbon cloth and one ply of infusion medium was sized and cut. The necessary materials and tools were organized and laid out in the designated work area. The mold, with a successfully applied and dried PVA film cover, was removed from the paint booth. If other molds needed PVA, the spray crew continued on to the next job.

The double-sided vacuum seal tape, called tacky tape, was placed along the outside edges of the mold where the clear packing tape once was. It was found, through experience, that placing the tacky tape entirely on top of the PVA release caused leaks to occur during the vacuum bagging process. This was the reason why masking the perimeter of the flange was important. However, the presence of the unprotected border of the flange posed new concerns.

Two solutions were found for this problem. Firstly, having a sufficiently large flange provided a gap between the reinforcement cloth and the tacky tapeline. Therefore, resin did disperse onto the unprotected edges of the mold since it only traveled where cloth was present. Secondly, in places where the flange was minimal, the tacky tape was slightly overlapped with the PVA release film. This allowed the infused resin to touch the tacky tape while not contacting any bare gel coat.

In the case of the boom mold, the tacky tape, with reverse adhesive side still covered, was overlapped with the release film line. The pre-cut infusion media and carbon reinforcement were placed in the mold. The vacuum bag was cut oversized widthwise and placed on the mold (Figure 5.5).

The infusion dispersion media between the carbon plies was custom cut to match the features of the boom. Two different media were used in the fabrication of booms. In order to reduce weight in the tail of the aircraft, the rudder was made with a lightweight infusion medium. However, to increase stiffness, the entire boom and vertical stabilizer was manufactured with a thicker infusion medium. Figures 5.6 – 8 show the placement of the infusion media for the boom. The red infusion mesh was sized to fit inside the vertical stabilizer while overlapping with the hexagonal infusion medium. The rudder was cut from the vertical stabilizer as discussed in Chapter 7. The airfoil-shaped cut at the nose of the boom in Figure 5.7 was made with the gel coat template mentioned in Chapter 4 (the gel coat template can be seen on the table, top left, in Figure 5.8).

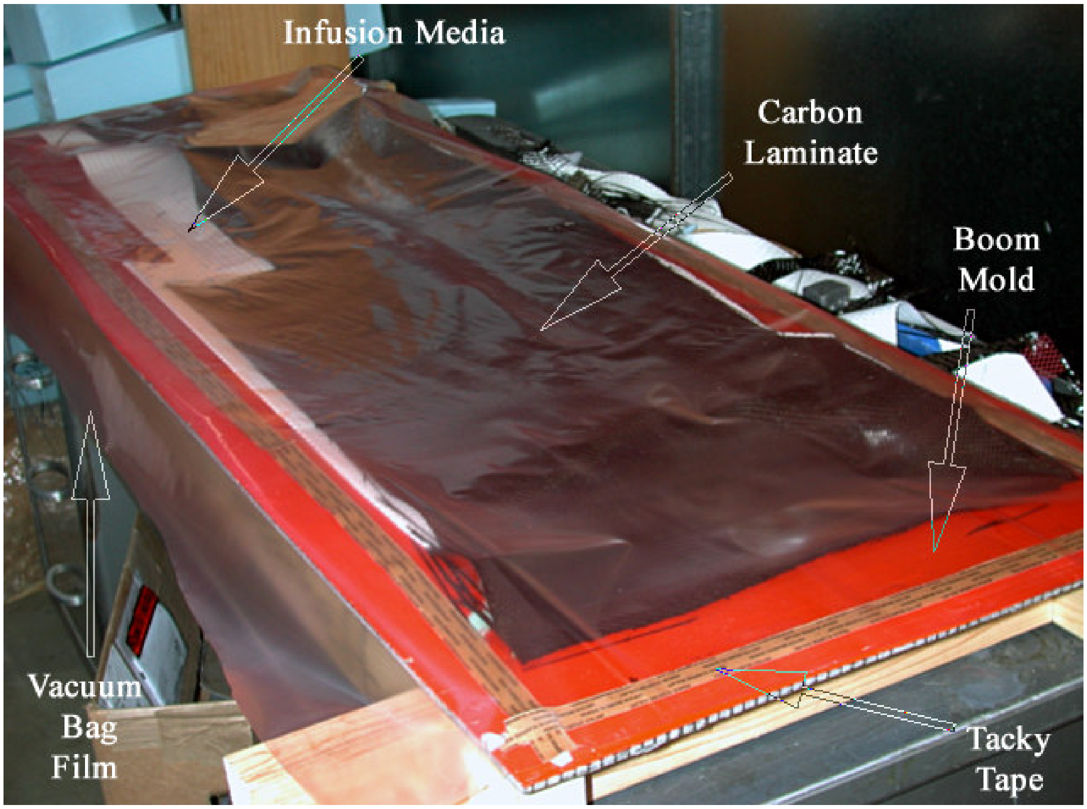


Figure 5.5. Boom Mold (Left Half) – dry lay-up.

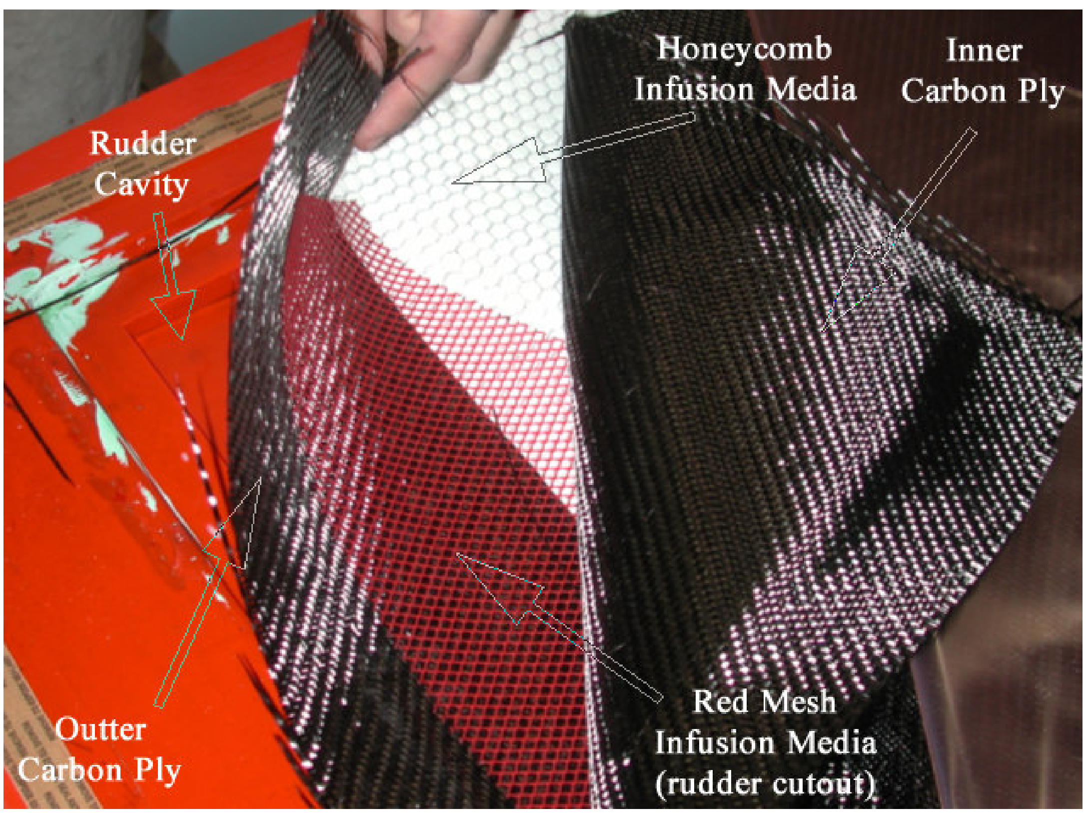


Figure 5.6. Red Mesh Infusion Medium – used in vertical stabilizer and rudder.

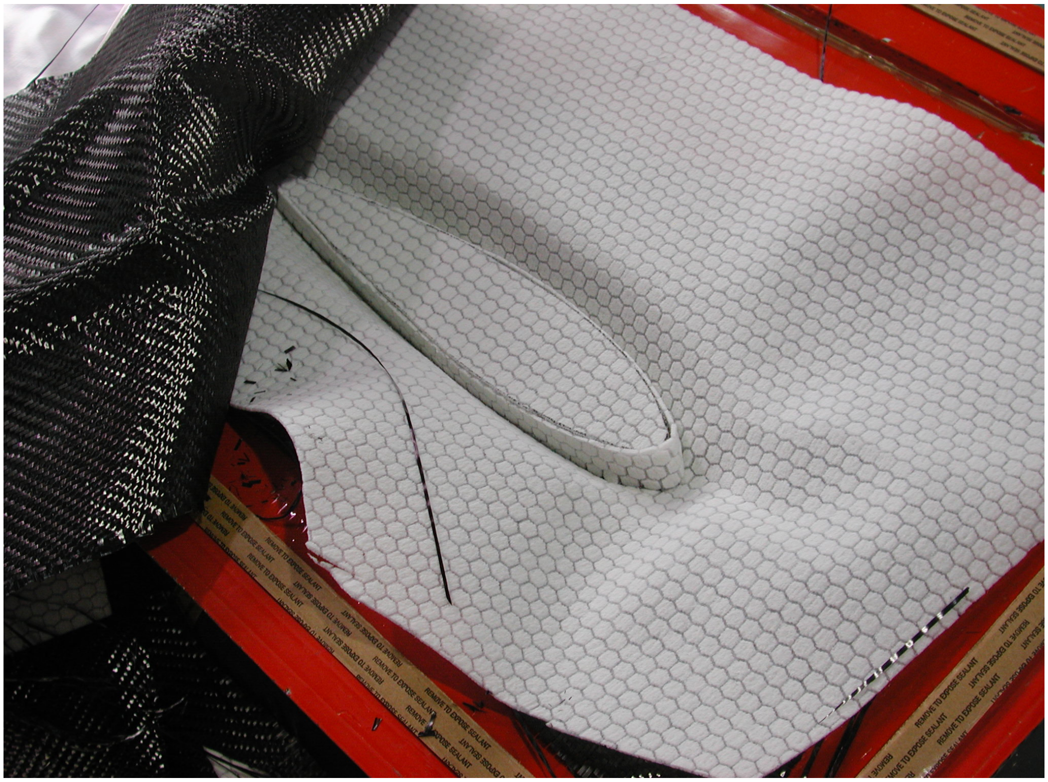


Figure 5.7. Airfoil Cutout – infusion medium airfoil cutout with “walls”.

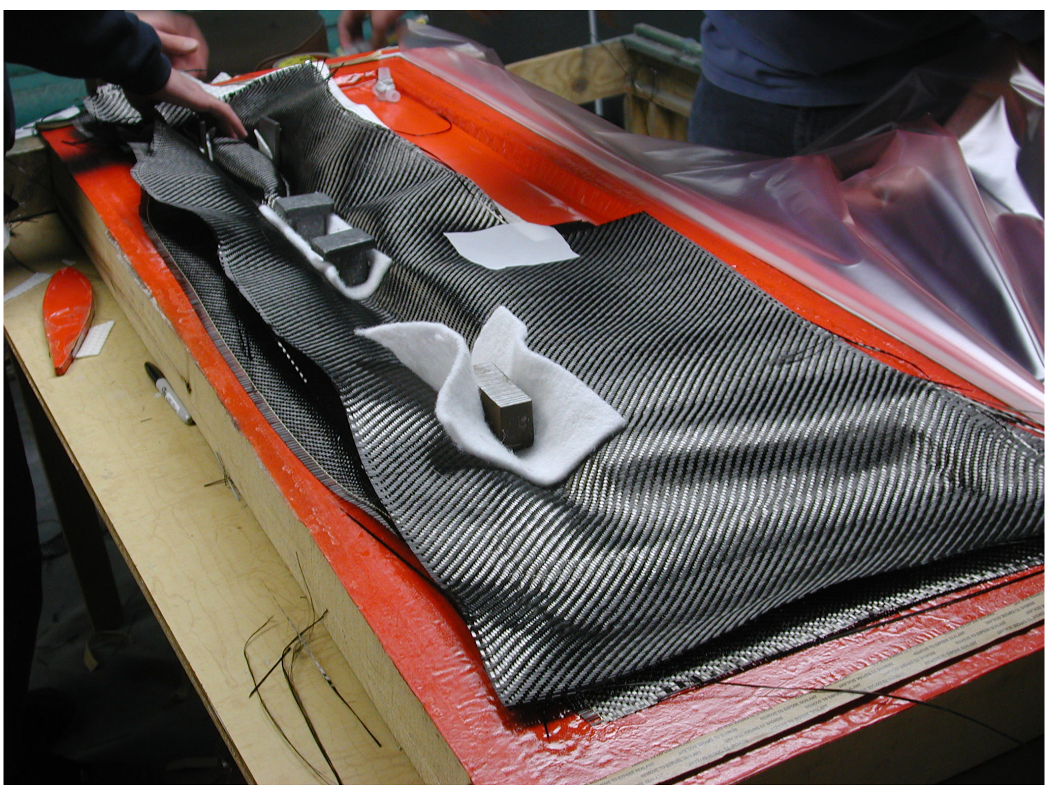


Figure 5.8. Carbon/Infusion Medium/Carbon Sandwich – worked into boom.

Small weights were placed inside the boom cavity to assist in the placement of the cloth and infusion media. By using the weights, one person could work the reinforcement in place without the assistance of more hands (Figure 5.8). Meanwhile, another worker attached the vacuum bag to the tacky tape. Once the long side of the bag was adhered to the tacky tape, a small cut was made for the "T" connector used as the suction port.

The dry lay-up process for the fuselage was similar to the boom. However, the fuselage was less cumbersome to fabricate because it did not contain any internal features like the airfoil cutout of the boom. To reduce fuselage weight, the red mesh infusion medium was used instead of the hexagonal dispersion cloth. The mesh did require relief cuts so it could conform to the curvature of the fuselage. In some places where the relief cuts resulted in an overlap, the excess mesh was trimmed so it only intersected itself.

5.2.4 Phase I – Inlet and Outlet Lines

The resin distribution line and the suction port were strategically located to maximize wet out. The distribution setup varied for the boom and fuselage. Due to the feature and size difference between the boom and fuselage, the inlet spiral tubing and outlet suction port required different arrangements.

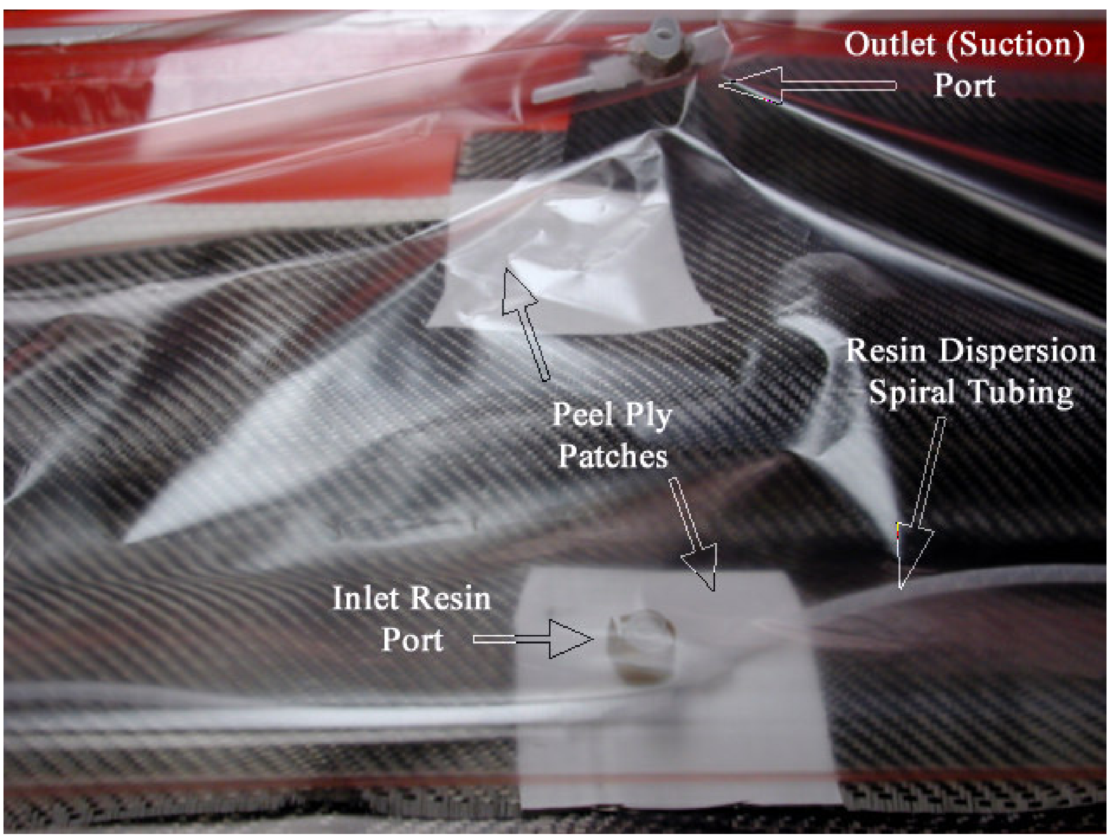


Figure 5.9. Boom – inlet and outlet ports detail, no vacuum applied.

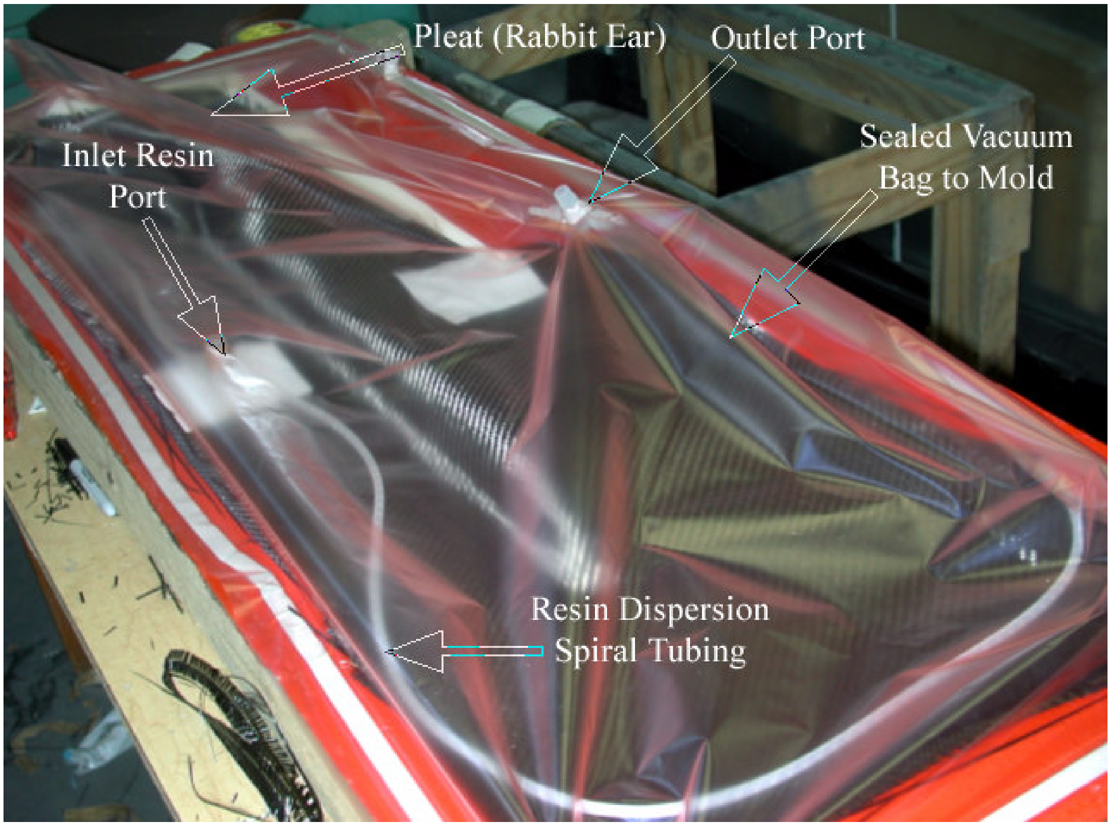


Figure 5.10. Boom – vacuum bag sealed, no vacuum applied.

For the booms, the resin flowed along a radial path toward the suction port. The spiral tubing partially curled around the nose of the boom while almost entirely curled around the rudder. The suction port was essentially a sink located in the center of the mold. The spiral tubing used was ¼-inch diameter while the "T" connector was ½-inch diameter. This allowed the spiral tubing to be one continuous piece that slid through the connector. The "T" connectors were prepped with a ring of tacky tape at the stem. Once a hole was made on the vacuum bag and the connector was pushed through, the tacky tape ring sealed the bag. Small patches of peel ply were placed under the "T" connectors to facilitate their removal once the part was cured (Figure 5.9). After the spiral tubing, "T" connectors and peel ply were in place the vacuum bag was sealed (Figure 5.10).

The evacuation of air required several helpers since the reinforcement cloth, spiral tubing, and ports needed to be held in place during suction. In the sharp contours of the boom, the cloth was tucked in and held in place with a plastic putty spreader. It was necessary to apply and release the vacuum several times to eventually work the cloth sandwich into place. The laminate tucked in some more with each cycle that the vacuum was released and re-applied. Eventually, the laminate took the exact shape of the boom and was ready to receive the resin (Figure 5.11). Lastly, the entire piece was scrutinized for leaks along the tacky tapeline.

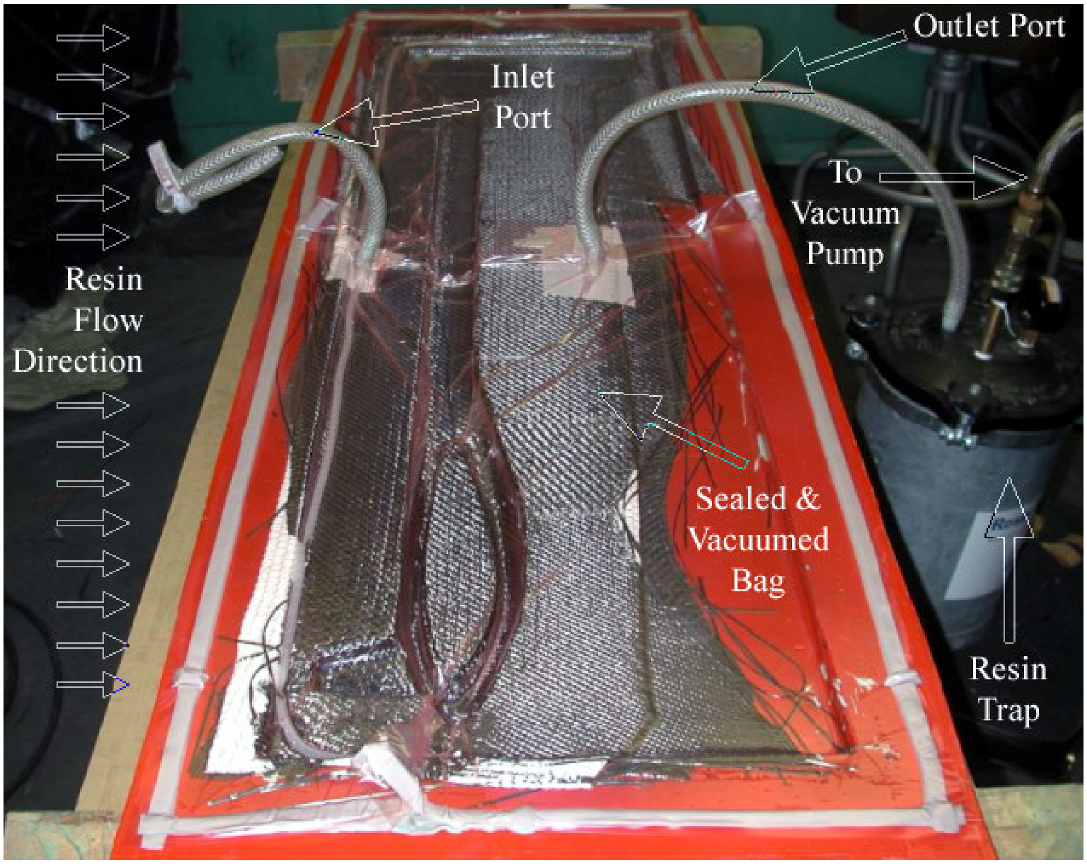


Figure 5.11. Boom – ready for infusion, vacuum applied.

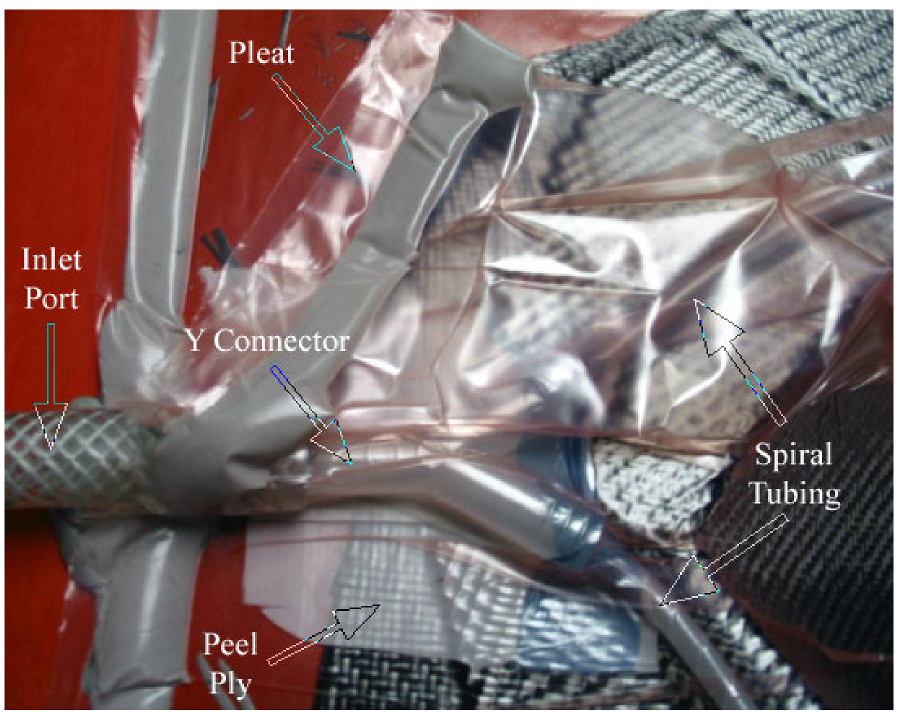


Figure 5.12. Fuselage – outlet port detail and “rabbit ear”.

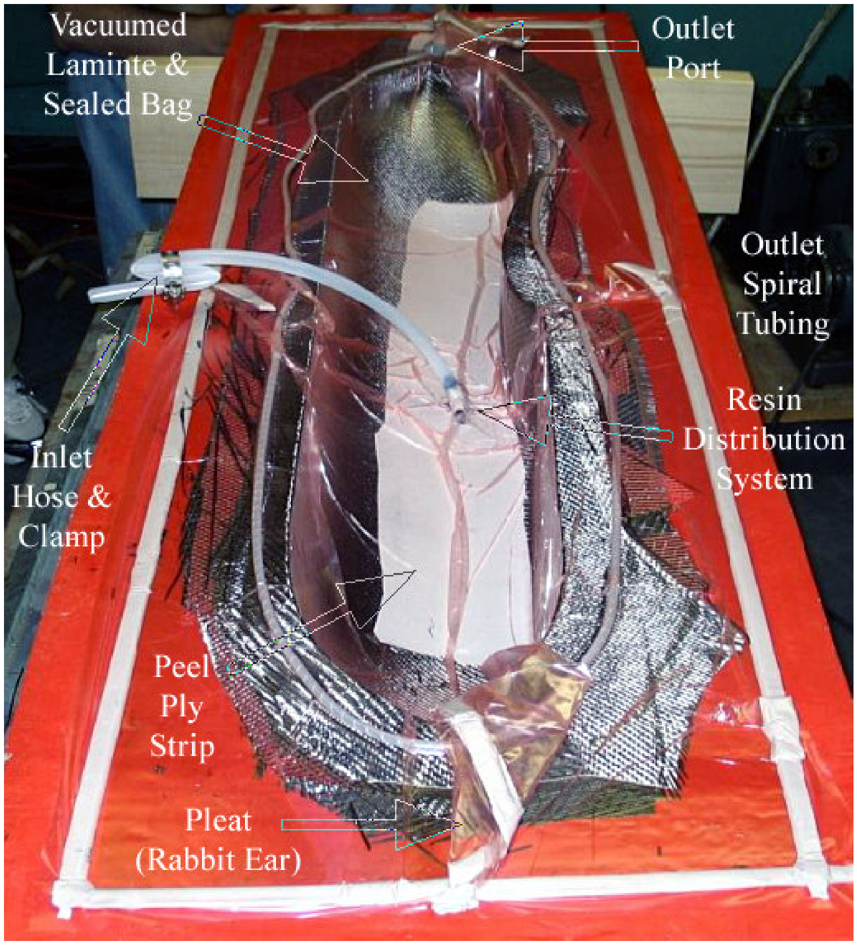


Figure 5.13. Fuselage – ready for infusion, vacuum applied.

The fuselage used a different inlet and outlet setup. The inlet spiral tubing was placed inside the fuselage; therefore, peel ply was placed along its entire length. Without the peel ply, the spiral tube would be impossible to remove cleanly, hence, adding weight to the aircraft fuselage. The perimeter of the fuselage was lined with the outlet spiral tubing. A "Y" connector was used on the outlet port since it laid flat on the mold flange (Figure 5.12). The fuselage mold was sealed and vacuumed in similar fashion as the boom mold (Figure 5.13). The fuselage also required several vacuum and release cycles until the laminate fully contoured to the mold.

5.2.5 Phase II – Resin Infusion

The vacuum-sealed boom and fuselage were injected with 1.25lbs of catalyzed resin each (Figures 5.14 & 5.16). It was possible to track the progress of the resin by the color of the carbon cloth. The carbon laminate turned dark as the resin soaked it. Once full wet out was achieved, the inlet hose was clamped off and the part was allowed 10 hours to cure (Figures 5.15 & 17).

Figure 5.14. Resin Infusion in Progress – right boom half.

Figure 5.15. Boom Resin Infusion Complete.

Figure 5.16. Resin Infusion in Progress – right fuselage half.

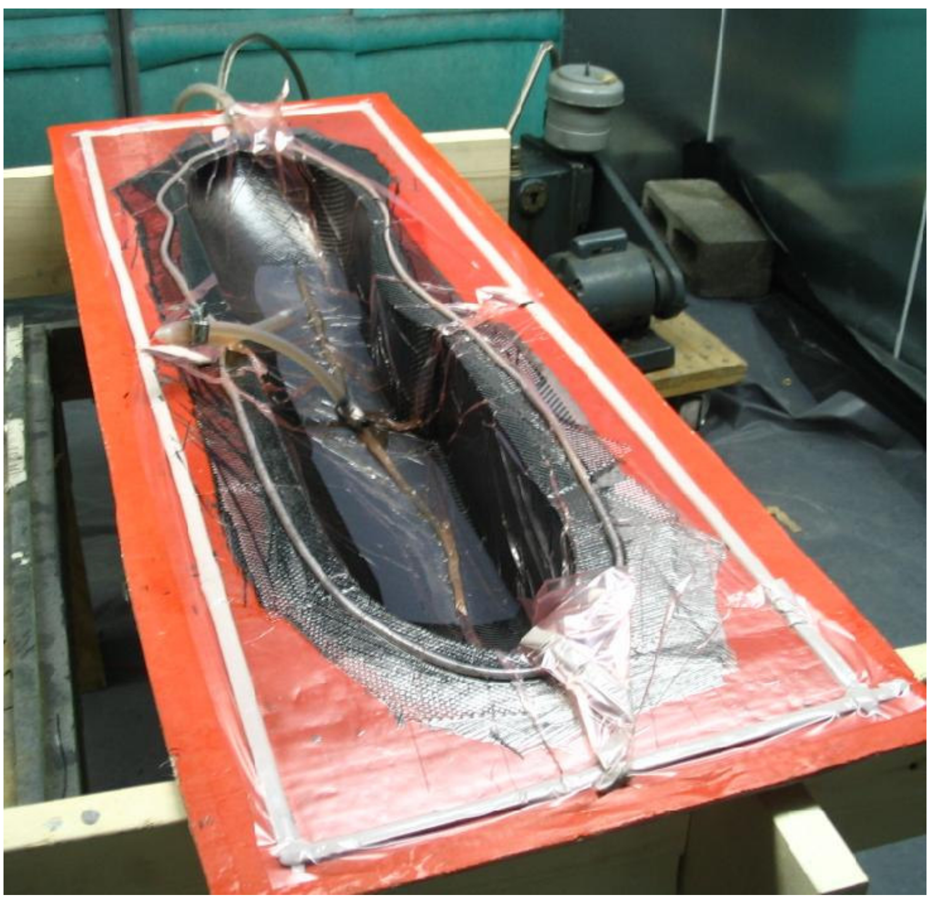


Figure 5.17. Fuselage Resin Infusion Complete.

5.3 De-molding

5.3.1 Releasing the Part

The primary tool used to release the part from the mold was compressed air with a wedge shape nozzle. The compressed air was injected evenly around the flange causing the part to "pop" off the mold (Figure 5.18). To remove the PVA release, the mold and part were rinsed off with water (Figures 5.19 & 20). The mold was re-prepped for another molding cycle. The fuselage part was de-molded in similar fashion (Figure 5.21). The resin inlet and outlet ports were removed, the part was rinsed with water and the fuselage was ready for trimming.

Troubleshooting for de-molding the part consisted of the same procedures as discussed in the Advice Section of Chapter 4.

Figure 5.18. Boom – de-molding process (from top left to bottom right).


Figure 5.19. Boom – de-molded part with release film.


Figure 5.20. Boom Mold and Part – PVA release rinsed off with water.

Figure 5.21. Fuselage Mold and Part – with PVA release and outlet port attached.

5.3.2 Clean-up

The PVA release film on both mold and part were washed off with water. The used vacuum bag material, tacky tape, spiral tubing, peel ply, resin mixing bucket, "T" & "Y" connectors and vacuum hose lines were discarded. The resin trap was opened and the hardened resin was discarded. The mold was either prepped for another infusion cycle or transported to storage.

5.4 Advice

5.4.1 Inlet and Outlet Ports – Where to Place Them

It is important to realize that the catalyzed resin tends follow the path of least resistance during infusion. Once the resin reaches the suction port, it will prefer to flow in that particular path; therefore, decreasing wet out dispersion rate in other portions of the laminate. A symmetric location of inlet and outlet resin ports may not be ideal depending on the features and size of the part. There are many possible setups for infusion and some might require multiple in and out ports along with the use of spiral tubing in one, two or all ports. In this project, for example, two completely different successful setups were used to permeate resin into the laminate.

For a given part, where locations of ports are not trivial, it may take some trial and error to find the ideal setup. It is highly advised to perform trial and error cycles using e-glass rather than carbon. This will reduce the cost associated with the trials and will allow the team to practice with less apprehension towards failure. Software that predicts the flow of resin during the VARTM process is available. However, licensing for such products can be costly. Acquiring such software is a calculated trade-off between project size, cost, time/deadline, required first-time success and required production rate.

Simple tricks can be used to manipulate the speed of wet out. One method of controlling infusion involves tilting the mold so gravity can aid or prohibit the flow. Raising the catalyzed resin container above or below the mold is another method of controlling wet out. It is important to note that the resin flows slower in reinforcement cloth that does not have infusion medium as part of the laminate. However, the overall single limiting factor that dictates the dynamics of the resin during infusion is its viscosity. Suitable epoxy or polyester matrix systems used for infusion should have a viscosity no greater than 1000 mPa-s or 1000 centipoise (cps). In this project, pigment-coloring additives were found to increase viscosity of the catalyzed polyester resin; thus, impairing the resins ability to wet out the laminate.

5.4.2 Work the Laminate

It is imperative to work the laminate completely into the cavity of the mold. Failure to do so typically results in two kinds defects: blistering or resin bridging. Trapped air on the surface of the mold diminishes the aesthetics of the part while trapped air between plies significantly degrades structural properties of the laminate.

Bridging is a natural occurrence inherent to Vacuum Assisted Resin Transfer Molding. It occurs when the laminate does not fully compress into the mold surface, especially in molds whose features do not readily allow the cloth to negotiate complex curvatures. During infusion, gaps are filled creating visible resin-rich pockets on the surface. The resin rich pockets not only add unnecessary weight to the part but are also subject to cracking, especially if the surface is subject to flexural stresses. Although impossible to avoid along edges with tight radii, it can be minimized by systematically working the cloth into place by means of applying and releasing vacuum as described earlier in this Chapter. This requires patience and several workers (Figures 5.22 & 5.23).

The bridging phenomenon can be observed in Figure 5.20 at the leading edge of the airfoil cutout. The cloth is unable to accommodate the change of curvature, especially in sudden 90-degree transition. The resin accumulates along the entire edge of the airfoil cutout creating a solid rim. Taking the time to deal with areas prone to bridging is highly advisable since resin rich pockets increase the weight while scarcely, if at all, enhancing structural properties of the part.

Figure 5.22. Working reinforcement into mold cavity.

Figure 5.23. Vacuumed part – check for bridging.

5.4.3 Working the Vacuum Bag

The vacuum bag has to accommodate the curvature of the mold without ripping. To aid the elongation demand placed on the vacuum film, pleats or "rabbit ears" are built into the seal (Figures 5.12. & 5.13). The vacuum bag film is widthwise cut oversize. The extra material is folded and sealed with tacky tape along the border. The rabbit ear provides the extra vacuum bagging material necessary to drape the mold successfully. Pleats are strategically located to prevent bridging of the vacuum bag. Places where the bag does not conform to the cavity jeopardize the entire bagging process. The unsupported vacuum bag may stretch beyond its limits and burst during vacuuming.

5.4.4 Document Important Quantities

Enough resin has to be mixed to fill both the ½-inch inlet and ¼ inch spiral tubing, while wetting out the entire part. The depletion of the catalyzed resin reservoir while not achieving complete wet-out posed two problems: 1) more resin had to be mixed "on the fly" and 2) air was injected into the part; thus, introducing air bubbles or pockets in to the laminate. This mistake could compromise both quality and utility of the part.

It is better to have resin left over in the mixing bucket than to run out during infusion. The next time a part is infused, reconsider the resin batch amount based on how much was left over. To do this, simply weigh the hardened resin and subtract 80% of this weight from the weight of the original batch. The 20% margin is there for insurance so there is always some resin left over. It is impossible not to lose some resin, but possible to minimize the waste.

The trial runs, necessary to learn the locations of inlet and outlet ports, are ideal for figuring out important quantities. Such quantities are dimensions of reinforcement cloth, infusion medium, and vacuum bag, lengths of spiral tubing, and vacuum tubing, and, finally, resin amount for infusion.

5.4.5 Storage

Storage considerations for mold and parts follow the same guidelines as previously discussed in Chapter 3. However, the parts require particular attention for these are fairly subject to warping. Recently de-molded parts may be dry to the touch yet not fully cured. If left inadequately supported, the part may permanently warp or bend out of shape.

5.4.6 Summary – VARTM Pros & Cons

The pros and cons associated with VARTM are summarized in Table 5.5. This manufacturing method offers superior productivity and repeatability. However, the process is unforgiving to mistakes, often resulting in total loss. There is no size limit on the part being created. Thus, VARTM is a preferred method for large-scale parts and production.

The greatest advantage of VARTM is the unlimited setup time. Resin infusion only takes place after the dry reinforcement is successfully vacuumed and conformed into the mold. The resin intake is minimal (compared to manual wet lay-up) since the mold is sealed and already at vacuumed conditions when infusion begins. This reduces weight while maximizing structural properties of the composite.

PROS	Good Fiber to Resin Ratio
	Less Resin Waste than Other Methods
	Consistent Resin Usage
	Unlimited (Dry) Setup Time
	Minimal Human Exposure to Resin and Vapors
	Good Parts Reproducibility
	Special Reinforcement Easily Added During Lay-up
	Shorter Production Time than Wet Lay-up
	Identical Parts Created Every Time
	Quick Turn Around
CONS	Mold Design is Critical - requires skill and experience
	Resin Bridging in Radii or Edges
	Reinforcement Movement During Vacuuming
	Potentially Complicated Setup
	Easy to Ruin Part
	Requires Perfect Vacuum Seal Every Time
	Trial and Error Process

Table 5.5. VARTM – Pros & Cons.

Chapter 6: Wing Making

6.1 Preparation

6.1.1 Materials and Tools

The materials, used for Foam Cutting and Wet Wrapping, are listed in Table 6.1.

Materials	Description
General Materials	Mixing cups, stir sticks, latex gloves, eye protection, masks, etc
Hot-Wire	Nickel-Chromium (Nichrome) Wire for Foam Cutter 24 WG
Foam	Low density foam, 8ft tall x 2ft wide x 4in thick
Tacky Tape	Vacuum tape used for sealing vacuum bag to mold
Vacuum Bag	Impermeable film cover used to seal mold during vacuum application
Breather/Bleeder	Cloth used in vacuum bagging that allows airflow
Release Film	High gloss non-perforated release film (not PVA)
Vacuum Port	Thru-bag vacuum connector
Hinge Materials	High quality hinges, balsa stock, servo control horn
Spar Tubing	Carbon-fiber composite spar tubing
Structural Inserts	Composite laminate insert – part of structure of wing
Carbon Cloth	3K 2x2 Twill 5.7oz/sq yard Carbon Reinforcement Cloth
Resin	Polyester resin used on carbon
MEKP Catalyst	Hardener used for polyester based primers, gel coats and resins
Spreader	Squeegees or “slicks” for spreading catalyzed resin during wet lay-up
Packing Tape	Tape used to secure release film
Sanding Paper	Sanding paper grits 220 to 400
MDF Board	Compressed wood-dust board
Wood Dowel	Non-tapered wood dowel
Solvent	Denatured Alcohol

Table 6.1. Wing Making (Wet Lay-Up) Materials.

Tools	Description
Cutting Instruments	Shears and/or sharp bladed tools (X-Acto Knives)
General Tools	Pliers, screw drives and Dremel
Measuring Equipment	Measuring tape, metal yardstick (or longer), T-square, digital scale
Sanding Blocks	Support for sanding paper
Cutting Aids	Steel straight edge and large cutting mat
Foam Cutter	CNC Foam Cutter with wing cutting software
Variac & Wiring	Hot wire power supply – provide current to hot wire
Lay-up Room	Well ventilated clean room that contains a wide cutting table
Vacuum Pump	Vacuum pump with adequate fittings, hose, etc
Power Sander	Woodshop power sander
Other Tools	Wood clamps/grips, misc. lead weights

Table 6.2. Foam Cutting and Wet Wrapping Tools.

The tools used for Foam Cutting and Wet Wrapping are listed in Table 6.2.

6.1.2 Labor and Task

The division of labor did not occur so much in phases; rather, the effort was divided into three main sections and one post-processing section: 1) CNC Wing Cutting, 2) structure integration, 3) wet lay-up and pre-assembly. It is just as possible to have one group perform all the work as having three distinct groups performing the piecewise tasks in sequence. The advantage to having multiple groups was that it allowed an assembly line type progression to occur. The wing cutters concentrated on making wing cores, while structure integration team outfitted the wing sections and, lastly, the wet lay-up crew applied the composite skin. The post-processing actions required just one person and mostly entailed trimming and hinge installation duties.

The labor and task descriptions are provided in Tables 6.3.

Labor	**Task Description**
Group 1 - Wing Cutters	CNC hot wire operators (2 to 3)
Group 2 - Structures	Install internal structure (2 to 3)
Group 3 - Wet Lay-up	Wet wrap and vacuum bagging (3 to 4)
Post Processing	Trimming and Hinging

Wing Making Groupings and Tasks.

The Advice Section of this Chapter contains further information on Labor and Task.

6.1.3 Introduction and Foam Blank Preparation

The construction methods developed in this Chapter involve CNC foam cutting, wet lay-up and vacuum bagging processes. The composite-skinned wings have a foam core with embedded carbon tubing for structural support and carry-thru. The foam sheets were cut to length according to the various parts (wings) being manufactured. To minimize waste, the cuts were arranged to maximize the number of blanks created per sheet. For example, from a given sheet, one outboard wing, two horizontal stabilizers and one wing center-section were generated.

The wing section cut from the foam blank was called the foam wing-core. The remaining foam was called the foam “beds”. The wing section, wether in bare foam or wrapped in composites, was stored inside the beds at all times. Prior to wet lay-up, the beds had a role just as important as the foam wing-core themselves (as explained later). It was important to oversize the blanks chord-wise. In another words, the span dimension of a blank matched the span of the wing-core while the chord of the blank was oversize by a few inches. The oversize in the chord dimension was necessary so the wing beds did not collapse (buckle) during vacuum bagging, thus, potentially crushing the wing and causing defects on its surface.

6.2 CNC Foam Cutter

6.2.1 Foam Cutter

The CNC foam cutter required some practice and considerable attention to operate successfully. As with any machining tool, undesirable events could occur at any time and needed to be stopped immediately. The risks, however, are far less than the ones involving milling, drilling or turning. As a cautionary measure, every attempt was made to remain clear of the hot wire during operation. The hot-wire, if set on high heat, can burn skin upon contact.

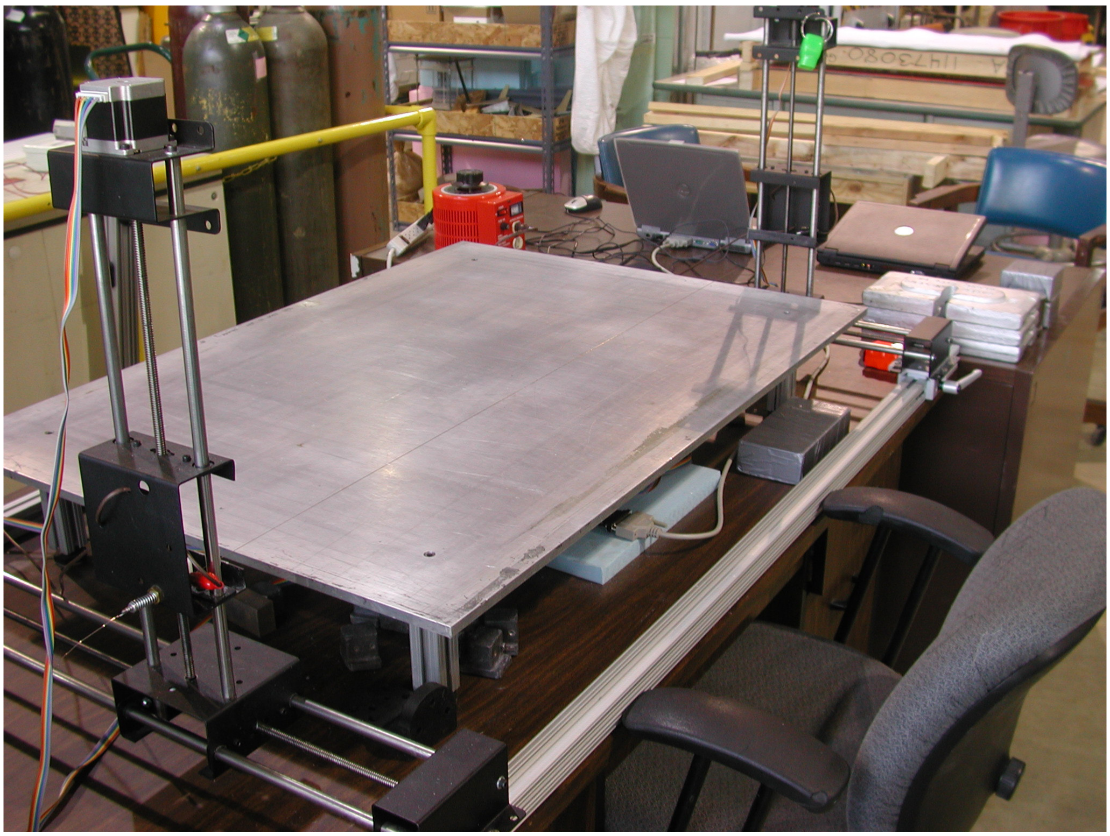


Figure 6.1. CNC Foam Cutter.

The machine consists of two towers with independent X and Y translation capability Figure (6.1). The towers are mounted on two rails, which allow the adjustment of separation between the towers. It is important to have the ability to move the towers closer to each other since a (needlessly) long hot wire will arch during cutting. In most cases, the distance between the towers was adjusted such that the foam blank barely fit between the moving carriages. The issues of wire arching/lagging are discussed further in the Advice Section of this Chapter.

The towers operate by means of a stepper motor installed in each rail. The corkscrew driven by the independent stepper motors translate the carriage either in the plane of the table or perpendicular to the table. The stepper motors are connected to a control box that is interfaced with a laptop. The CNC Foam Cutter operator uses software on the laptop to setup and execute the cut (Figure 6.2). The wing that was cut in Figure 6.2 was tapered in both leading and trailing edges, had spar hole cuts (main spar and rear alignment spar) and weight saving cuts both ahead and behind the spar.

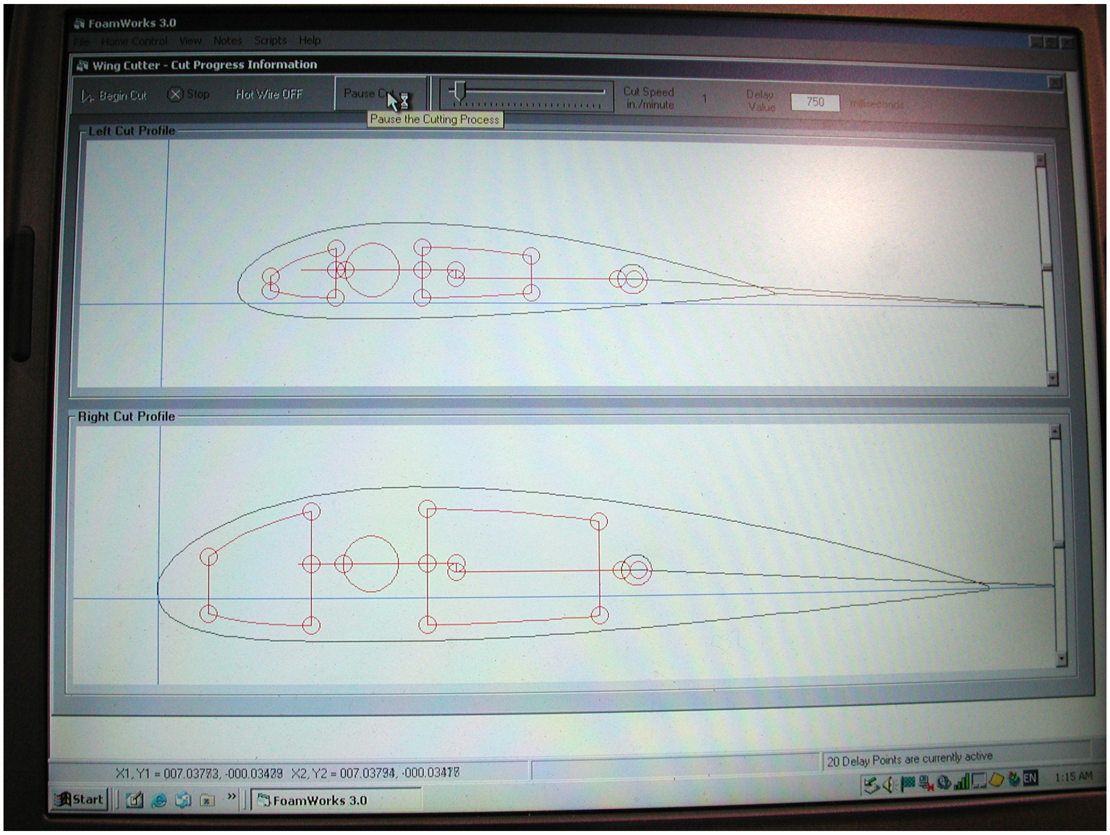


Figure 6.2. Laptop Screen – foam cutter software running.

Note: the example in Figure 6.2 is not a wing cut used in the project. The example in Figure 6.2 was chosen because it demonstrates the machine's ability to create wing taper and internal features.

6.2.2 Wing Cutting

The CNC cutter was programmed to cut the wings according to the sizing parameters listed in Table 2.1 and specified in Figure 2.1. The wing, in its entirety, consisted of the two (left and right) outboard sections and one center-section. Internal cuts were made in both outboard and center-sections as illustrated in Figures 2.3 and 2.4. The center-wing also featured cuts necessary to interface the center-wing/boom system to the fuselage. The horizontal stabilizer was a simple NACA0012 wing cut without any internal cuts.

Actual wing cutting required practice and attention. Although details about the operation of the CNC Foam Cutter are not explicitly developed, the preparation for the center wing-section is discussed below since it contained the most number of embedded structural and interfacing parts. The procedures described for the center wing section apply for both outboard wings and horizontal stabilizer.

The desired, final product bare foam, center wing-section is shown in Figure 6.3. (This is how it was done…)

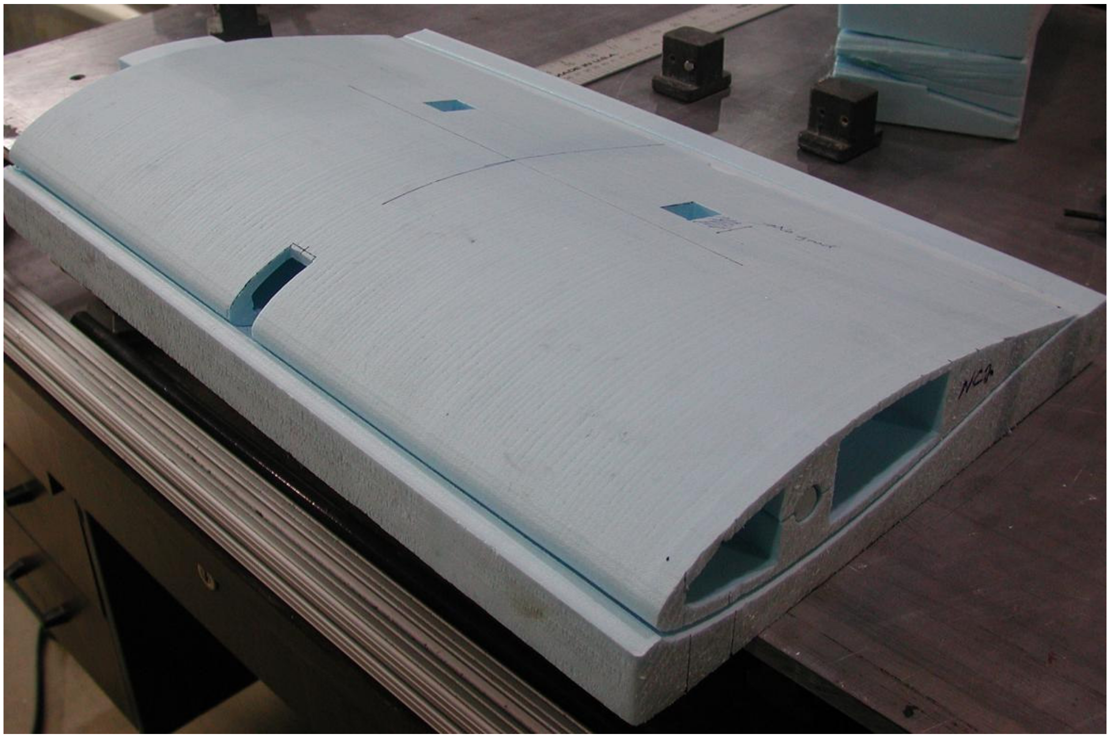


Figure 6.3. Bare Foam Wing Center Section – all cuts completed.

The foam blank was set on the cutting workspace and the wing center-section program was initialized. The internal cuts were made first, then the airfoil/wing cut and, finally, the structural/interfacing cuts.

The process began by making a (strategically located) ¼in. diameter hole in the foam blank. The wire was fed through this hole/tunnel and connected to either column. The wire was switched on and the cut was executed. At the end of the internal cut, the wire was snipped off in either end of the blank foam and the towers were moved to a clear location on the table.

A new wire was installed and the towers were moved to the designated airfoil cut start point. The wire was switched on and the outer wing cut was made. At this point, the foam blank is in three pieces: a wing core with internal cuts, an upper wing bed and a lower wing bed. Figure 6.3 shows the center section sitting in its lower bed. At this stage, the cuts that are yet to be made are the fuselage interface/mounting thru-holes and the spar end caps notch. The wing was carefully measured and marked with the locations of the cuts (Figure 6.4).

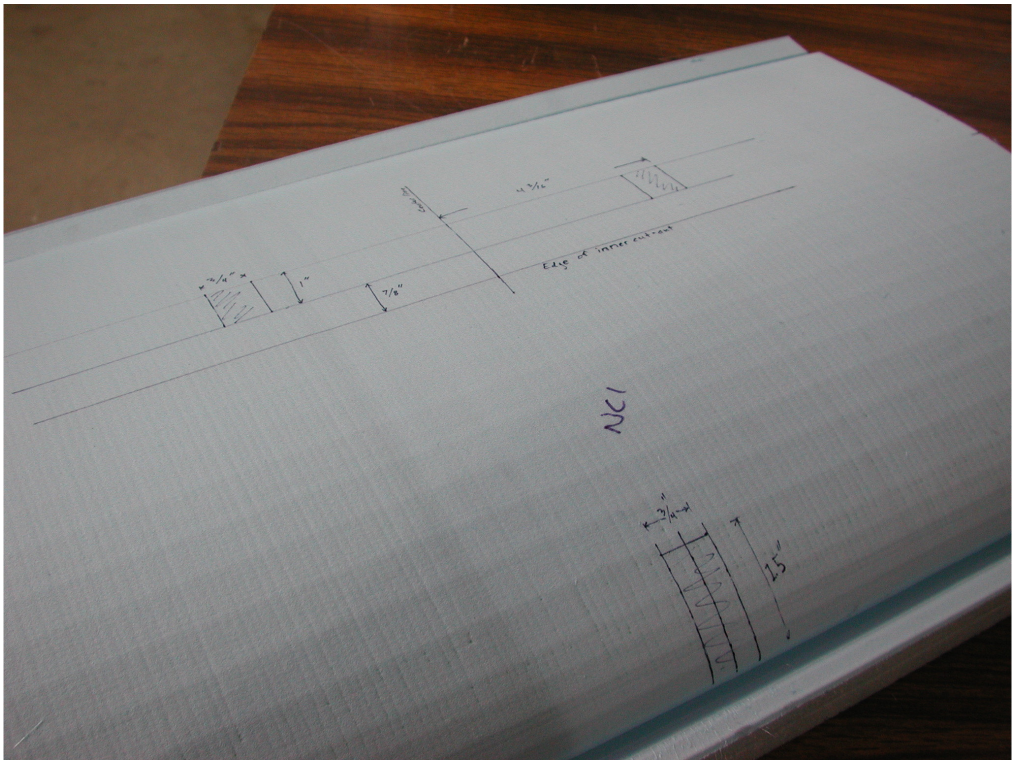


Figure 6.4. Wing Center-Section – interface mounting thru-holes marked.

It was important to measure and double measure before doing anything. In this example, a mistake was found. The left rear mounting thru-hole was misplaced. The error was corrected and new markings were made on the wing as noticed in Figures 6.5 & 6.6. The wrong marking was labeled "no good".

Design side note. The fuselage longitudinal axis ran parallel to the airfoil chord line. The designed angle of incidence was implemented during vehicle design and milling of the boom plugs. The airfoil-shaped slots in the booms were machined (milled) to the required angle of incidence. However, since this airfoil is highly cambered, it generates substantial lift even at zero angle of attack. Therefore, the angle of incidence required for level flight at cruise speed is very shallow. As a result, the wing is almost unnoticeably pitched up when the aircraft is viewed at a distance. The wing cutout in the bottom of the fuselage was made such that it naturally sat on the center section-wing with both fuselage longitudinal axis and chord line parallel. This facilitated the assembly of the fuselage and center wing-section mounting as explained in Chapter 7.

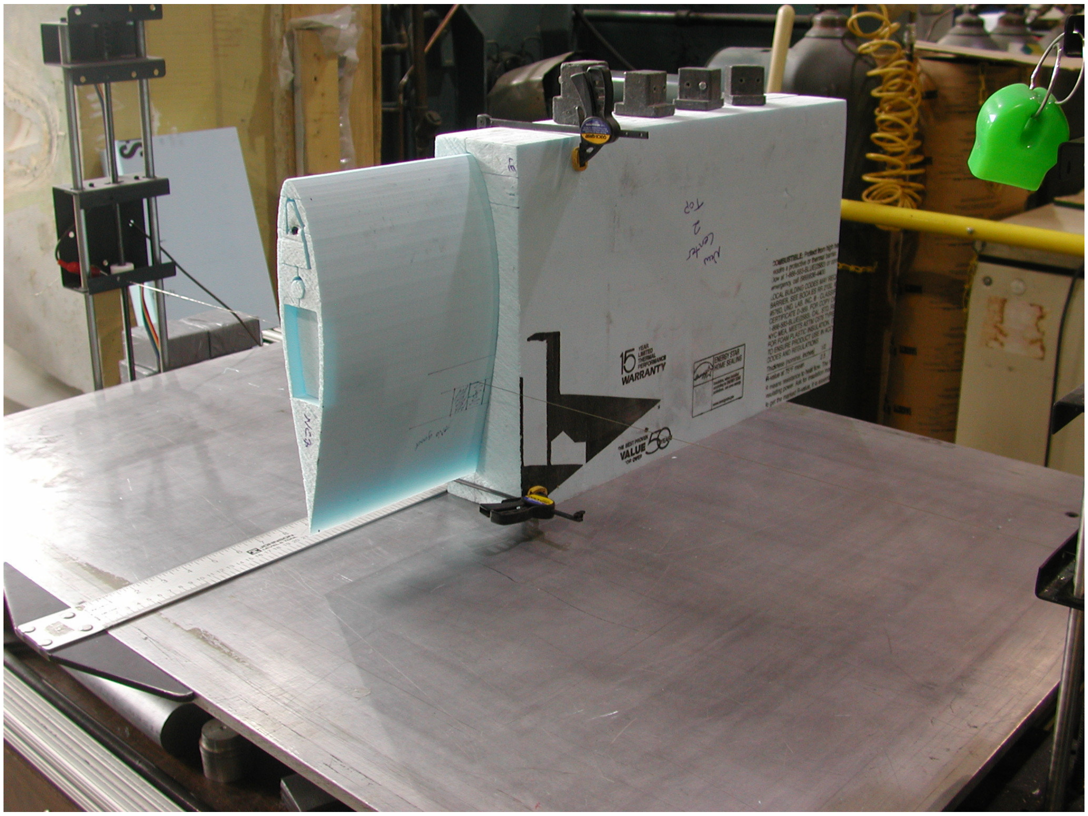


Figure 6.5. Center Wing-Section – mounting thru-hole being cut.

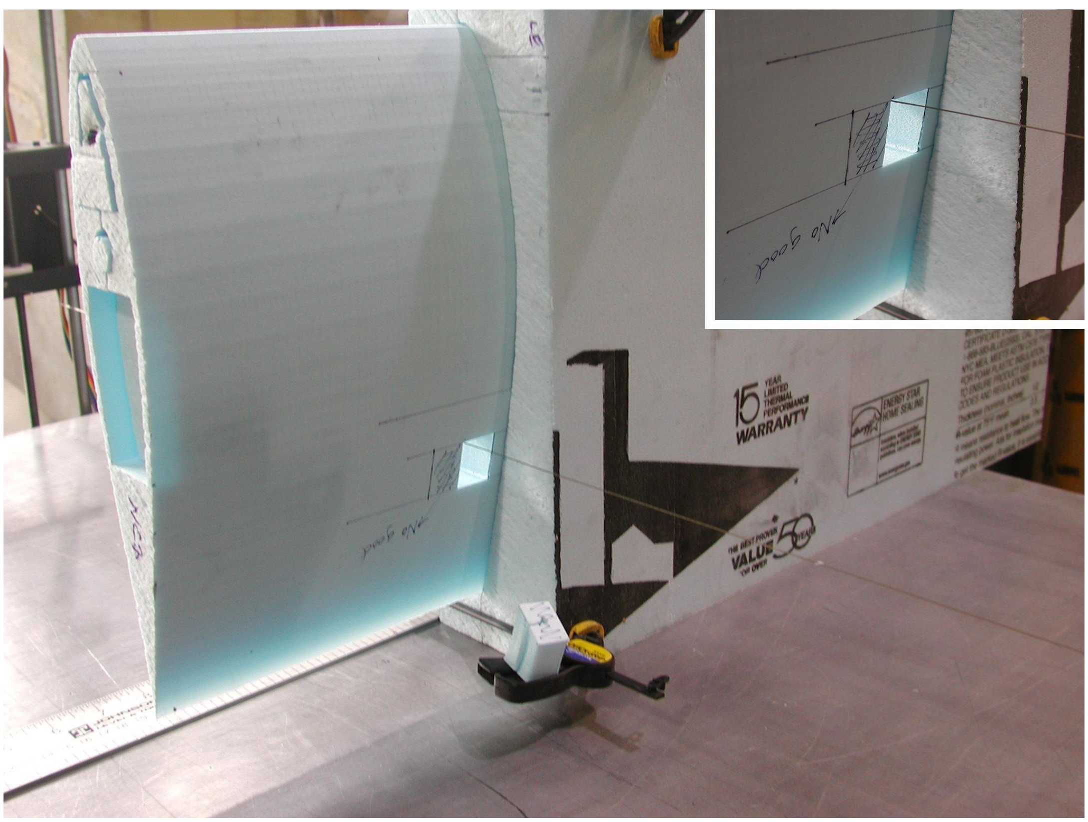


Figure 6.6. Center Wing-Section – mounting thru-hole done, detail view top right.

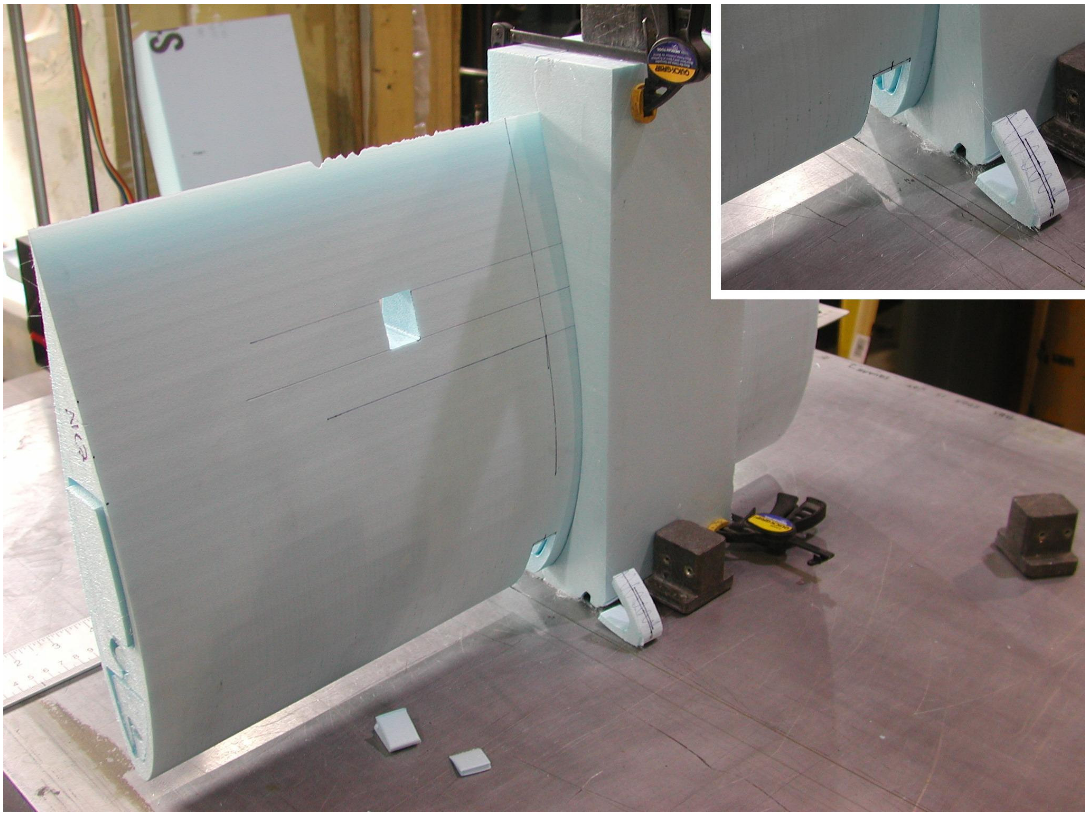


Figure 6.7. Center Wing-Section – front support-pin cutout, detail view top right.

To make the cuts, the center wing-section was oriented such that the hot wire ran perpendicular to the chord line of the airfoil (Figures 6.5-7). The wire was fed thru a hole made with a pin and the cut was executed (Figure 6.6). The front alignment pin for the center wing-section was cut next (Figure 6.7). At this point, the preparation of the bare foam center section was almost complete. The wing was re-oriented so the notches for the spar end caps could be made (Figure 6.8).

> *Caution.* Notice in Figure 6.8 the jagged trailing edge. A good wing will have a perfect trailing edge (TE) fresh from the CNC machine. The defects found in the trailing edge were caused due to careless handling of the foam wing. The trailing edge is especially fragile since it is so thin at the TE and prone to tearing. Typically, this damage is not a problem since the composite cloth will cover the imperfections. Furthermore, resin will fill the spots where the foam is missing. However, if a missing piece of the trailing edge is large enough, the reinforcement cloth will not hide the blemish and, probably, will be weak at that location. Damage on the leading edge (LE) tends to be more serious. The reinforcement cloth will form to the contour of the wing and will not hide foam core defects. The leading edge may also be weakened because the reinforcement cloth may be prone to buckling in the locations where the foam core is already indented. The bottom line is, do not damage the foam core.

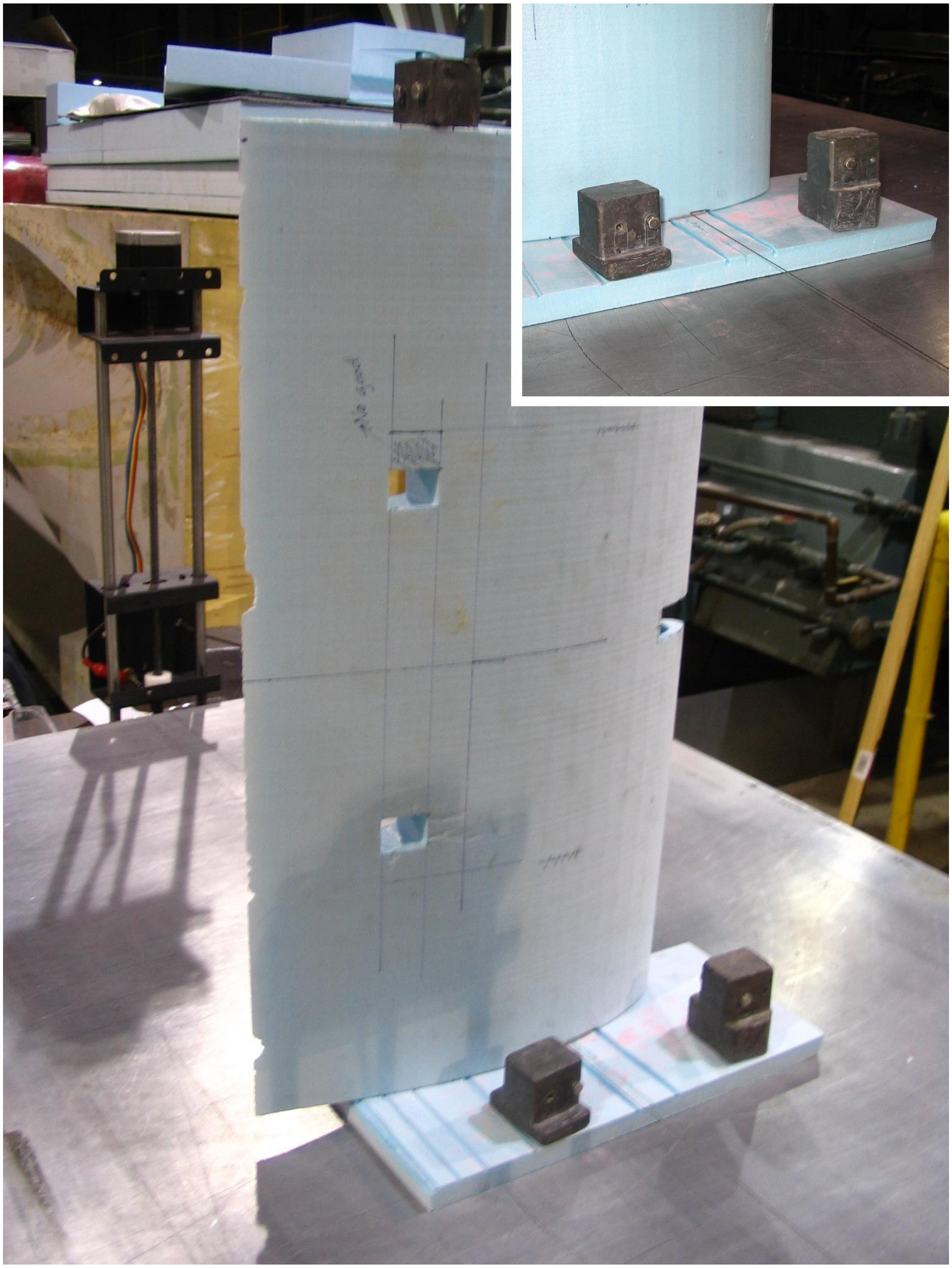


Figure 6.8. Center Wing-Section – notch being cut for spar end caps, detail view top right.

Once the wing had all the necessary cuts (Figure 6.3), it was ready for the integration of internal structure.

6.3 Foam Wing Preparation – Structure Integration

6.3.1 Internal Structure

The parts used for the structure of either outboard or center sections were sized and cut separately. Both outboard and center sections had a fixed spar sleeve with end caps. The carbon tubing, used for the spar sleeves, was cut to size and lightly sanded at the ends. The reason for sanding the ends of the spar tube is that resin adheres better to the roughened surface. The end caps were custom cut with a thru-hole for the fixed carbon sleeve. After, the spar sleeve was slid in place, the tips of the sleeve (on the outside) were wetted with catalyzed resin and the end caps were placed.

> *Caution.* When gluing the spar sleeve and end caps it is extremely important to prevent excess resin from dribbling into the spar. Resin-drops in the sleeve will prevent the (long) carry-thru internal spar from sliding through. To help prevent resin contamination inside of the sleeve, a couple of sheets of paper towels were rolled into a plug and jammed in each tip. Once the sleeves and end caps were placed and glued, the paper towel plugs were removed and a flashlight was used to inspect the inside of the spar sleeve. If any resin seeped into the spar sleeve, it was cleared away with either Denatured Alcohol or Acetone by squirting it into the tube. Acetone rinses away resin very effectively, but it also damages the foam; therefore, denatured alcohol was the preferred choice.

The rear support inserts in the foam wing-core were custom cut and fitted. The holes for the fuselage mounting bolts were centered on the block, which was already cut and test fitted in the foam wing-core. If the block fitted snuggly and the bolthole was correctly made, the blocks were sanded to match the curvature of the airfoil/wing. Likewise, the front pin support was also sized, cut, drilled and shaped to match the curvature of the wing, in this case the leading edge. The drill hole made in the front support block was intended for the alignment pin/dowel. These “blocks” were cut from a medium density fiber (MDF) board. The MDF was used because it sanded easily with a power sander. (Before reading further, refer back to Figures 2.3. and 2.4 and take note of what has been accomplished so far.)

6.3.2 Foam Joining

The center wing-section did not require foam-to-foam joining because it was designed as one piece. However, the outboard wing was cut in parts; therefore, needed gluing/joining together. In addition, the foam beds of the outboard wings were also glued to form one continuous upper and lower bed. To attach the pieces together, acetone-free contact glue was sprayed to the ends of the wing pieces then mated together. The result was a continuous outboard foam wing-core with matching upper and lower beds (Figure 6.10 – note the wing beds on the table in the back).

6.4 Wet Lay-up

6.4.1 Process Description and Introduction

The wet lay-up (hand lay-up) process involved the manual distribution of catalyzed resin onto a cloth. Typically, in molding processes using wet lay-up, the catalyzed resin is poured into the mold then the reinforcement cloth is introduced to the wet surface. A roller is used to aid in the spreading and impregnation of the resin onto the reinforcement. Once the user has laid and rolled all of the reinforcement as desired, the part is allowed to cure.

The curing process can be open-molded or vacuum-sealed with bagging material or other kinds of semi-rigid to rigid coverings. The application of the vacuum bag promotes good consolidation between layers and aids in the removal of trapped air. The mold making technique described in Chapter 4 is in a sense a modified hand lay-up process. The random directional matting (used in Chapter 4) was both manually placed and rolled; however, the catalyzed resin was applied via spray gun and allowed an open cure.

For wing making, the wet lay-up process is again modified to fit the application. The catalyzed resin was introduced to the reinforcement and evenly dispersed. The wetted cloth was then wrapped around the wing and placed inside the foam beds. The wrapped wing while packaged inside its beds was subjected to pressure in one of two ways: 1) 20lbs weights were stacked on top of the upper bed or the entire bed and wrapped wing assembly was placed inside a vacuum bag.

6.4.2 Wrapping the Wing

The wing center-section and the horizontal stabilizer were wrapped in a single ply of carbon cloth. The wet lay-up process for these two sections was relatively easy to perform since these had constant chord (non-tapered). For the most part, symmetric three-dimensional shapes with constant dimensions are easier to wrap because these shapes can be flat-wrapped. However, since the outboard wing had a trailing edge taper, it was more complex to wrap-up. The taper (span-wise change in chord) caused the wing to change dimension not only in the chord length, but also in airfoil thickness.

The CNC wing cutting procedures discussed in Section 6.2 focused on the central wing section since it contained the most number of features. For this section, the outboard wing-section is the subject of interest since it required the most attention. The internal constructs and external application of the reinforcement is illustrated in Figure 6.9. The outboard wing-section had reinforcement “cuffs” in three locations: the wingtip, the wing root and the foam joint where the spar sleeve ended (Figure 6.9).

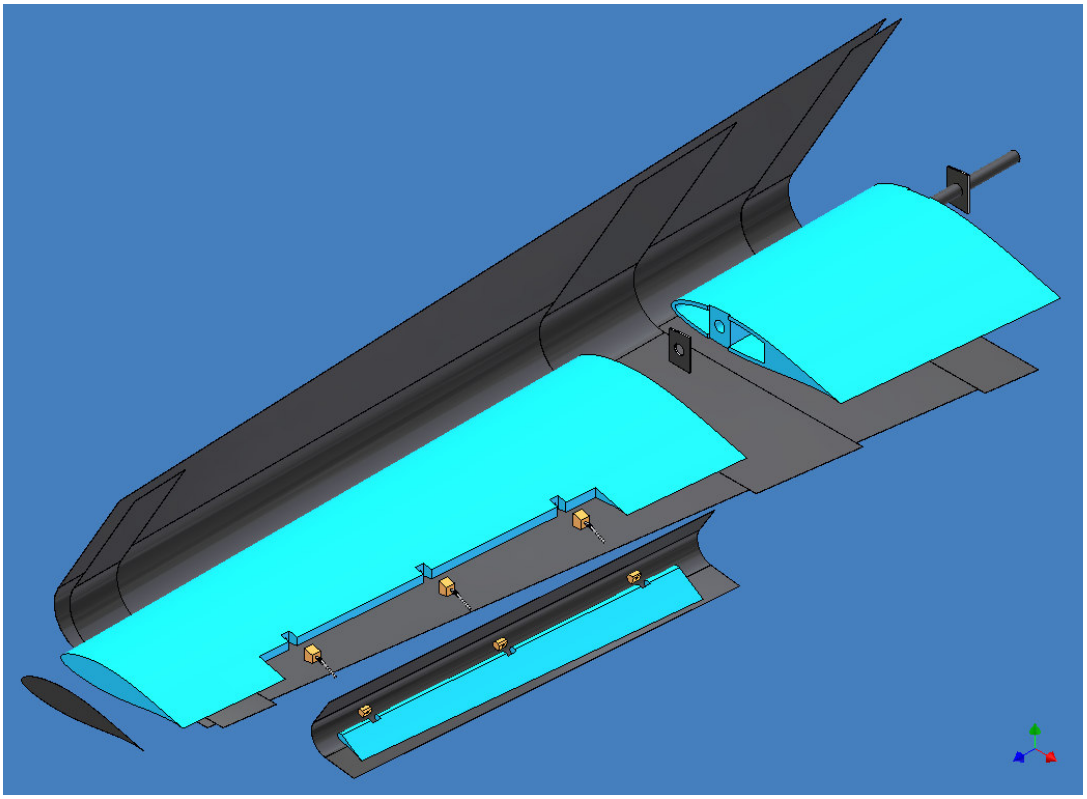


Figure 6.9. Outboard Wing Construction – explode view (see Figure 2.5).

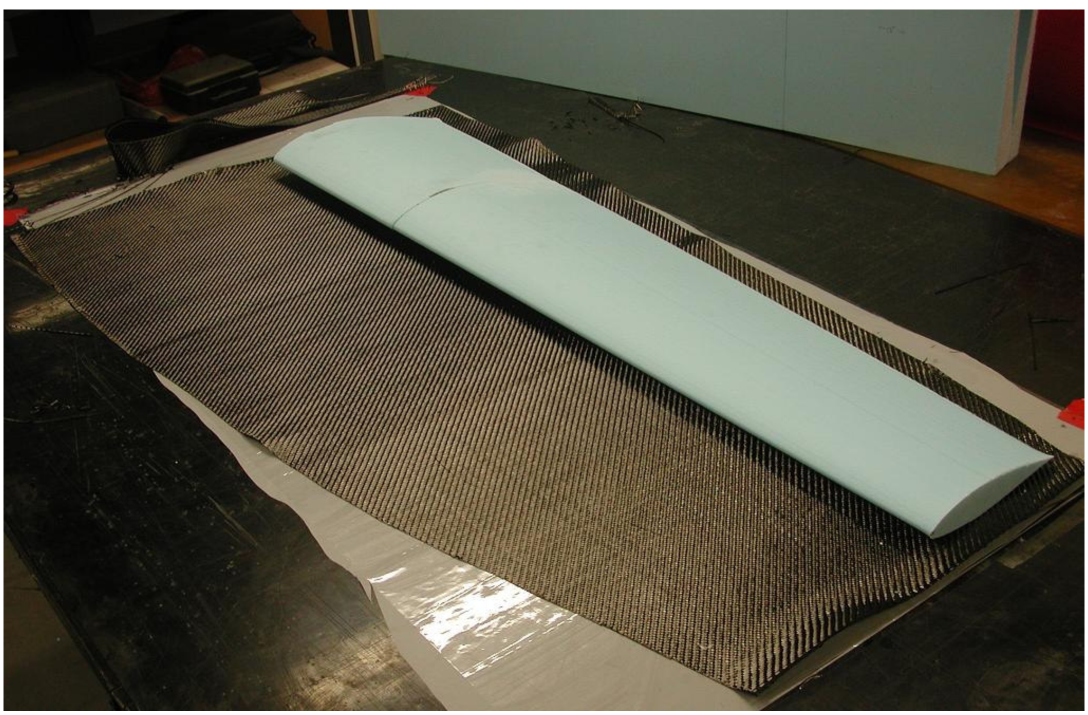


Figure 6.10. Outboard Wing-Section – wet lay-up preparation.

The outboard wing-section was cut, assembled and ready to receive the reinforcement skin. Once the carbon cloth was sized and cut, the work area was prepped for the wet lay-up process. An oversized sheet of release film, taped by the corners, was placed on the cutting table. The dry carbon reinforcement was carefully laid on of the release film. A silver marker was used to mark important locations on the cloth, like the location of the foam core wing and locations of the carbon strips (cuffs). The additional carbon reinforcement strips were placed on top of the "big" carbon sheet after it was impregnated with catalyzed resin.

The actual wings and surfaces of the aircraft used carbon cloth; however, the wet lay-up example shown below uses E-Glass with a resin dyed red. The author has purposely done this to facilitate the reader's ability to see the resin since the contrast is red on white. The release film used is green and is contrasted by the black cutting mat.

The dyed catalyzed resin was first poured on the reinforcement cloth then distributed with a spreader (Figures 6.11). The target fiber volume fraction was about 35%. In another words, the overall composite skin, when cured, had a weight distribution of 35% cloth to 65% resin. Next, the reinforcement strip was placed then wetted out (Figure 6.12).

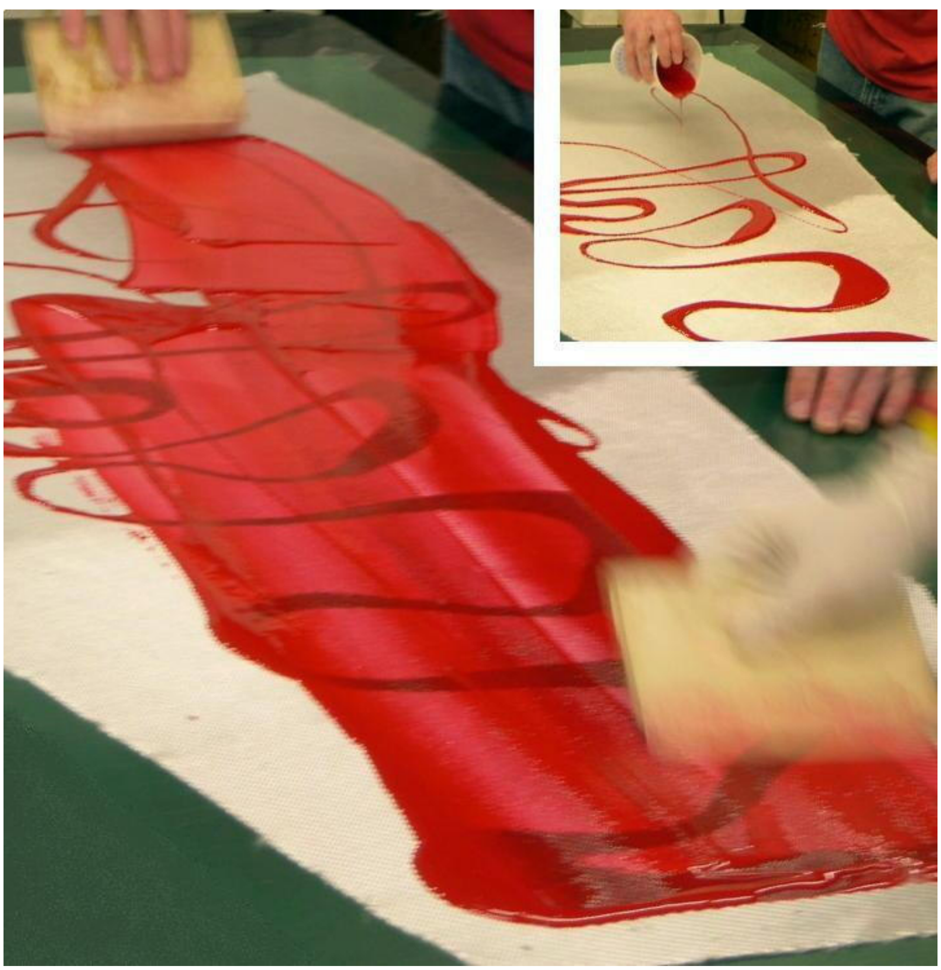


Figure 6.11. Outboard Wing-Section – wet lay-up, detail view top right.

Figure 6.12. Outboard Wing-Section – reinforcement strip wet lay-up.

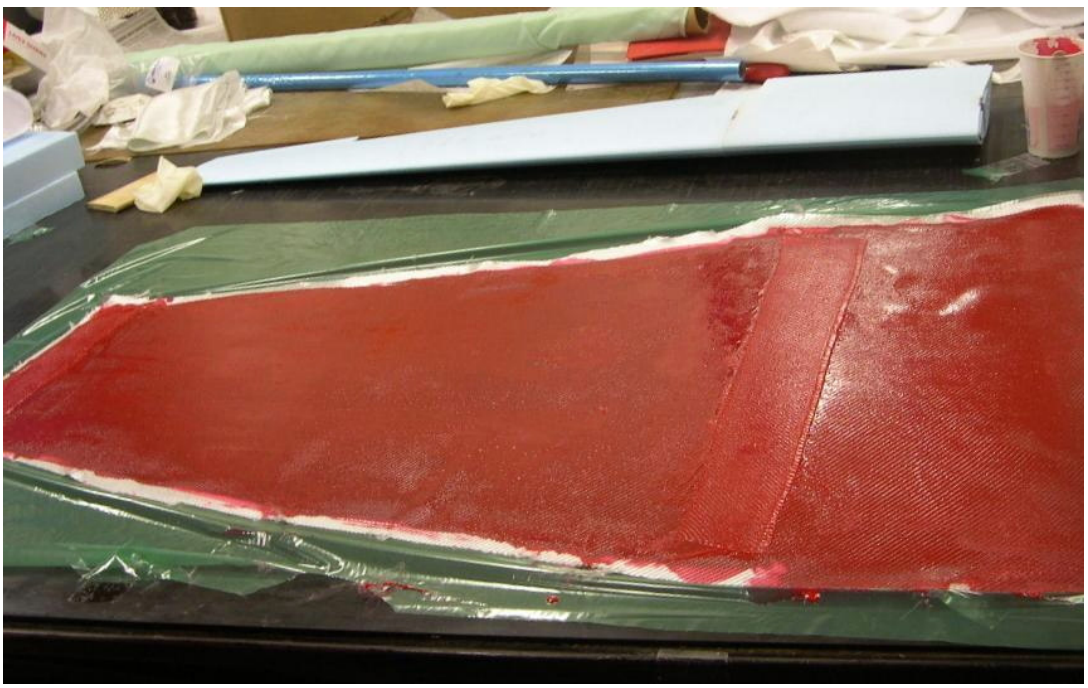


Figure 6.13. Outboard Wing-Section – wet out complete, foam core ready to wrap.

Once the hand lay-up was complete, the wing foam-core was ready to be wrapped. The leading edge of the wing was placed on the center of the impregnated reinforcement cloth. To facilitate the wrapping process, the bottom bed was placed under the wing (under the release film). The cloth was worked around the leading edge and wrapped over the top surface of the wing towards the trailing edge. Wrinkles created by the manipulation of the cloth during wrapping were smoothed out by hand with a soft cloth.

To apply pressure, the packaged wing was either placed in a vacuum bag or pressed down with ten 25lbs weights. When using weights, a scrap Plexiglas sheet was placed on top of the encased wing (Figure 6.14). The purpose of the Plexiglas sheet was to prevent the weights from crushing the foam bed, thus, applying uneven pressure. The 25lbs weights proved to produce parts of equal quality as those cured with vacuum bagging. The process was made simple and cheaper by using the stackable weights.

Figure 6.14. Outboard Wing-Section – wrapped and ready to receive weights.

6.4.3 Cure and Clean-Up

All aircraft parts manufactured with wet lay-up were allowed to cure overnight or for at least 8 hours. No special clean up was required for this process; dry materials (vacuum bagging materials, release film, etc) were discarded after use along with used gloves, stir sticks, mixing cups, etc.

6.5 Moving Surfaces and Horizontal Stabilizer

6.5.1 Ailerons and Elevator

The CNC foam cutting and wet lay-up methods used for the moving surfaces (ailerons and elevator) and horizontal stabilizer are similar to those used for the wings. The foam was CNC cut and wrapped with carbon reinforcement similarly to the wings; however, the preparation involved varied drastically.

The elevator was a non-tapered cut easily handled by the CNC cutter. The elevator was then repositioned so the balsa-block hinge support cutouts could be made. The balsa blocks were custom cut and sanded to the shape of the elevator (Figures 6.15 & 6.16).

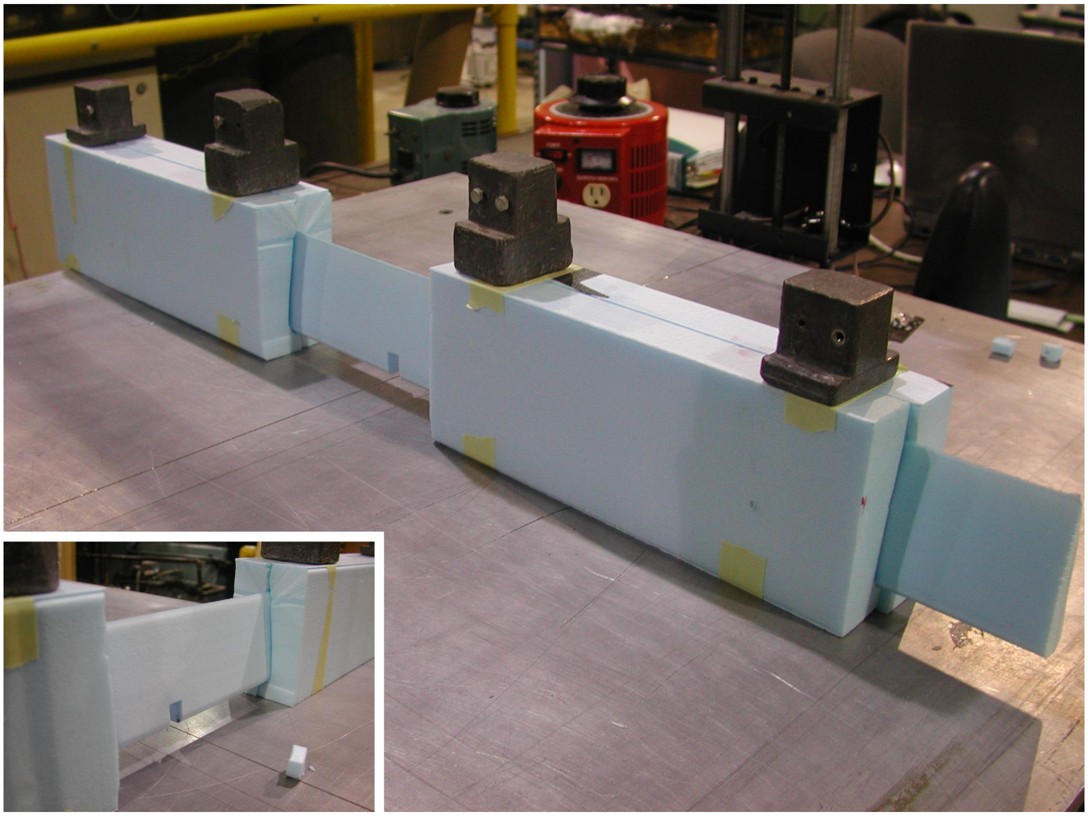


Figure 6.15. Elevator – hinge support cutout, detail view bottom left.

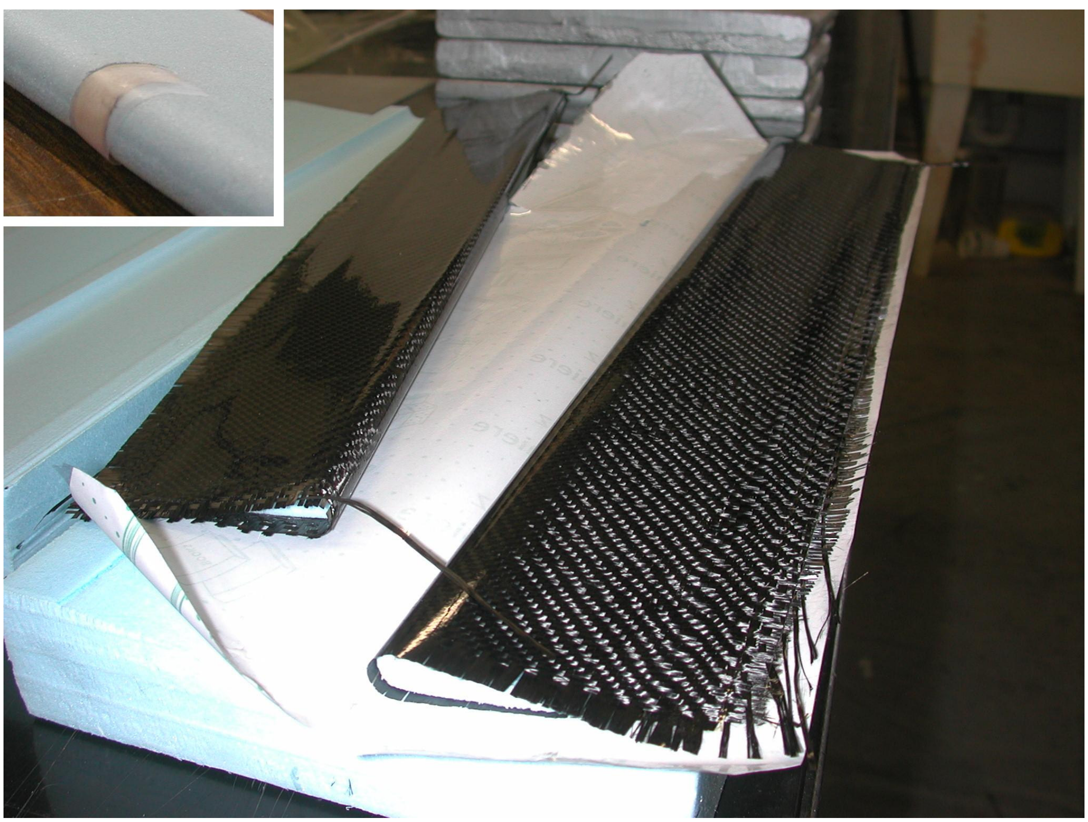


Figure 6.16. Untrimmed Elevator Wrapped in Carbon – detail view top left.

The location of the balsa blocks was recorded since, when wrapped in carbon, the blocks could not be seen. The ailerons were manufactured in similar fashion to the elevator. However, due to the taper of the wing, the aileron cut was more complicated and required much more attention than the elevator.

6.5.2 Horizontal Stabilizer

The horizontal stabilizer was a solid foam core wing wrapped in carbon reinforcement. The wet lay-up for this part was simple since the airfoil was both symmetric and non-tapered. The installation of the elevator to the horizontal stabilizer was the same as the installation of the ailerons to the outboard wing-sections. This process is discussed in the Section 6.6.2.

6.6 Pre-Assembly

6.6.1 Trim Wing to Size

The trimming process did not vary from part to part. All wings and moving surfaces were trimmed and sanded in similar fashion. The first step was to reduce the excess reinforcement at the tips of the wing. Most of the excess material at the tips was removed with the Dremel then hand-sanded the remaining materials with a straight block down to the foam core.

In some cases, depending on how much excess material was present, the operator elected to make two passes with the Dremel. In Figure 6.17, the operator was making the first pass; then, a second pass was made to trim the excess material closer to the foam. Once enough material was removed, the manual dry sanding started (Figure 6.18).

Figure 6.17. Outboard Wing-Section – trimming the ends.

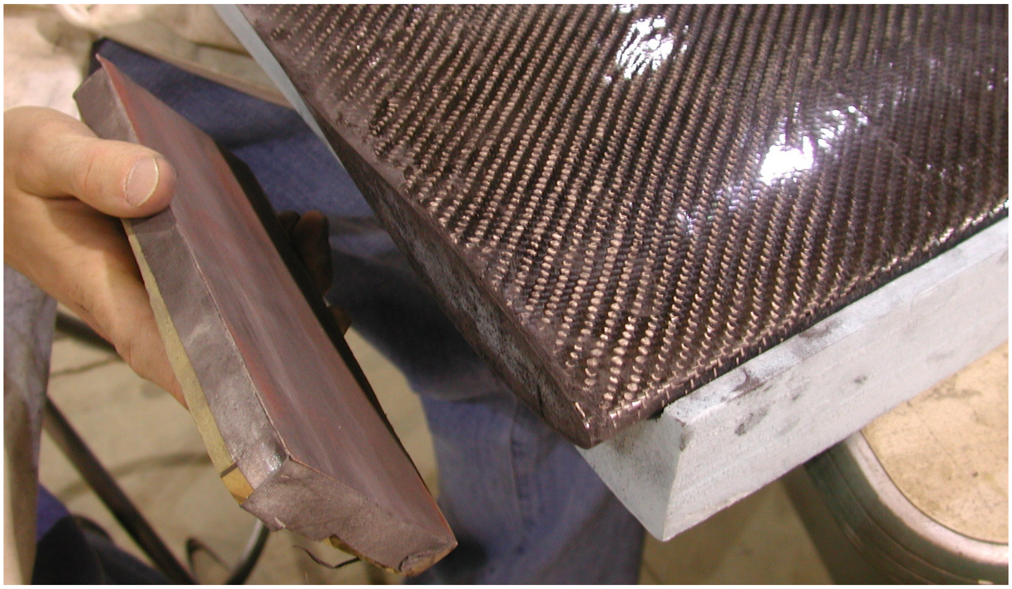


Figure 6.18. Outboard Wing-Section – sanding the ends.

The trailing edge was trimmed based on the desired tip and root chord lengths; it was hand cut with a sharp razor along a steel/aluminum straight edge. The straight edge was secured to the wing by means of 3 small double-sided tape strips.

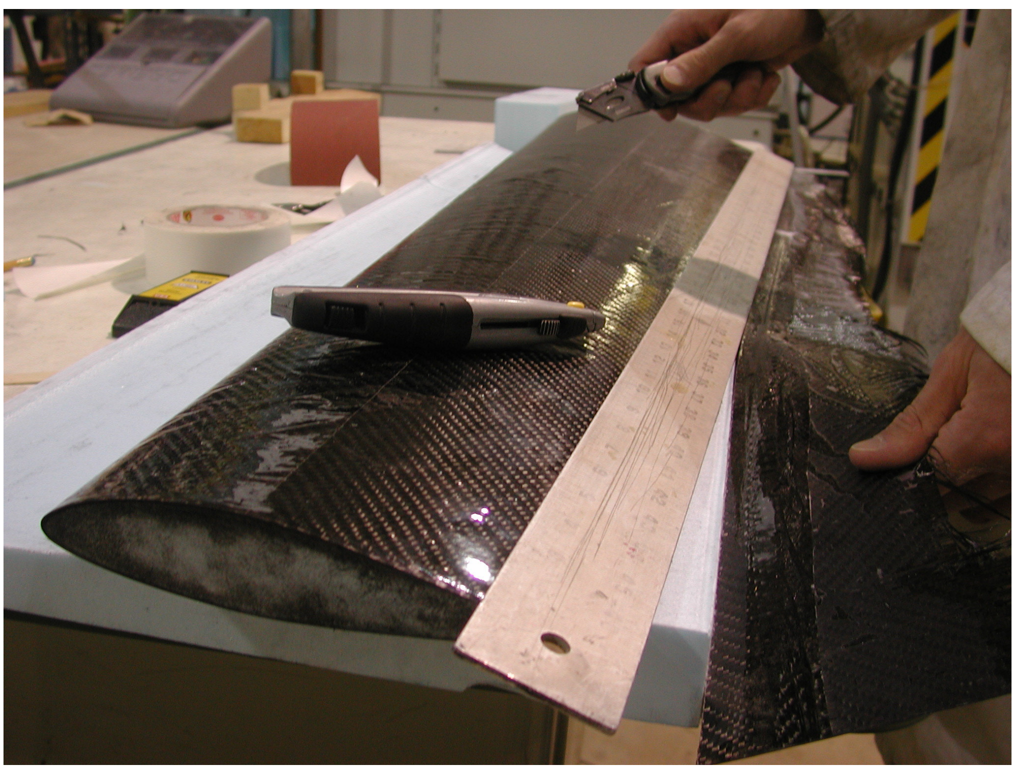


Figure 6.19. Outboard Wing-Section – trimming the trailing edge.

Hints: 1) Do not use too much double sided tape, it makes the removal of the straight edge difficult and can result in damage to the composite skin or cause de-lamination of the skin from the foam core.

2) Place the straight edge on the wing surface and not on the part being trimmed, this is important because if the razor slips, it scratches/cuts the piece being cut off.

Cutting the cloth by hand required several passes with the knife (Figure 6.19). Moreover, several replacement blades were used since the tip dulled quickly. The razor technique was preferred for cutting the trailing edge because it produced the sharpest TE quality possible; sharp enough to slice up unsuspecting fingers or hands (Figure 6.20).

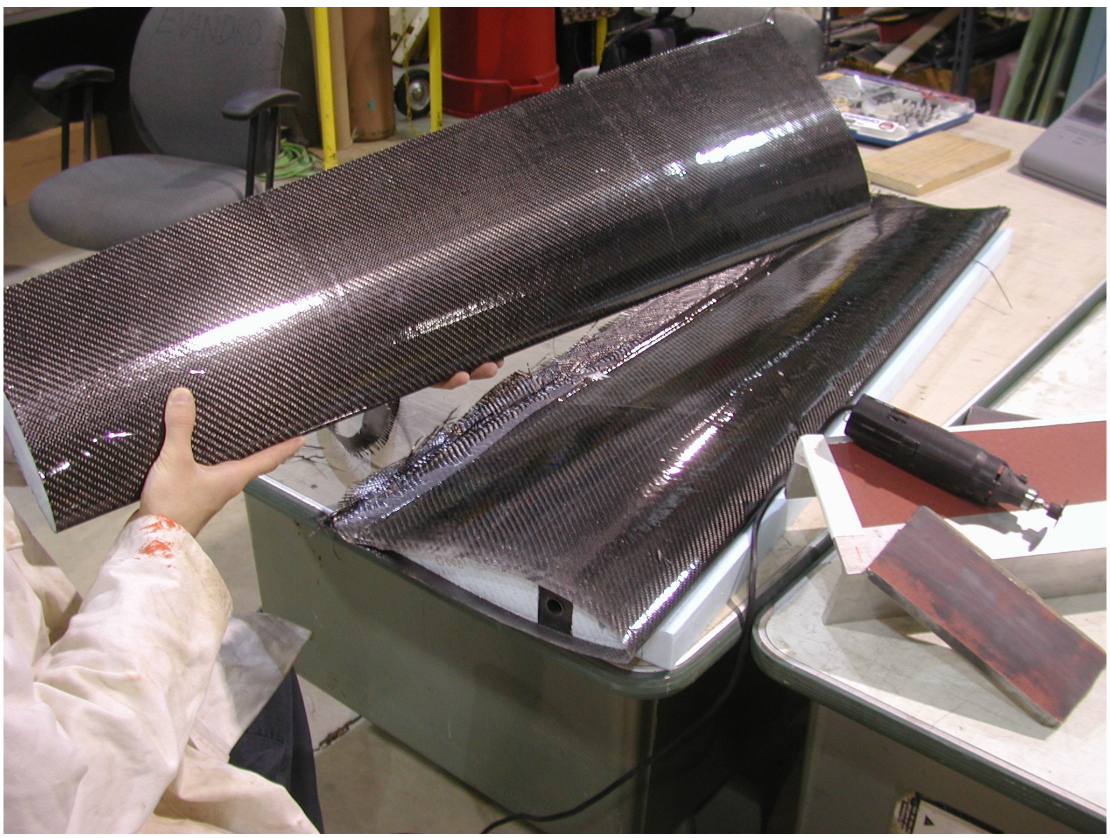


Figure 6.20. Outboard Wing-Section – trimming complete, next wing on queue.

Construction side note: The foam beds have been invaluable during the entire wing lay-up process. The surface quality of the foam beds, or lack thereof, is reproduced onto the wing surface during curing. Hence, the preservation of the foam beds is just as important as the preservation of the bare-foam wing-core themselves. However, once the foam core is wrapped and cured, the wing beds serve a different purpose. The beds do not have to remain unharmed. As seen in Figures 6.17 – 20, the foam bed is used as support for the wing. During the trimming of the trailing edge, the blade digs into the wing bed once it cuts through the composite laminate, thus, the wing beds will endure some damaged. From this point forward, the purpose of the beds is to provide a work support for the wings and to encase the wings when stored or transported.

6.6.2 Moving Surface Hinging and Cutout

The moving surfaces were first outfitted with the hinges. The hinges were installed in the center of the balsa inserts installed prior to the wet lay-up. The hinges were carefully installed so the travel of the hinge arms were oriented in the correct direction. Measurements were used during the installation of the hinges, but the best tool for the job was the "eyeball" (Figure 6.21). Once properly aligned, the hinges were glued in place.

Figure 6.21. Elevator Hinge Installation.

The wings and stabilizer were trimmed so the moving surfaces could be installed. Similarly to the trimming of the trailing edge, the moving surface cut-out was performed with a bladed instrument and straight edge. The exposed foam of the wing was sanded with a round block whose curvature matched the curvature of the moving surface (Figure 6.24). This allowed the round leading edge of the aileron/elevator to fit perfectly with the wing/stabilizer.

The balsa support blocks for the wings/stabilizer were sized, cut and installed to the exposed hinge arm. At this point, the blocks were not glued to the hinge arm (Figure 6.22). The wing/elevator was prepped to receive the balsa support blocks. Once the entire process was done and the blocks fit snuggly, the balsa hinge blocks were glued, in the proper orientation, to the exposed hinge arm (Figure 6.23).

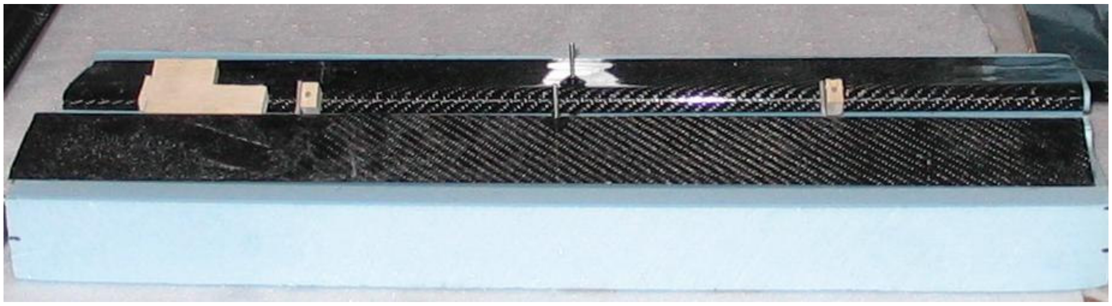


Figure 6.22. Elevator Hinged and Balsa Support Blocks Prepped.

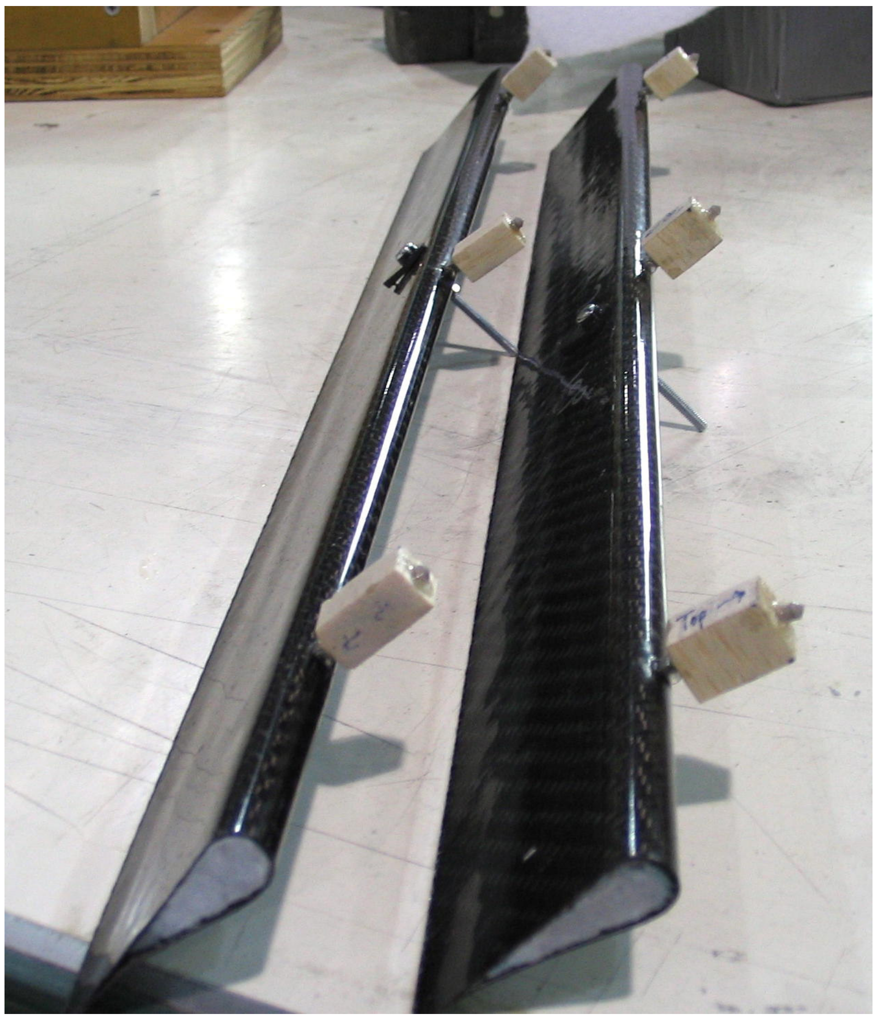


Figure 6.23. Ailerons Hinged with Balsa Blocks Glued.

The moving surfaces were also outfitted with the servo control horn. A horn was installed to each moving surface at its center (Figures 6.22 & 6.23). The servo control horn is attached to the servo push rod as explained in Chapter 7. Finally, the moving surface was test fitted to the wing/stabilizer (Figure 6.25).

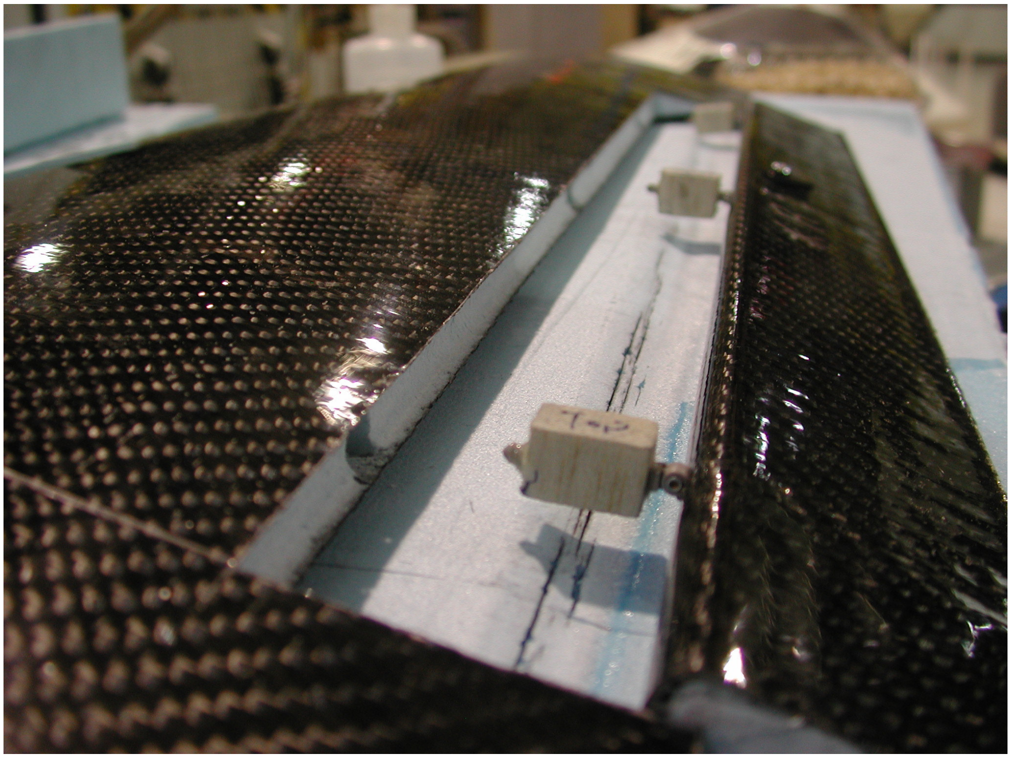


Figure 6.24. Aileron Hinge Detail.

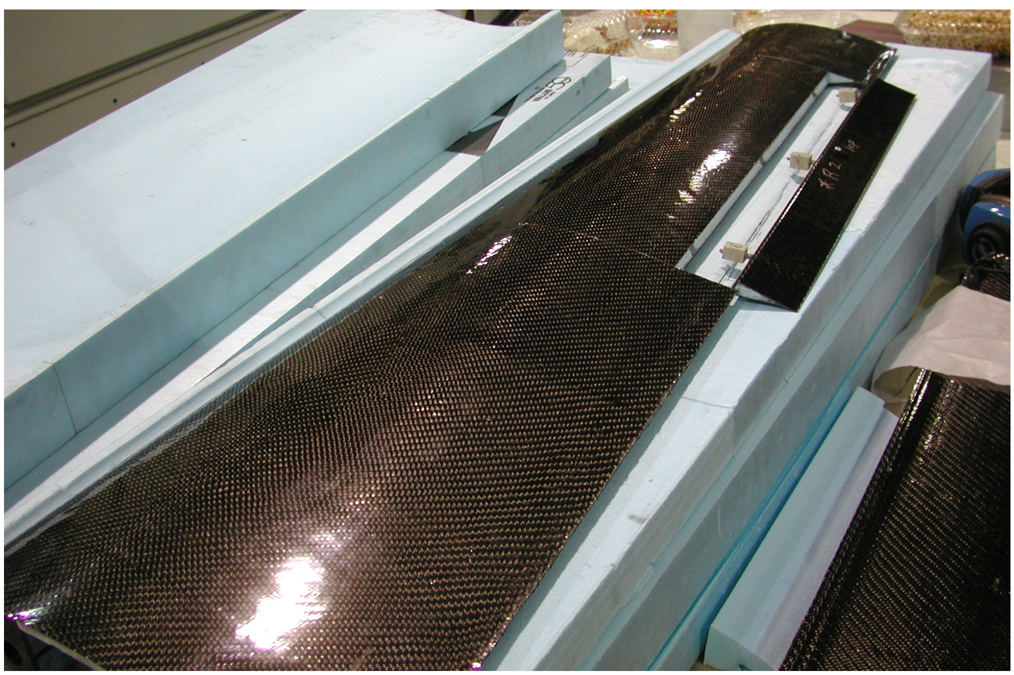


Figure 6.25. Aileron Hinging and Preparation Complete.

6.6.3 Final Product

The complete wing sections and horizontal stabilizer are shown in Figures 6.26 - 28 (with moving surfaces in place).

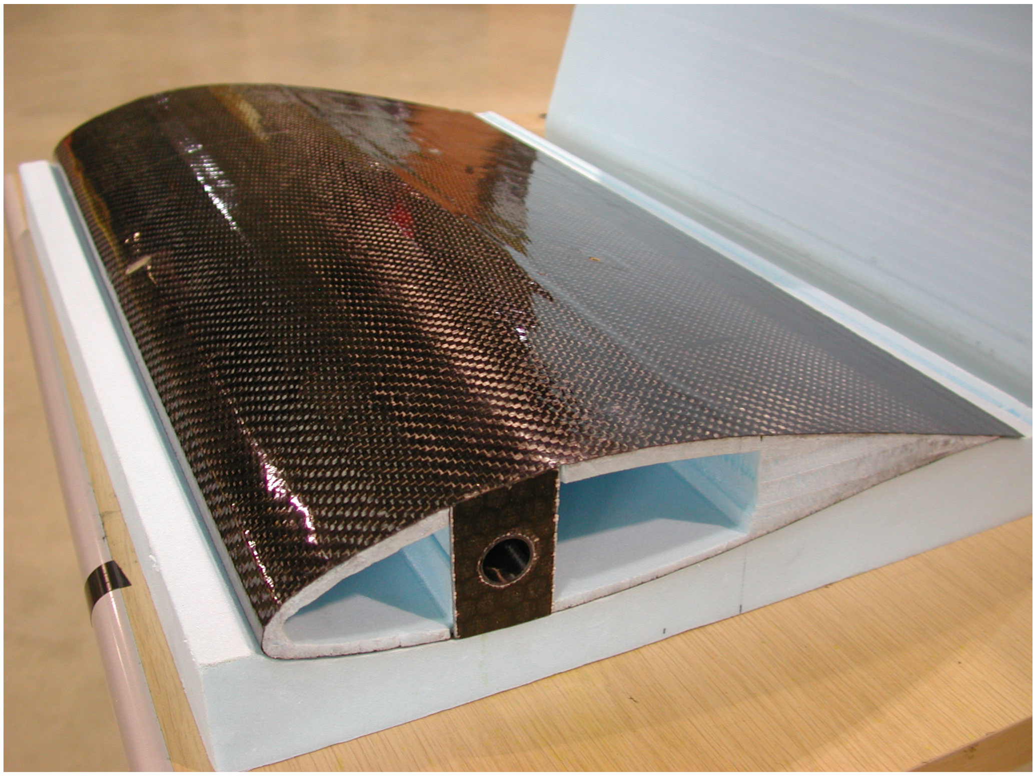


Figure 6.26. Center Wing-Section Complete.

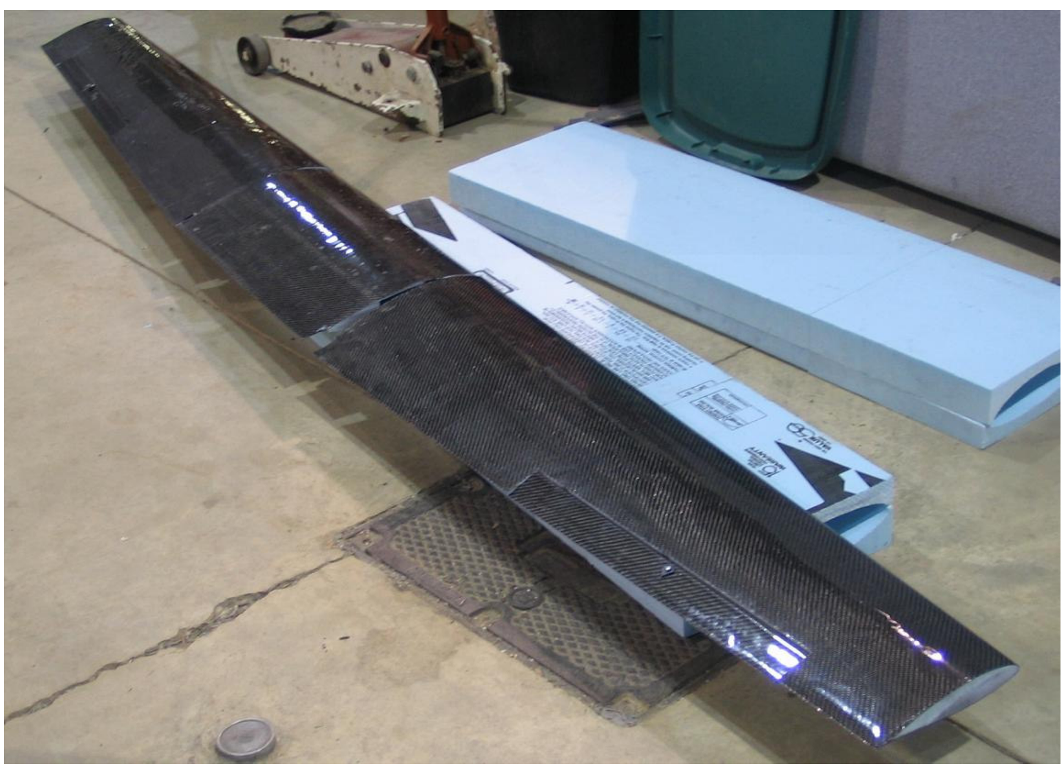


Figure 6.27. Entire Wing Complete – outboard and center sections.

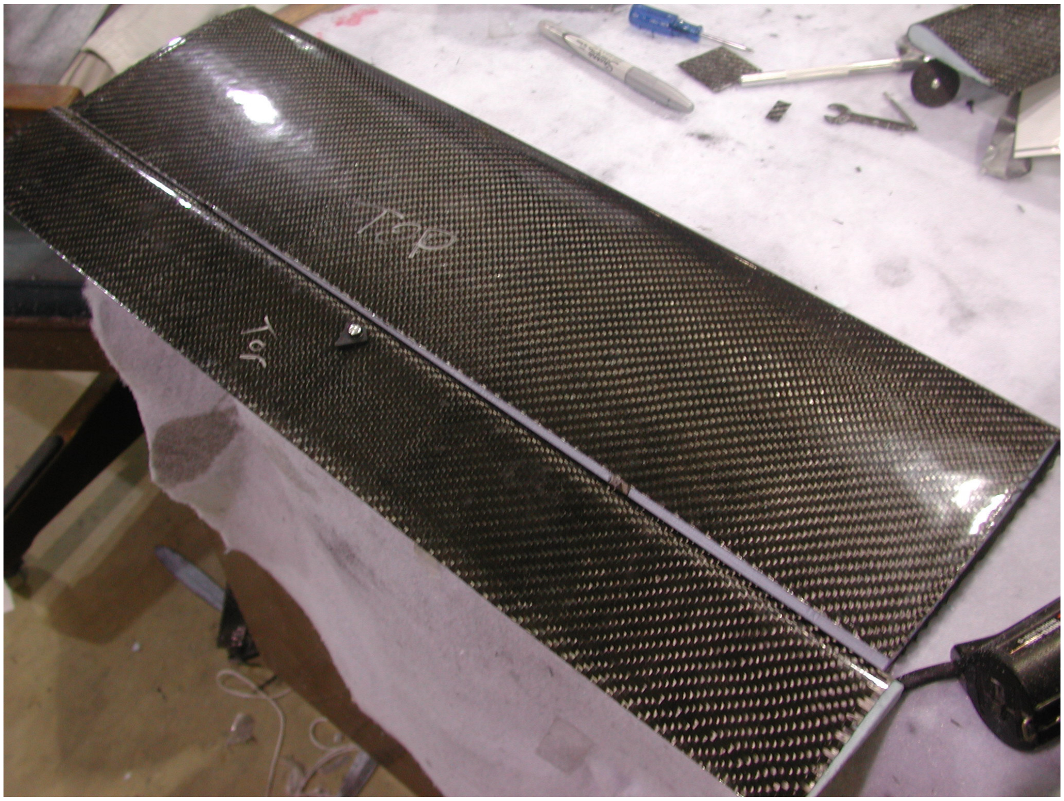


Figure 6.28. Horizontal Stabilizer and Elevator Complete.

Construction side notes:

1) The elevator in Figure 6.28 is longer than the horizontal stabilizer with good reason. For that matter, the horizontal stabilizer is also span-wise oversized. The reason for over sizing the stabilizer is because it will be inserted into the boom, as discussed in Chapter 7. Similarly, the elevator is oversized because the exact length to cut it depends on the rudders. The spacing between the booms provides the upper limit on the length of the elevator; however, the amount of rudder "throw" (i.e. rudder deflection) further restricts the length of the elevator because of the twin boom setup. The result is that both rudder and elevator must operate freely without any risk of binding with each other. For now, the elevator is left oversized.

2) The moving surfaces have the hinges glued in, but are not permanently installed. Although assembled, the moving surfaces are not glued into place. To eliminate any chances of damaging the moving surfaces and their hinges, the final gluing of the moving surfaces was done *after* the entire aircraft was wired, integrated and fully assembled. At this point, both ailerons and elevator are removable (Figures 6.27 & 6.28).

6.7 Advice

6.7.1 More on Labor and Tasks

The most important point about division of labor at this stage (Chapters 6 & 7) of the construction is to identify individual talents/skills. For example, group members with machining skills are encouraged to perform tasks that involve machining. From a teaching standpoint, it may appear attractive to divide the work evenly so everybody learns a bit about everything. However, in practice this is hardly the most optimized group setup. Individual talents can vary so much that it is often safest to restrict some specialized activities to individuals that are either comfortable with or have prior experience in performing the specific task.

In cases where members have minimal prior experience, the entire process has to be learned from scratch. For example, cutting foam wings with the CNC cutter is often a novelty. However, once a particular subset of individuals is expert at CNC cutting, these workers should be the only ones to perform this duty. If the need arises for a second group to cut wings, at least one member in the new group should be borrowed from the original group. This is important because it ensures repeatability in the process while minimizing common errors.

As the project nears the assembly phase, mistakes can cause substantial setbacks because parts of the airplane are near completion. For example, alignment problems or erroneous location of a spar hole can completely scrap an entire subsection of the aircraft. For this reason, the workforce, when subdivided, needs to stay consistent. Individuals who have specialized in a particular function must execute it from start to finish.

In summary, known individual strengths/skills must be exploited. It is too risky to allow inexperienced hands to perform critical tasks this late in the construction, especially when knowledgeable/experienced individuals are on hand. Once team members learn and become comfortable with a particular duty, these individuals or group focus on that portion of the build exclusively.

6.7.2 CNC Foam Cutter – Hints for Successful Cutting

The ideal conditions for cutting foam are under low heat and low speed. This guarantees good resolution during cutting, repeatability, and prevents the wire from lagging in the center. The wire, while lagging during cutting, will round sharp corners and cause chord variance along the span of the wing. Lag in the wire is not corrected by increasing the heat; rather, is corrected by decreasing the cut speed setting on the CNC machine. Just be patient.

6.7.3 The Hot Wire Bow

The 8'x 2'x 4" foam boards were marked and cut into foam blanks intended for wing cutting. This procedure was primarily performed with the Hot Wire Bow Cutter (Figure 6.29). Making these simple gravity cuts with the bow was advantageous since it alleviated the work queue for the CNC Foam Cutter.

Figure 6.29. Wing Blank Being Cut with the Hot Wire Bow.

6.7.4 How to Ruin Your Work in Seconds

There is no other chemical more harmful to foam than Acetone. It is extremely important to keep any Acetone or Acetone-Based fluids away from the foam blanks, foam beds, foam wing-cores, etc. The Acetone will dissolve the foam in seconds. If there is any doubt about chemical compatibility with the foam, just read the label. However, the best test is to try some of it on a scrap foam piece. If the chemical reacts, lock it up, warn everyone about it, and keep it away!

6.7.5 Summary – Wet Lay-up Pros & Cons

In a general sense, wet lay-up processes have similar advantages and disadvantages no matter the variation. The pros and cons associated with the customized wet lay-up (hand lay-up) process for wing making are summarized in Table 6.4.

This process, when used in wing making, can be very effective. The quality of the part can vary from technician to technician; nevertheless, the method can generate high quality high output when performed carefully and methodically. As suggested before, individuals (team members) that demonstrate proficiency in particular areas are encouraged to work on those same tasks during the build. By having the same group constructing the wings from start to finish, from a quality control aspect, the process repeatability and consistency in overall finish of the wings/surfaces are achieved.

PROS	Low Capital Investment (compared to other methods)
	Simple and Straightforward Method
	Good Turn Around with Experienced Technicians
	Negligible Molding Costs since Foam Beds are Used
	Foam Beds Perfectly Match the Wings
	Easy to Setup
CONS	Labor Intensive (wrapping can be tricky)
	Human Exposure/Contact to Resin
	Quality Consistency Requires Experienced Technician
	Reproducibility Requires Experienced Technicians
	Easy to Ruin Part

Table 6.4. Wet Lay-up – Pros & Cons.

6.7.6 Storage and Inventory

The completed wing and horizontal stabilizer sections were always stored inside the foam beds. In turn, these were organized in a shelving system where the work-in-progress and the finalized work were kept separate (Figure 6.30).

Figure 6.30. Organized Foam Cores and Finished Wings.

Chapter 7: Assembly

7.1 Preparation

7.1.1 Tools and Materials

The materials, used for vehicle assembly, are listed in Table 7.1.

Materials	Description
General Materials	Mixing cups, stir sticks, latex gloves, eye protection, masks, etc
Resin	Polyester resin used on carbon
MEKP Catalyst	Hardener used for polyester based primers, gel coats and resins
Packing Tape	Tape used to secure release film
Sanding Paper	Sanding paper sheets grits 220 to 400, sand paper roll 8in. wide
Syringe	Syringe used to inject resin
Solvent	Denatured Alcohol

Table 7.1. Assembly Materials.

Tools	Description
Cutting Instruments	Shears and/or sharp bladed tools (X-Acto Knives)
General Tools	Pliers, screw drives, drill bit set, etc
Measuring Equipment	Measuring tape, metal yardstick (or longer), T-square, digital scale
Sanding Blocks	Support for sanding paper
Height Gage	Precision table height gage with inscriber tip
Wood & Metal Shop	Shop drill press, band saw and power sander
Dremel	Handheld rotary cutting tool with various cutting bits
Rotozip	Table mounted rotary cutting tool
Shop Vac	Vacuum for dust clean-up
Level Cutting Surface	Marble/Granite cutting top
Other Tools	Wood clamps/grips, misc. lead weights

Table 7.2. Assembly Tools.

7.1.2 Labor and Task

The division of tasks for the assembly phase was grouped based on individual skills and abilities. The assembly itself was divided into two parts. The difference between the two parts was the level in which assembly and integration was occurring. Part I focused on the finalization of individual pieces of the aircraft. Part II was a higher level of assembly where the pieces came together to make the whole. The Advice Section of this Chapter contains further information on Labor and Task.

7.1.3 Assembly Flowchart

See Figures 1.4 (Part I) and 1.5 (Part II) for vehicle assembly flowchart.

7.2 Machining and Joining Parts

7.2.1 Machining

Two pieces required special machining for this project. These pieces were used in the main landing gear installation (Figure 7.1). One piece was permanently installed in the boom as the interface for the removable gear strut assembly. The second piece was a transition part that allowed the strut extension to thread into the fixed internal gear support.

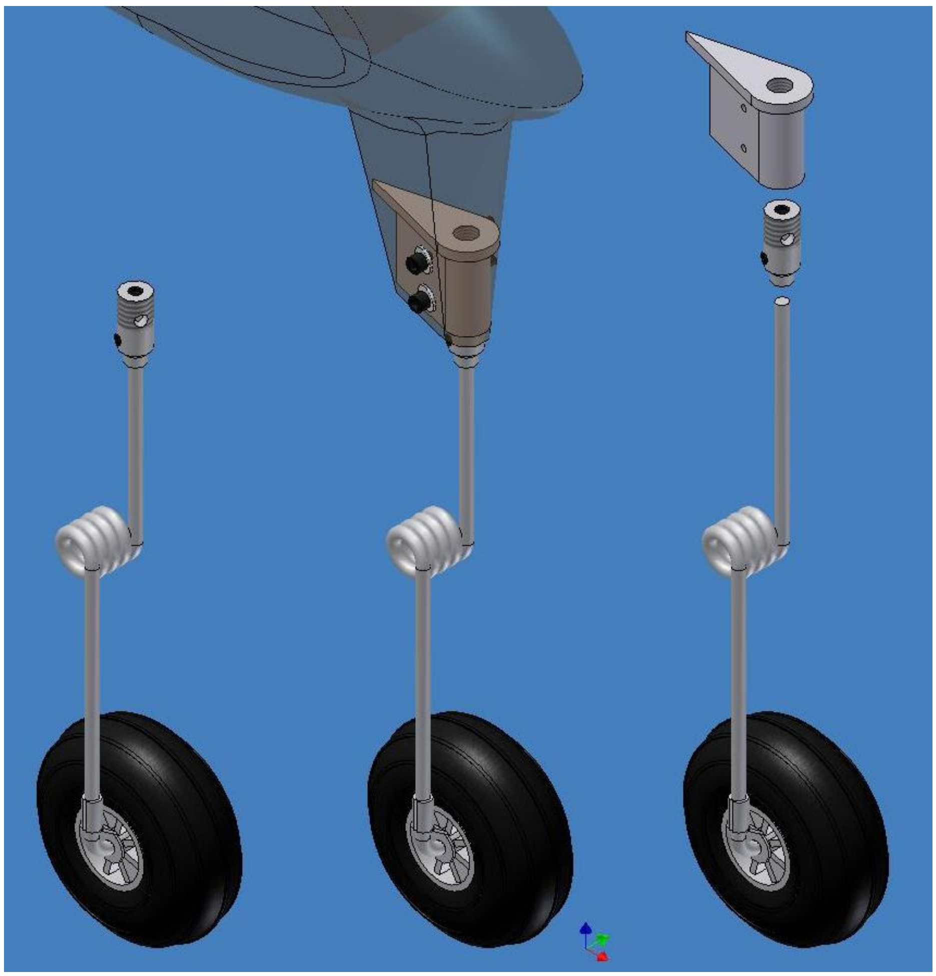


Figure 7.1. Main Landing Gear Assembly (see Figure 2.6).

7.2.2 Trimming, Trial Fitting and Cut Outs

All of the molded parts required trimming. The first step to trimming was the removal of the planar surface of the flange. This was done using a band saw. The machinist cut away much of the flange while leaving enough material for the entire piece to sit flat on the granite-cutting top. The pieces of the flange cut by the band saw were kept and used as internal structure for the fuselage.

Figure 7.2. Trimming Tools and Parts.


Figure 7.3. Boom Trimming in Progress – inscribed line detail view, top right.

For the pieces to mate to one another, the remainder of the flange had to be removed. This was done with a rotary tool using a diamond blade disk. The cutter was fixated on the granite such that the blade was oriented in a parallel plane ¼ inch above the granite surface. Prior to cutting, a line was inscribed on the part with a height gage that had an inscriber tip. The line served as a guide during trimming (Figures 7.2 & 7.3).

The trimming procedure for the flange was the same for the booms and the fuselage. This trimming process was found to be very efficient and repeatable. The end result, when trimmed correctly, required little post processing (fine sanding) and mated right away with its the corresponding half.

In cases where the trimmed parts needed further leveling to mate properly, the parts were sanded on a continuous sanding paper strip stapled to a butcher-top table (Figure 7.4). The parts were sanded and mated to perfection.

Figure 7.4. Fuselage Ready for Hatch Cutout – fine sanding, detail view top left.

After trimming the various parts and mating them together, the pieces were ready to receive their respective cutouts. In the case of the fuselage, the hatch cut out had to be made. This cutout was performed by hand using the lines imprinted on the fuselage during VARTM. The hatch cutout guideline can be seen in Figure 7.4.

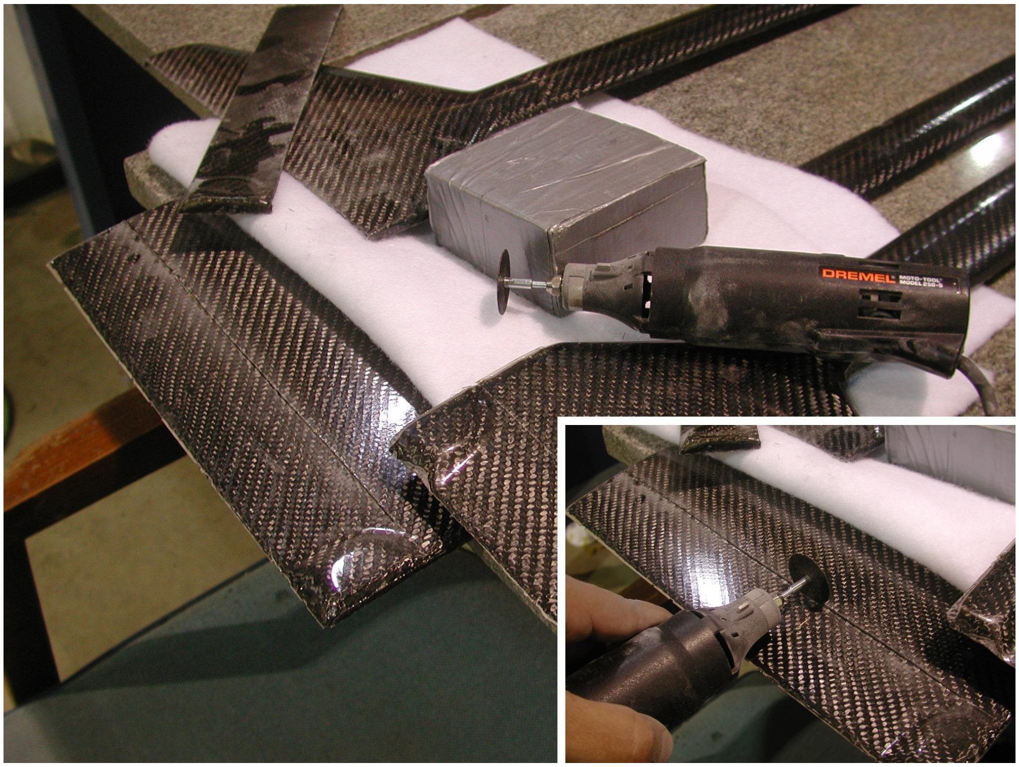


Figure 7.5. Rudder Cutout – free hand cutting, detail view bottom right.

Figure 7.6. Rudder Cutout Complete for all Boom Halves.

The rudder was cut off from the vertical stabilizer by hand with the Dremel (Figure 7.5). The rudder was sized and marked with a straight edge and a pointer. The rudder was then cut free hand following the line just as previously done with the fuselage hatch. The complete set of rubber halves, sufficient for two airframes, is shown in Figure 7.6.

7.2.3 Joining

The joining processes for the fuselage and hatch were similar. The booms, however, used a slightly different technique.

7.2.3.1 Joining the Fuselage

The sanded and mated fuselage halves were trial fitted very carefully to ensure a flush seam. The fuselage halves were held together by packing tape on the outside. The tape was carefully placed so no air bubbles or wrinkles were present at the seam line (Figure 7.7).

Figure 7.7. Fuselage Joining – taped seam, detail view top right.

The internal surface of the taped fuselage halves was sanded along seam (Figure 7.7). It was important to roughen up the inside surface so the joining reinforcement strip could adhere better. A carbon strip was wet laid inside the fuselage along the entire seam. An oversized peel ply sheet was placed on top of the reinforcement strip to remove excess resin. After full cure, the peel ply was removed and the fuselage was in one piece (Figure 7.8). The clear packing tape was also removed from the outside perimeter, revealing a flush and gapless seam that required no additional finish.

Figure 7.8. Fuselage Joined.

7.2.3.2 Joining the Hatch

The fuselage hatch was joined similarly to the fuselage. The hatch halves were mated and joined together via the wet lay up of a reinforcement strip with peel ply. The hatch halves were taped together along the outside surface, sanded in the inside surface and, lastly, joined with a reinforcement strip (Figure 7.18).

7.2.3.3 Joining the Booms

The boom halves were joined by means of injecting catalyzed resin into the mated halves. The initial preparation involved was similar to that of the fuselage and hatch. The boom halves were matched and mated with packing tape along the seam. As previously done, the packing tape held the two halves together and was carefully placed such no bubbles or wrinkles were present on the seam itself.

Once prepped, a small batch of resin was catalyzed and poured into a large diameter syringe. The catalyzed resin was injected into the closed part and allowed to flow internally along the seam. The excess resin drained out the front of the boom (Figures 7.12 – 14). However, the preparation for this particular piece required more than fine sanding and mating with packing tape. The main landing gear interface needed to be housed in the landing gear fairing as well as the horizontal stabilizer cutout. The necessary preparations for the booms are discussed in the next subsection (7.2.4).

7.2.4 Before Joining – Horizontal Stabilizer Cutout & Main Landing Gear

The cutout for the horizontal stabilizer was made on the designated internal boom halves. The location of the horizontal stabilizer was measured and marked accordingly. A bare foam stabilizer was used as a template to aid in the location of the stabilizer. The foam stabilizer was shaped at the ends to the contour of the boom/vertical stabilizer. By doing this, the foam horizontal stabilizer sat perpendicular to the surface.

A silver permanent ink marker was used to mark the airfoil shape on the boom/vertical. The horizontal stabilizer centerline was also drawn and measured to ensure proper angle of attack. The cutout was made inside the marked profile with a Dremel as to undersize the slot/fit (Figure 7.9). The cutout was carefully sanded to snuggly fit the composite wrapped horizontal stabilizer (Figure 7.9 – top left and bottom right detail views). See Figure 2.7 for technical drawing of elevator assembly.

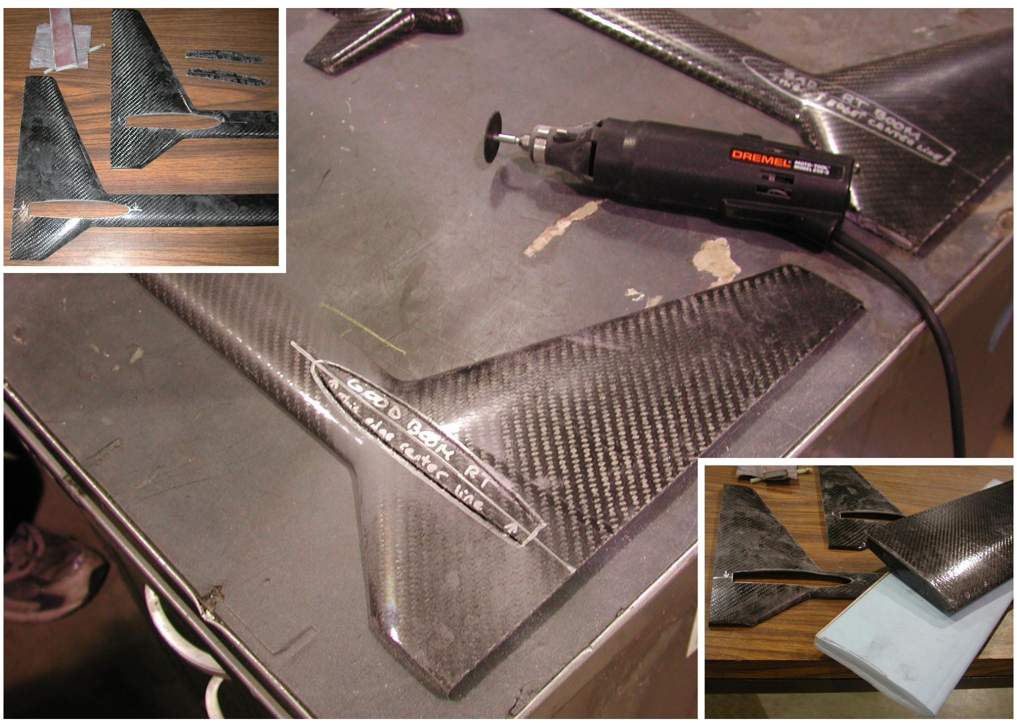


Figure 7.9. Horizontal Stabilizer Cutout – top left and bottom right detail views.

> *Construction side note:* It was very important to note that the horizontal stabilizer cutout established a left and right designation. The cutouts were made on the internal facing boom halves of the twin boom configuration. Prior to cutting, any boom half pair could have been a left or right boom. It was very important to keep track of the work and not end up with two left or two right booms.

The next step was to install the landing gear assembly as illustrated in Figures 7.1 and shown Figure 7.10. To do this, the gear interface was embedded before the boom halves were permanently joined.

Figure 7.10. Landing Gear Interface – detail view bottom right.

The first step was to trial fit the landing gear interface to the boom halves. In most cases, this required "dremeling" the inside of the gear-strut fairing with a small sanding tube attachment. Once the fairing was properly sanded, the interface sat in place flush to the inner surface. Measurements were taken to ensure proper location of the interface and markings were made on the boom with a silver sharpie. The gear strut and wheel were screwed on so a visual inspection of the orientation and alignment of the overall assembly could be made. The strut was removed and top and bottom holes in the interface were covered with packing tape. The holes for the fixating screws of the interface were made with a hand drill. The hole pattern was then transferred to the opposite boom half and the boom was taped together. The installation of the main gear strut following the above instructions is shown in Figure 7.11.

> *Construction side note:* The top and bottom-treaded hole in the interface was taped shut so the injected resin did not plug the hole during joining. This was *very* important to remember because hardened resin could plug the hole or fill the internal thread, thus, making it very difficult to attach the rest of the landing gear strut. The border of the boom halves was roughened with sand paper in the inside as well. For the same reason mentioned before, the roughened surface provided the resin a "grip" on the surface.

Figure 7.11. Installation of Main Strut Interface (from top left to bottom right).


Figure 7.12. Boom Joining – resin being injected (close-up).


Figure 7.13. Boom Joining – resin being injected.

Once the horizontal stabilizer profile cutout was made and the main gear strut interface installed, the boom was ready for joining. The boom halves were mated (taped) together and the screws of the interface were tightened with a nylon lock nut.

At this point, the boom was joined with resin. The catalyzed resin was injected into the horizontal stabilizer cutout (Figure 7.12). The boom was held at a 45-degree angle over a wastebasket. The excess resin drained out of the main gear fairing where the gear interface was installed (Figure 7.13). The resin wet out could be observed through the clear packing tape along the seam as it ran down the boom. Once the working time of the resin expired, the booms were allowed to cure in a safe location (Figure 7.14). The resin was known to have reached its gel stage because the remainder inside the syringe was both hot and solidified.

Figure 7.14. Left and Right Boom Pair Injected with Resin.

After full cure, the booms were permanently joined. The tape was not removed until the entire aircraft was fully assembled. The packing tape was left on until the last moment so it could protect the finished surface during further handling and assembly.

7.3 Internal Structure – Fuselage and Hatch

7.3.1 Internal Structural Components

The structural components of both fuselage and hatch are detailed in Figure 2.2.

7.3.2 Materials used for Internal Structure

The internal structures of both fuselage and hatch were made from the flange material leftover from the fuselage and boom parts. A template was made and the outline of various internal parts was traced on the flange pieces. The individual structural members were cut with a band saw.

7.3.3 Nose Cutout

The nose of the fuselage needed to be cut to expose the motor shaft. Moreover, the cutout was made such that there was enough clearance between the spinner back-plate and the cowling. In an effort to simplify the motor installation, the nose cutout also included the cooling cutout (Figure 7.15).

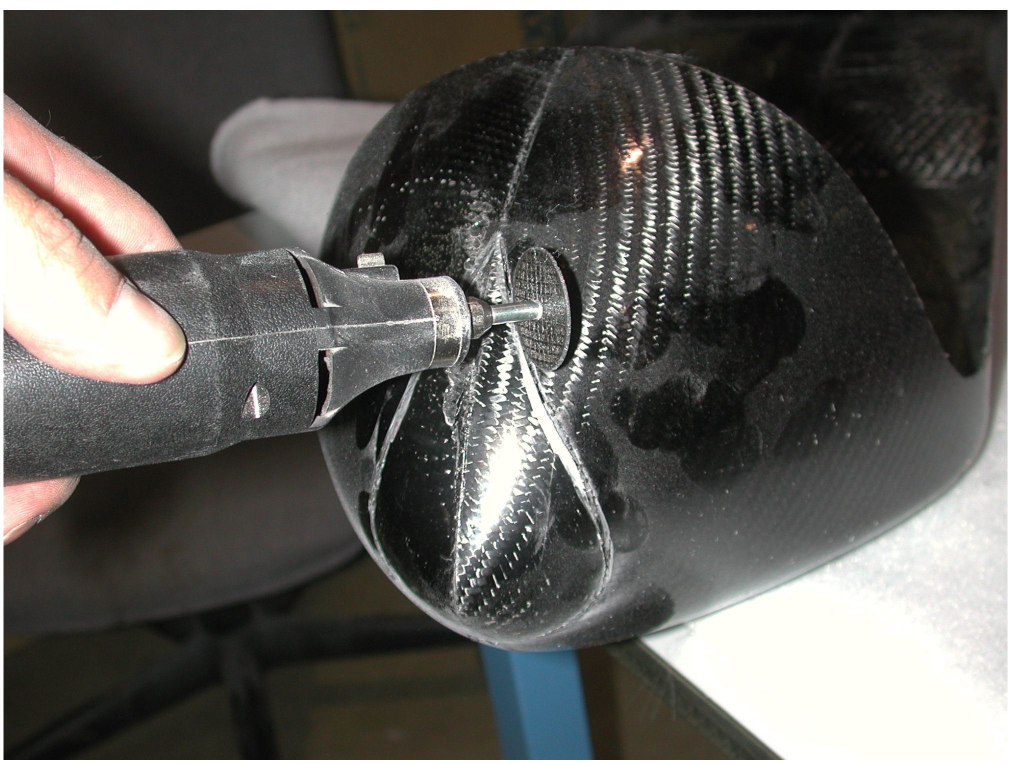


Figure 7.15. Nose Cutout for Propeller and Cooling.

7.3.4 Trial Fitting

The structural pieces were hand sanded to match the internal contour of either fuselage or hatch perfectly. Several markings were made in both structural parts and fuselage/hatch. The markings were used as a visual guide during gluing. Figure 7.16 shows the internal structure in place, but not glued. A string was taped in either end at the top of the fuselage to serve as a centerline. The motor was installed on the firewall and placed in the fuselage (Figure 7.16).

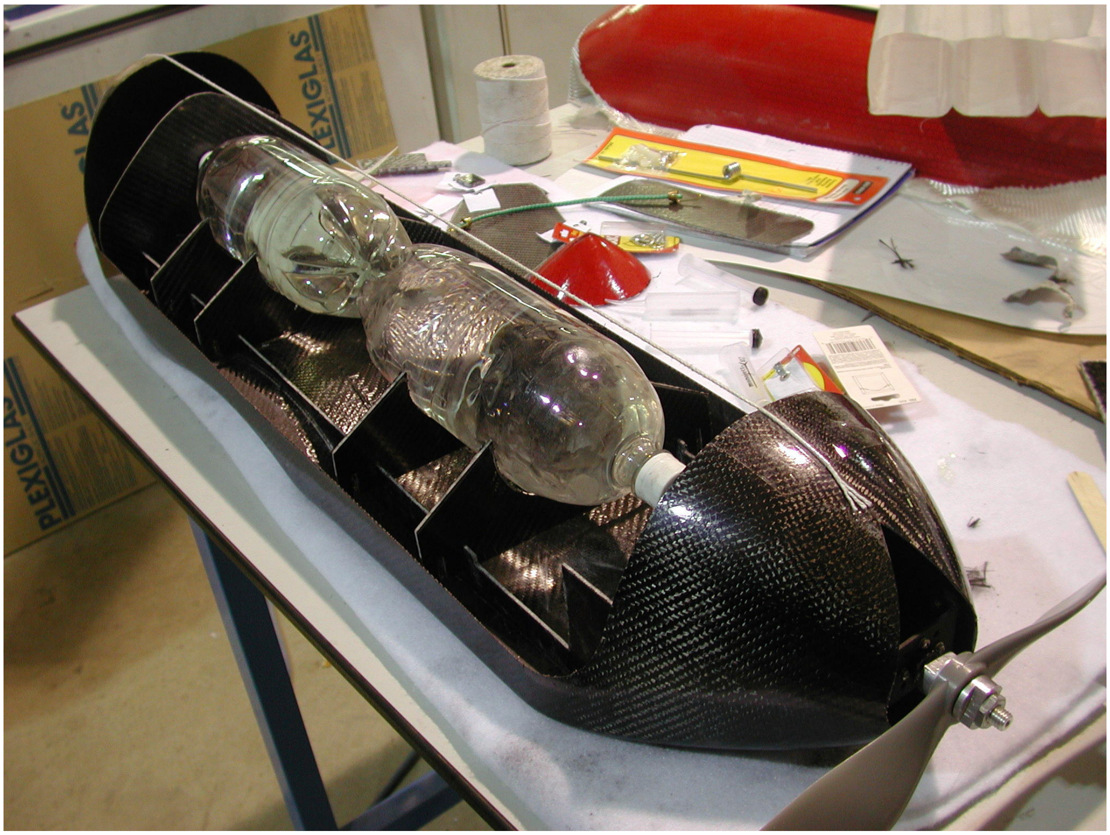


Figure 7.16. Internal Structure Trial fit with Simulated Cargo (see Figure 2.8).

7.3.5 Fuselage and Hatch Internal Structure Installed

Once properly aligned and marked, the internal structure was glued in place. This was done by wet laying strips of carbon cloth along the structure and the fuselage/hatch. Figure 7.17 shows a hatch being joined while at the same time having its internal structure installed. A completed fuselage is seen in the background of Figure 7.17. The front alignment pins of the hatch were glued in place and the matching holes of the pins were drilled in the fuselage firewall.

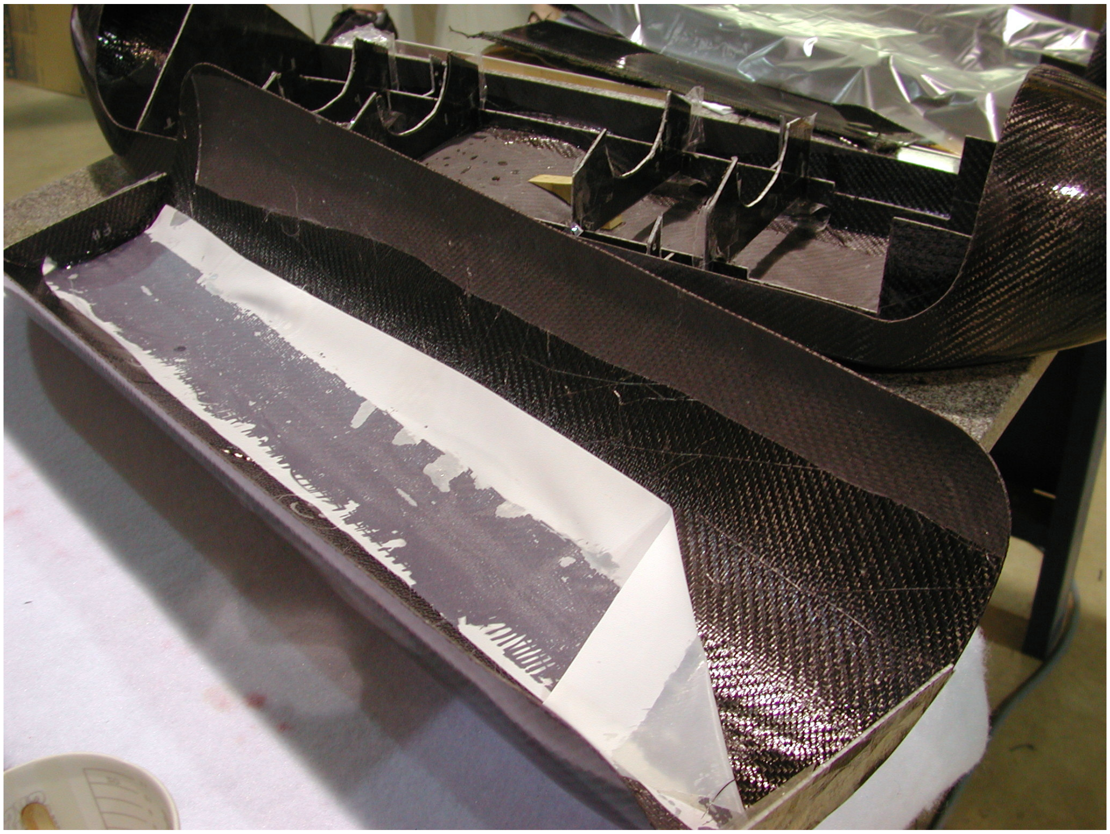


Figure 7.17. Hatch and Fuselage with Internal Structure Glued in Place.

7.3.6 Vertical Stabilizer and Rudder Internal Structure

The rudder halves were joined in a similarly fashion to the booms. Catalyzed resin was injected into the mated and taped rudder halves. Balsa inserts were sized and shaped to fit in both the vertical stabilizer and the rudder. The balsa strips "closed" the boom and rudder and provided material for the hinges to be installed in to (Figure 7.18).

> *Construction side note:* The booms were covered with packing tape to protect its surface from scratches and/or resin contamination. When working with resin in other portions of the boom, it was very easy to unknowingly contaminate the latex gloves and make finger print on objects. To remove the risk of ruining the glossy carbon finish, the entire boom(s) was covered with packing tape (Figure 7.18). The balsa strip installed in the vertical stabilizer was glued flush to the end of the boom while the balsa strip glued in the rudder had its rounded side exposed.

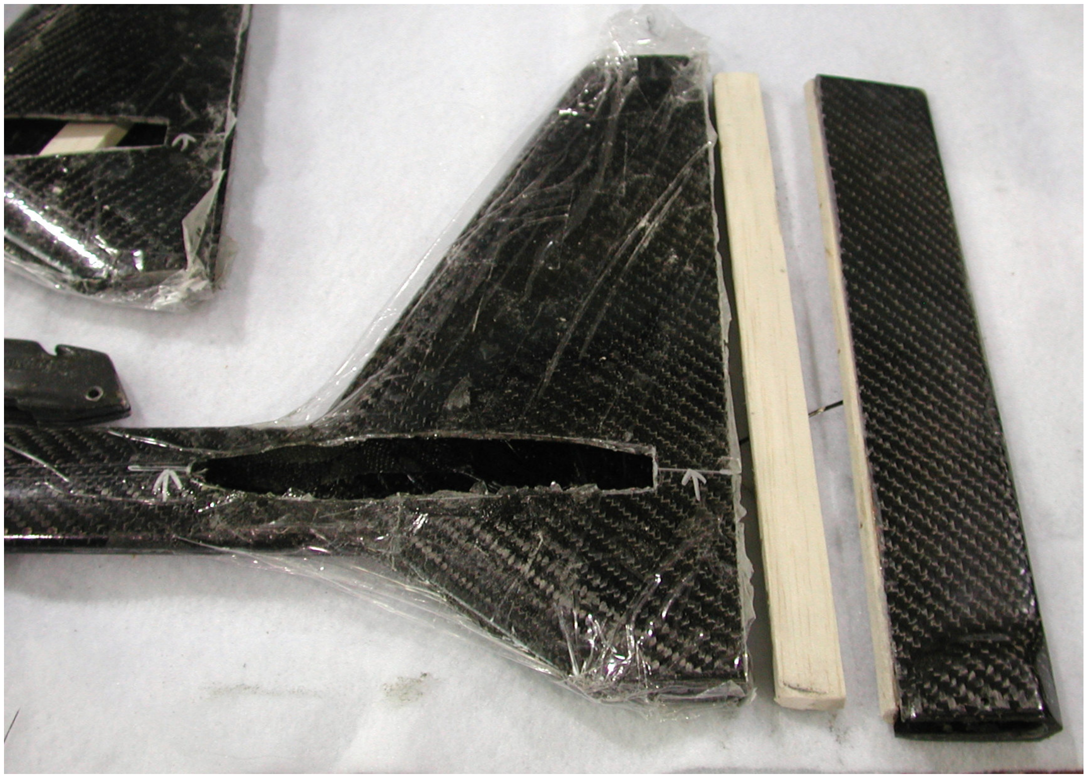


Figure 7.18. Vertical Stabilizer and Rudder Hinging Balsa Strip (see Figure 2.6).

7.3.7 Wing and Fuselage Mating

The fuselage was mounted on the center wing-section via a pin connection in the front and two mounting bolts in the rear of the wing (Figure 2.3). The first step was to fabricate the front pin support that was glued inside of the fuselage. The fuselage-mounting block, made from MDF Board and shaped to the leading edge curvature, was drilled prior to installation. This hole received the alignment dowel that was installed in the leading edge of the wing (Figure 7.19 bottom left detail view).

The rear boltholes had already been made on the support blocks that were embedded in the center wing-section. During wet lay-up, the carbon skin covered the boltholes (Figure 2.3). The boltholes were located and the carbon skin was carefully drilled out. The bolt holes were transferred to the fuselage by means of a pointer bolt fitted into the holes (Figure 7.19 top left detail view). In another words, a bolt with a sharp point was placed through the center wing and was used to etch the location of the bolts on to the fuselage. The inscribed bolt locations were checked both visually and with measurements (Figure 7.19). Lastly, the rear bolt pattern was drilled through the fuselage, thus, allowing the fuselage and center wing-section to be fastened together (Figures 7.20 & 7.21).

Figure 7.19. Fuselage and Center Wing-Section Mating (see Figure 2.4).

7.4 Assembly Interim – Part I End, Part II Begin

7.4.1 Vehicle Lay Out – Trial Fit

Several major components of the aircraft were now manufactured and partially assembled. At this point of the construction, the various parts were laid out side by side on the floor. Doing this not only allowed the visualization of the finished product, but also boosted the team's enthusiasm. All of the major components available were trial fitted and checked against each other (Figures 7.20 & 7.21).

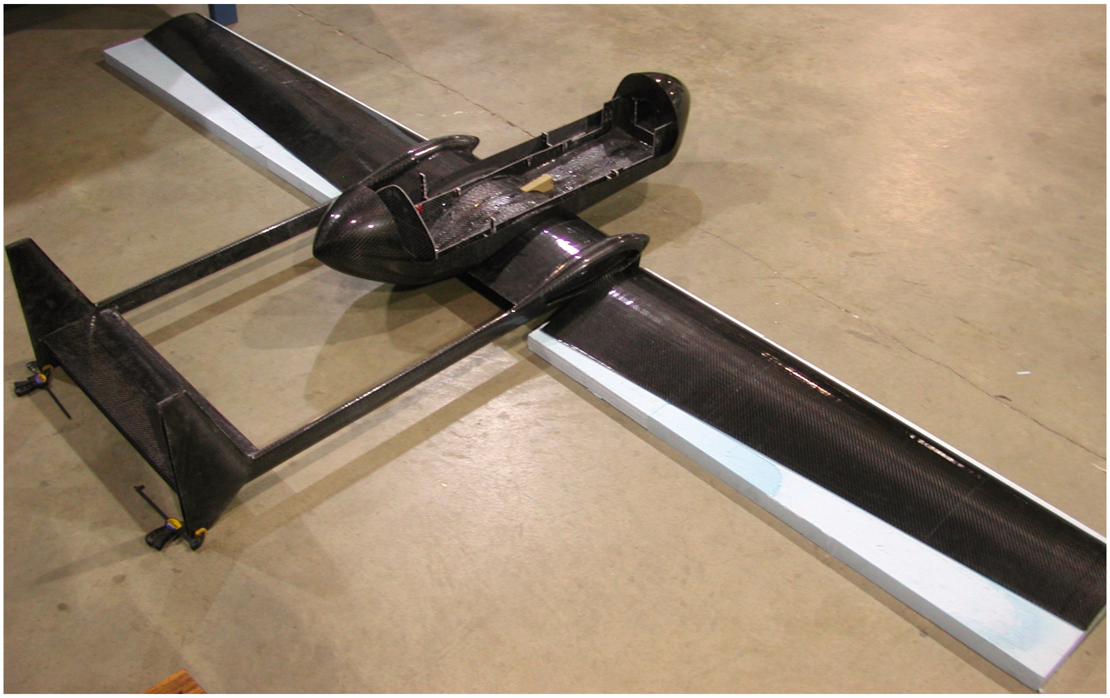


Figure 7.20. Aircraft Major Components Laid-Out.

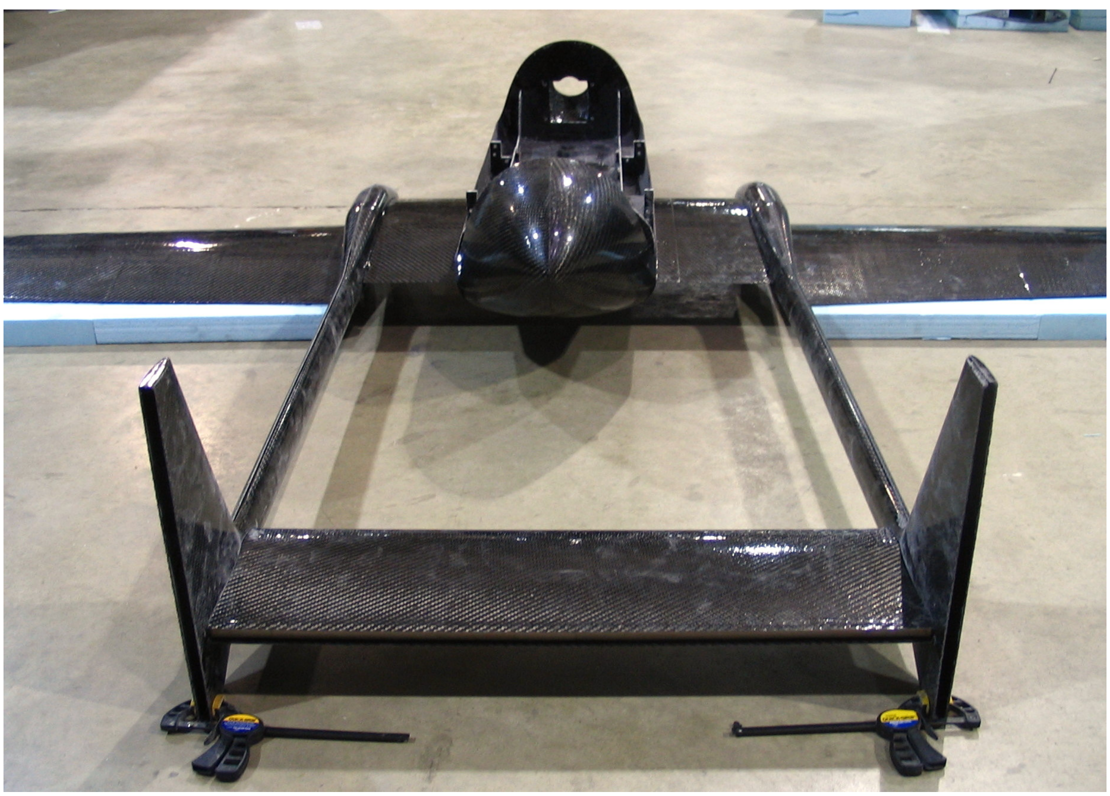


Figure 7.21. Aircraft Major Components Laid-Out.

7.5 Wiring and Servo Installation

7.5.1 Boom Preparation

The booms had to have the spar and wiring holes drilled prior to wiring. The load transfer spar ran inside the spar sleeves, which were installed in the wing outboard sections and the center section during wing fabrication (Figure 7.22). The load transfer spar was a single-piece carbon composite tube and the only structural member to cross the boom.

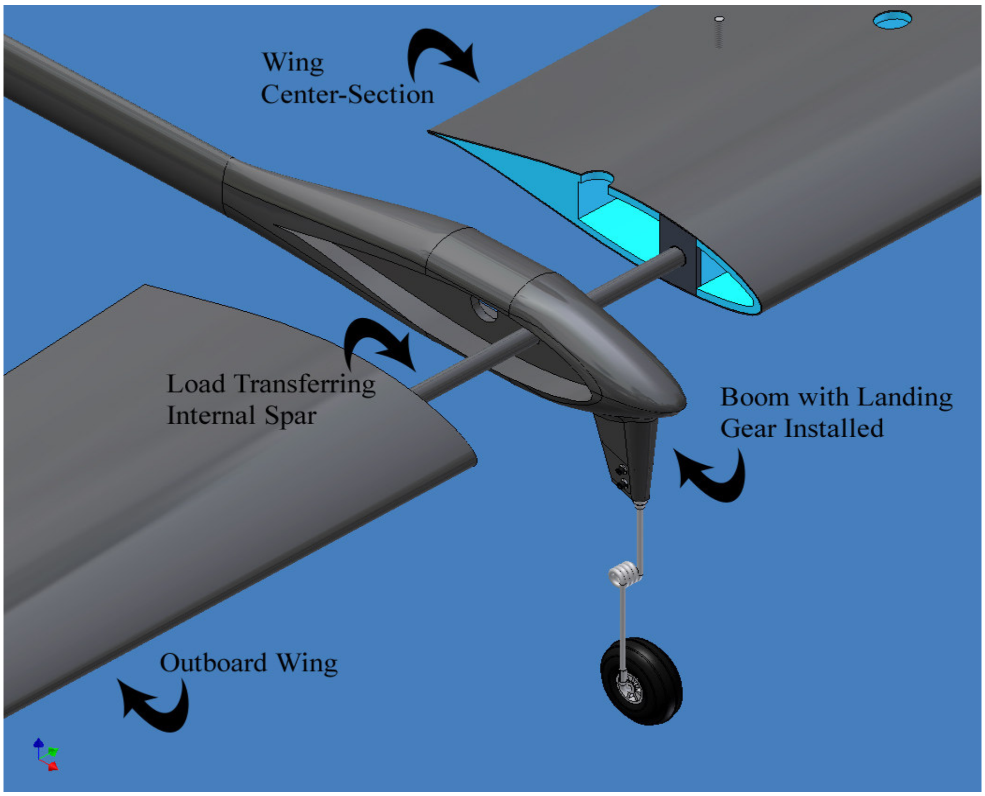


Figure 7.22. Load Transferring Spar and Assembly.

The two holes were done on a drill press. A foam wing template was used to locate the spar hole (Figure 7.23). This process was done by hand with a small piece of the spar tubing and a drill bit inside the spar (Figures 7.23 & 7.24 detail view). The drill bit was hand turned and etched a small center point on the boom. Based on this marking, the spar hole was drilled with the adequate spade bit on the drill press. The template guaranteed a perfect spar hole alignment with the outboard wings and center wing section. Furthermore, the process was repeated with success with the remaining booms.

The wire access hole was drilled with a hole saw bit. This hole did not require a specific/repeatable alignment. However, the template was used to locate the wire access hole in a reasonable "ball park" (Figure 7.25). Once the spar and wire access holes were complete, the boom was ready for wiring.

Figure 7.23. Spar Hole Template in Place – ready to locate spar hole.

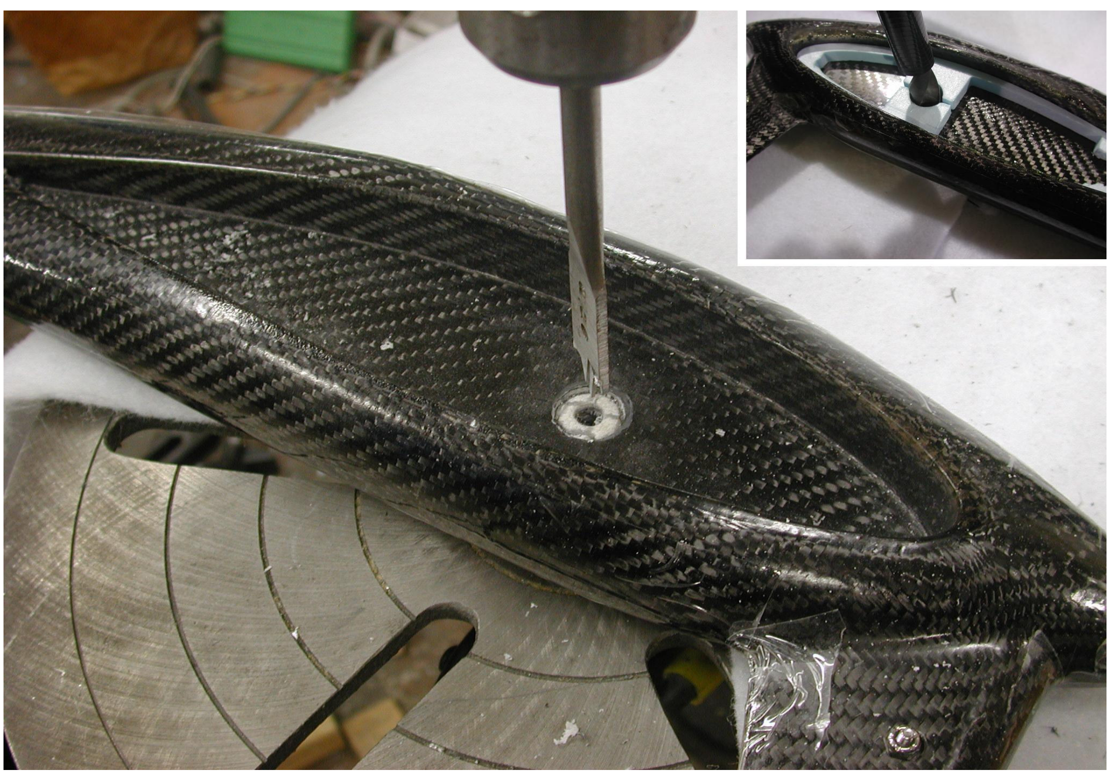


Figure 7.24. Spar Hole Marked and Drilled – detail view top right.

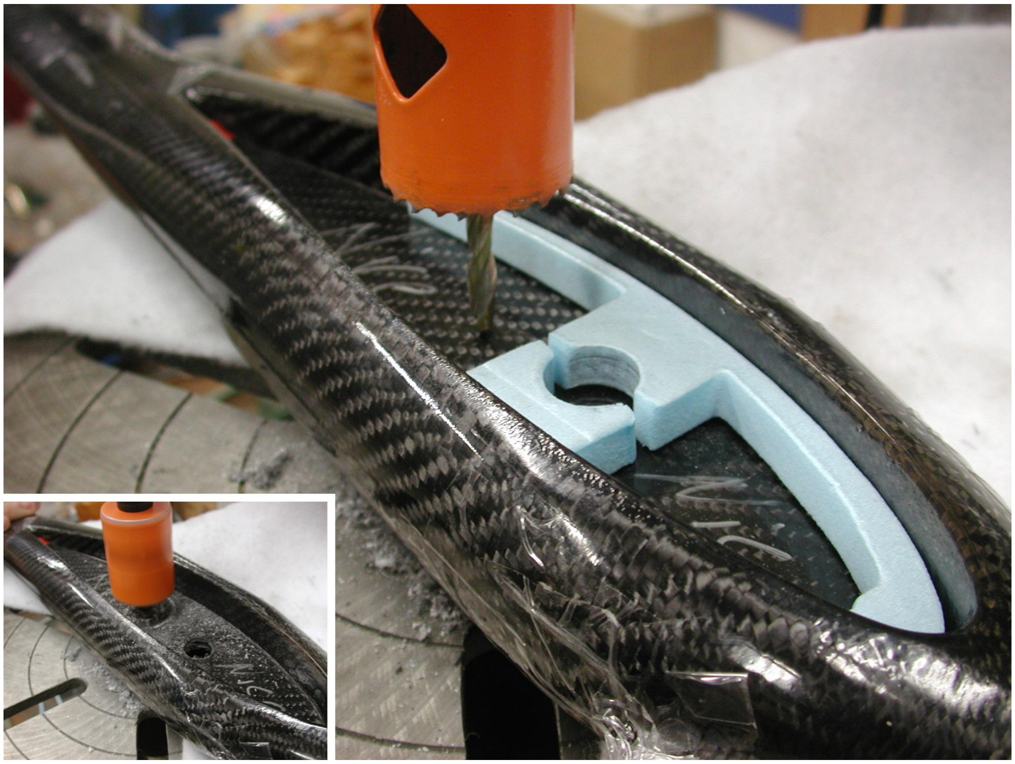


Figure 7.25. Wire Access Hole Marked and Drilled – detail view bottom left.

7.5.2 Running String

A weight, small enough to pass through the small cavities/holes, was attached to the end of the string and acted like a plum bob. The malleable string and weight were dropped through the part and rescued ("fished") out the other end. The string was cut such that at least 12 inches was exposed out either ends. The loose ends were then secured with packing tape.

In the case of the outboard wings, the servo nest had to be made first then connected with a wiring "tunnel". Similarly, the horizontal stabilizer also had its servo cavity made then its wiring access tunnel burrowed. The stringing and wiring for the wing structures are developed below.

7.5.3 Installation of Servos

7.5.3.1 Rudder Servo Installation

The rudder servo was located/hidden immediately below the horizontal stabilizer (Figure 2.5). To install the rudder servo a cutout was made that allowed the servo to be seated in the lower portion of the vertical stabilizer. The servo wire extension was taped to the end of the string and "threaded" through the boom (Figure 7.26). The rudder servo was then secured with its mounting hardware (Figure 7.27).

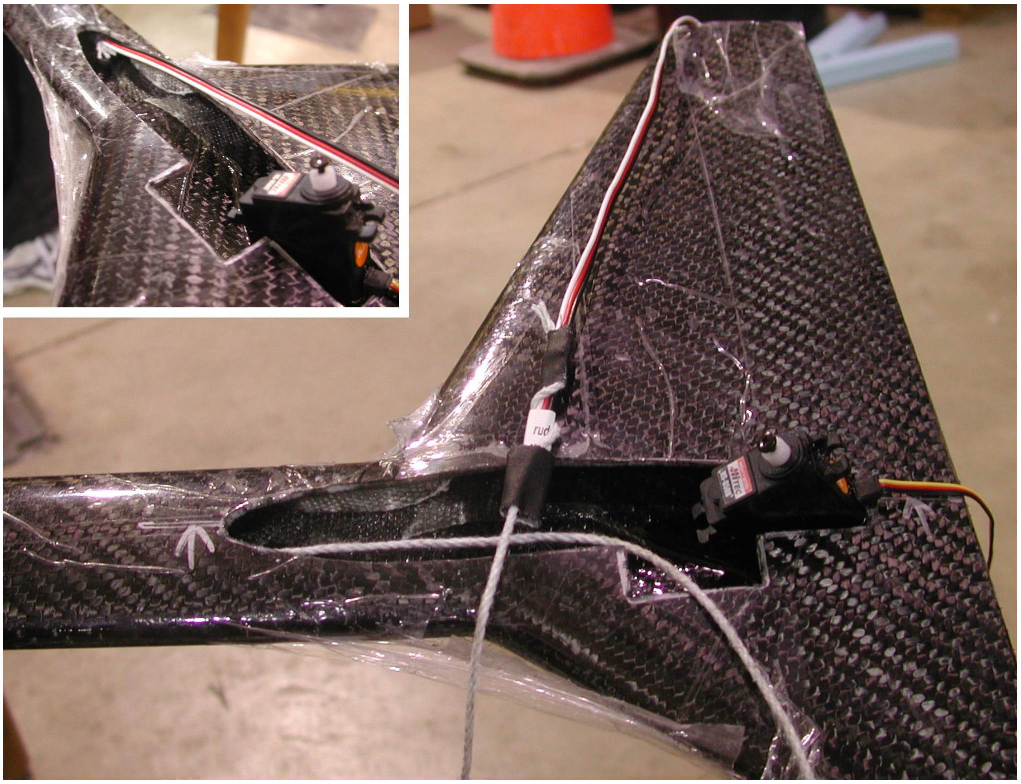


Figure 7.26. Rudder Servo Installation – detail view top left (see Figure 2.6).

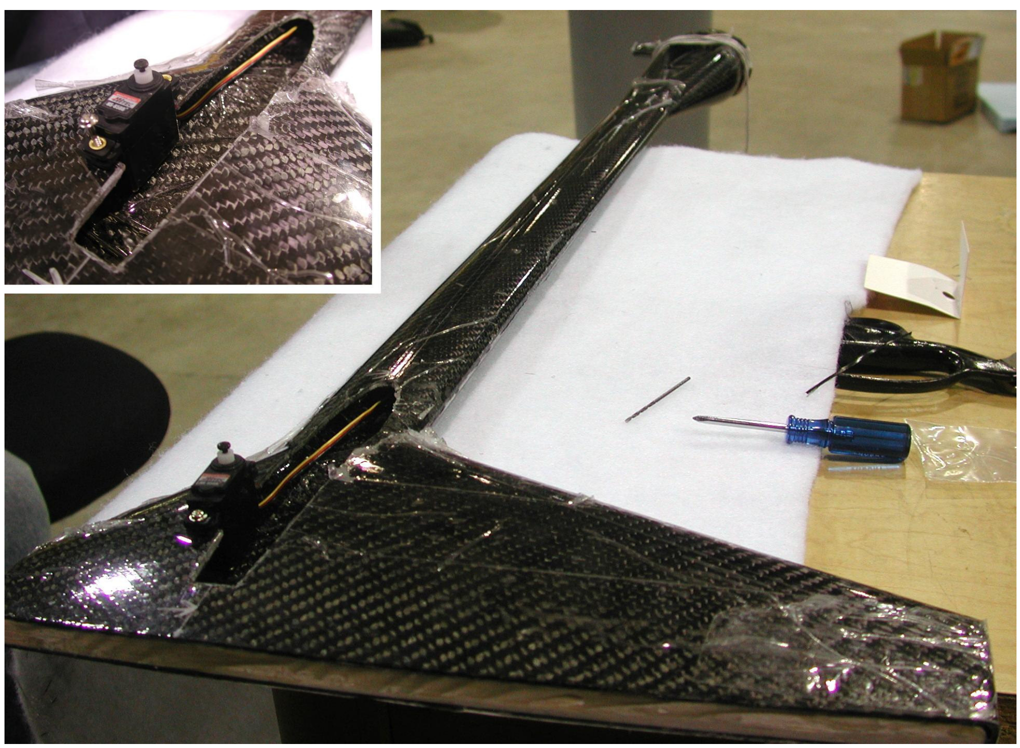


Figure 7.27. Rudder Servo Installation Complete – detail view top left.

7.5.3.2 Elevator Servo Installation

The elevator servo installation followed the reverse sequence of steps as the rudder installation. In the cases of the elevator and ailerons, the servos were first located and housed *then* wired. The reason for wiring after installation will soon be apparent.

The servo was located such that the control arm was connected to the (span-wise) center of the moving surface. The servo was installed at the center of the moving surface to minimize twist of the aileron/elevator when deflected.

Once located, the servo outline was traced onto the wing surface. Using a straight edge and a sharp X-Acto knife, the outlined servo shape was cut out from the carbon skin; thus, once peeled away exposed the foam core.

The bare foam was removed with the Dremel and the servo was trial fitted in place. The wire tunnel was then drilled through the wing foam core to allow access to the servo wire (the wire tunneling and stringing procedures are shown in the next subsection). The servo extension wire was connected to the string and pulled through the horizontal stabilizer (Figure 7.28).

Before sinking the servo in place, the servo was turned on. The servo direction and deflection was adjusted accordingly (Figure 7.29). Finally, the servo was buried into its tight foam housing. Only after the entire aircraft was completely assembled was the elevator servo pushrod connected to the elevator control horn.

The servo, once sunk in place, was secured with packing tape. However, just as easily, a well-placed decorative decal can secure the servo and hide it from view.

> *Construction side notes:* It is of paramount importance to create the servo nest as snuggly as possible to the servo. To sink the servo into the foam core correctly requires practice and patience. This procedure is easy to do, but equally easy to mess up.
>
> The depth of the servo bay is equal to the physical dimension of the servo depending on the orientation the servo is being installed. In another words, the servo should be flush with the wing/stabilizer skin surface. The servo, once sunk in place, was secured with packing tape. However, a well-placed decorative decal can be used to secure the servo in place as well, thus, almost completely hiding it from view.
>
> As mentioned before, the moving surfaces are only permanently glued in place once the entire vehicle is completely assembled. Moreover, the servos are only connected to their respective surface once the moving surfaces are glued in place.

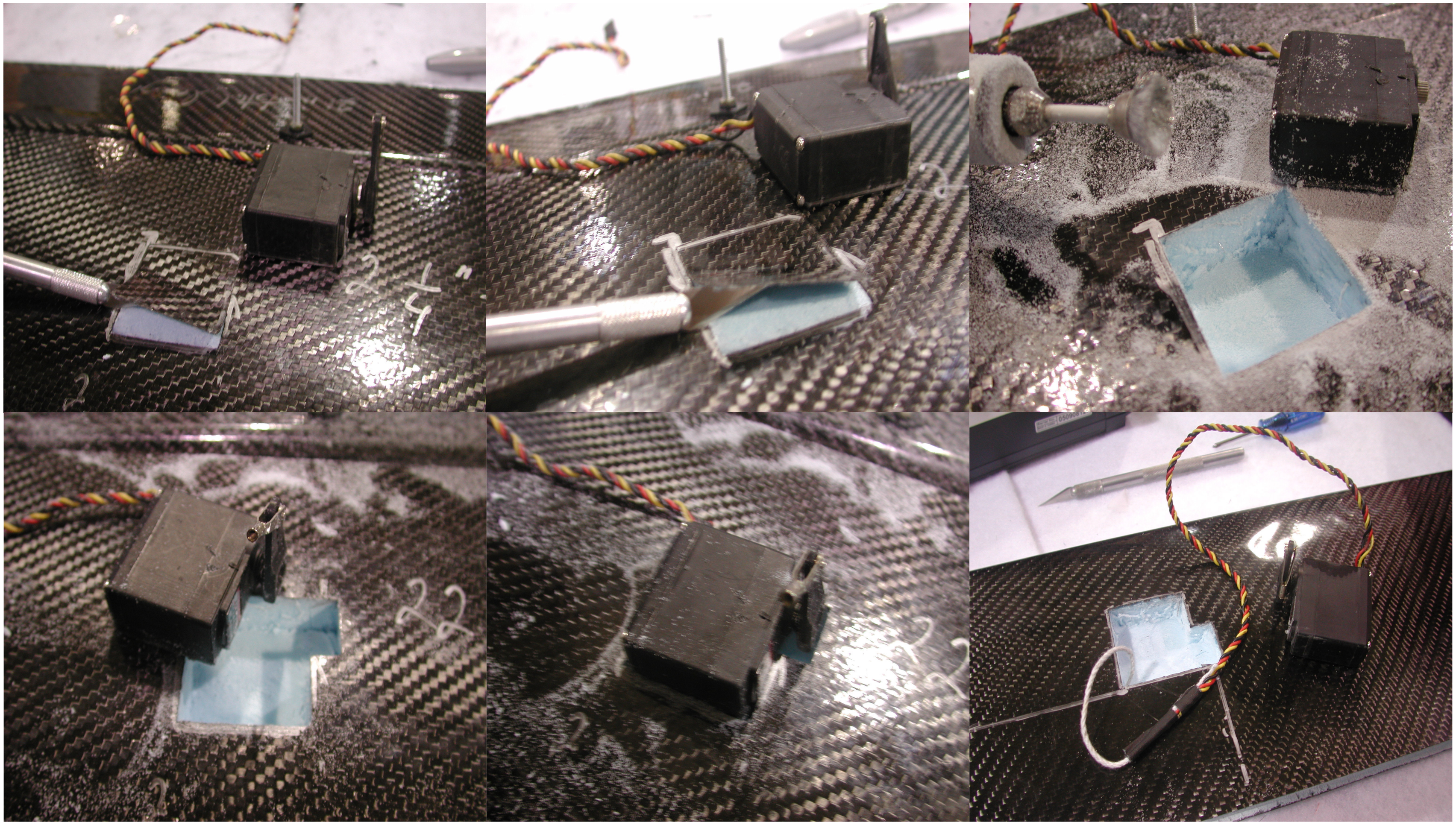


Figure 7.28. Servo Installation (from top left to bottom right).

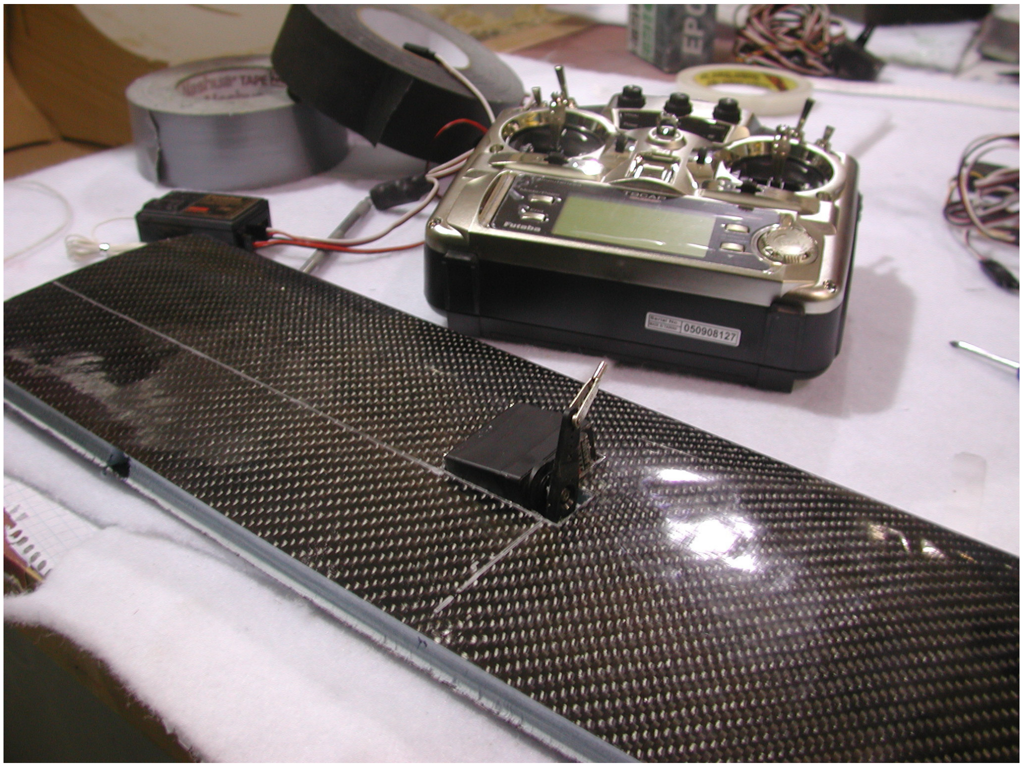


Figure 7.29. Elevator Servo Installed – ready for installation into wing foam-core.

7.5.3.3 Aileron Servo Installation

The aileron servo was installed in similar fashion to the elevator servo. However, the tunneling process required to allow wiring connection to the servo is described in this section.

The aileron servo was located and nested in place accordingly. A solid ¼ rod with a sharp point was used to tunnel the foam up to the servo cavity. To complete this process successfully, the operator visualized the path necessary to reach the servo nest (Figure 7.30). The sharp-tipped rod was inserted into the wing at the root chord and hand turned. The tunnel was slowly burrowed until the sharp tip was visible in the servo bay. The tunneling rod was then carefully retracted from the wing.

A second smaller diameter rod, with the string attached to its tip, was inserted into the wire access tunnel (Figure 7.30 top right detail view). The string was captured and taped to the aileron servo wire extension (Figure 7.30 bottom left detail view). The string was pulled back, from where it came from, while at the same time wiring the servo extension inside the wing.

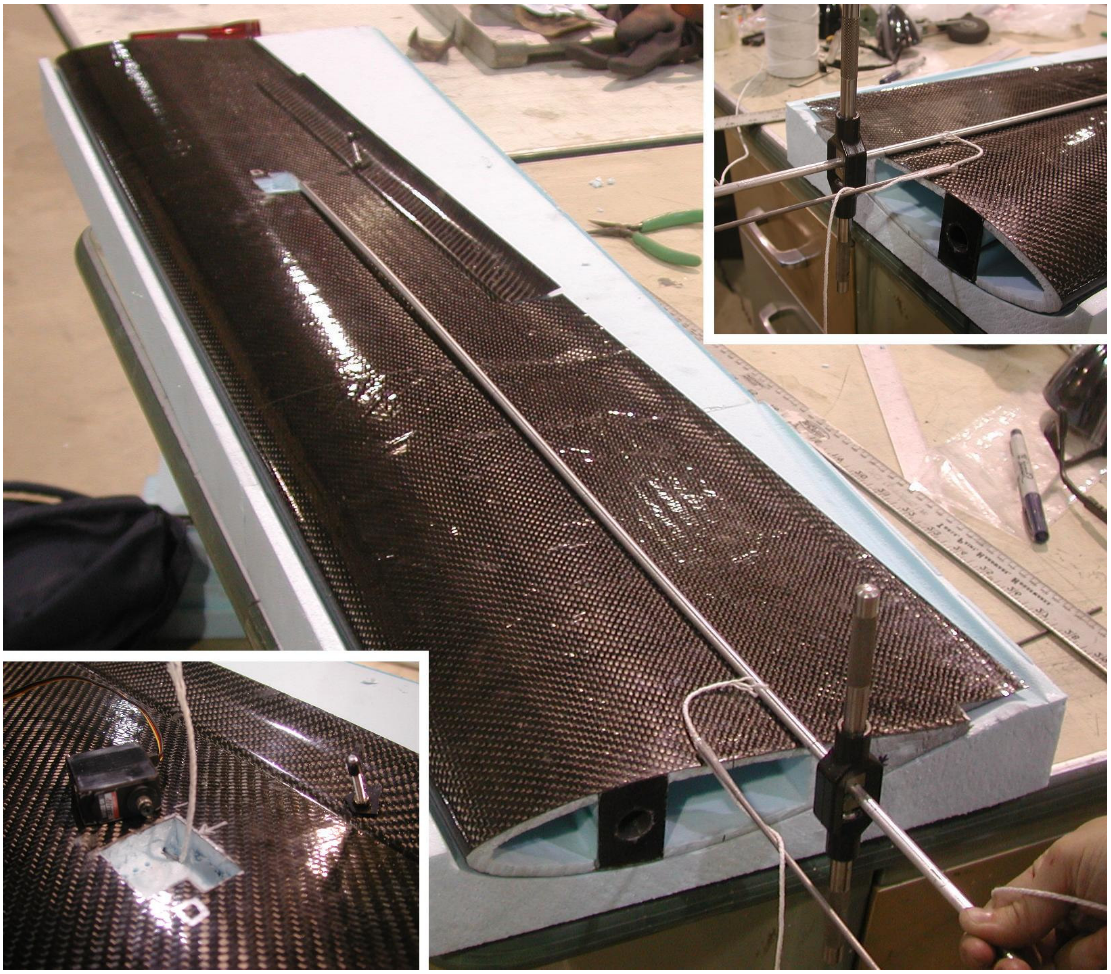


Figure 7.30. Hand Made Wire Access Tunnel – detail views diagonal corners.

7.6 Final Vehicle Assembly – Twin Boom Joined

7.6.1 Considerations Prior to Joining

The rudder and elevator servos were at this point placed and wired in. The next step in the assembly was to join the twin boom section of the aircraft. Two aircrafts were constructed and both received a slightly different treatment. The choice here was to either leave the servos in place or remove them prior to joining the twin boom body. The risk involved was that excess resin could run inside the boom and glue the string or wire permanently in place. As a result, the glued string could not be used to thread wire through or the glued wire extension could not be swapped if necessary.

7.6.2 Joining Subsections

7.6.2.1 Twin Boom Joined with Stringing in Place

For the first airframe, the team sided with caution and removed the servos prior to joining. While removing the servo extensions, the string was threaded through in the booms and horizontal stabilizer again (Figure 7.31). At this point, the twin boom assembly was carefully aligned and permanently glued into one piece. After the resin cured, the servo extensions were rethreaded through the booms and the servos were reinstalled. The joining/gluing procedure is detailed in the next subsection.

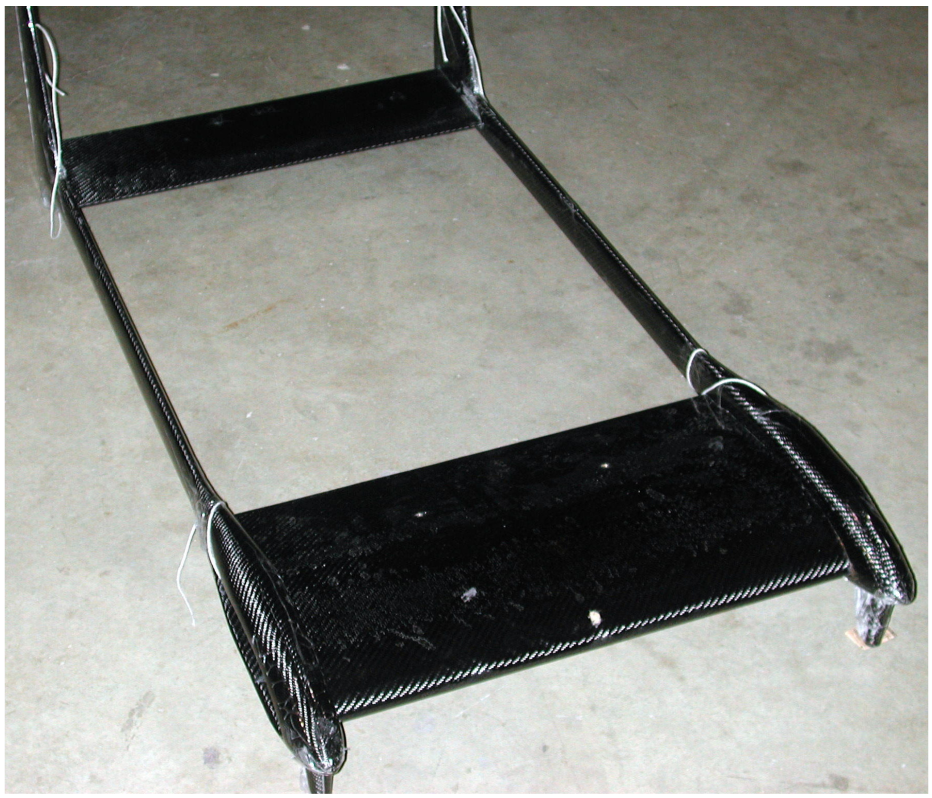


Figure 7.31. Twin Boom Sections Ready to be Joined.

7.6.2.2 Twin Boom Joined with Servos and Wiring in Place

The second airframe inspired more confidence; therefore, the twin boom section was joined with the servos and wire extensions in place. The initial step was to fully wire the twin boom section. The servo wire extensions were pulled through the wire access port drilled on the center top surface of the center wing section (Figure 7.32).

The tips, soon to be inserted into the booms, of the center wing section and horizontal stabilizer were roughed with a 400 grit sand paper. The sanded surface was lightly coated with catalyzed resin and the twin boom assembly was mated into one piece.

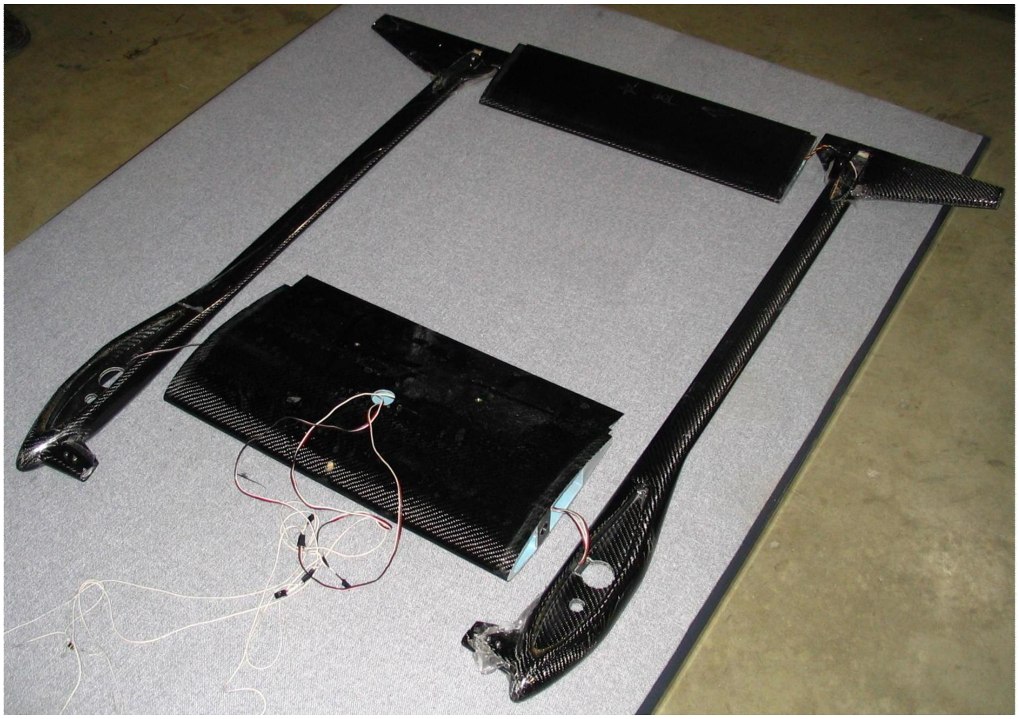


Figure 7.32. Twin Boom Sections Ready to be Joined.

The most important details were to make sure that the two boom shafts were parallel to one another (from a top view) and the vertical stabilizers parallel to one another (from a front view). A precision metal ruler was used to measure the distance between the seam of the booms both at the front and at the rear of the twin boom assembly (Figure 7.33).

Once the assembly was allowed to set, a bead of resin was laid down along the seam of the inserts. This resin bead gave the twin boom assembly a finished look and also sealed the joint line, thus, preventing dust/dirt from entering the twin boom assembly (Figure 7.33 bottom right frame & 7.34 left frame). Since holes or slits along the joint seam can generate noise, the resin breadline also prevented the aircraft from whistling during flight.

Figure 7.33. Twin Boom Assembly Joined.

7.7 Moving Surfaces

7.7.1 Moving Surfaces Final Assembly

The moving surfaces were permanently glued in place. The manufacturing and assembly work for the ailerons and elevator were completed in Chapter 6 and now were ready to be permanently installed. The first step was to glue the ailerons to the wings and install the servo push arm.

The next step was to install the rudders permanently. The hinges were located and glued to the rudder as done before for the other surfaces. A chrome sticker was placed along the hinging balsa strip to provide a finish to the hinge line (Figure 7.34). The tail wheel was held in place via an axle with a collar attached to either end (Figure 2.5). Lastly, the rudders were connected to the servo (Figure 7.34 & 35).

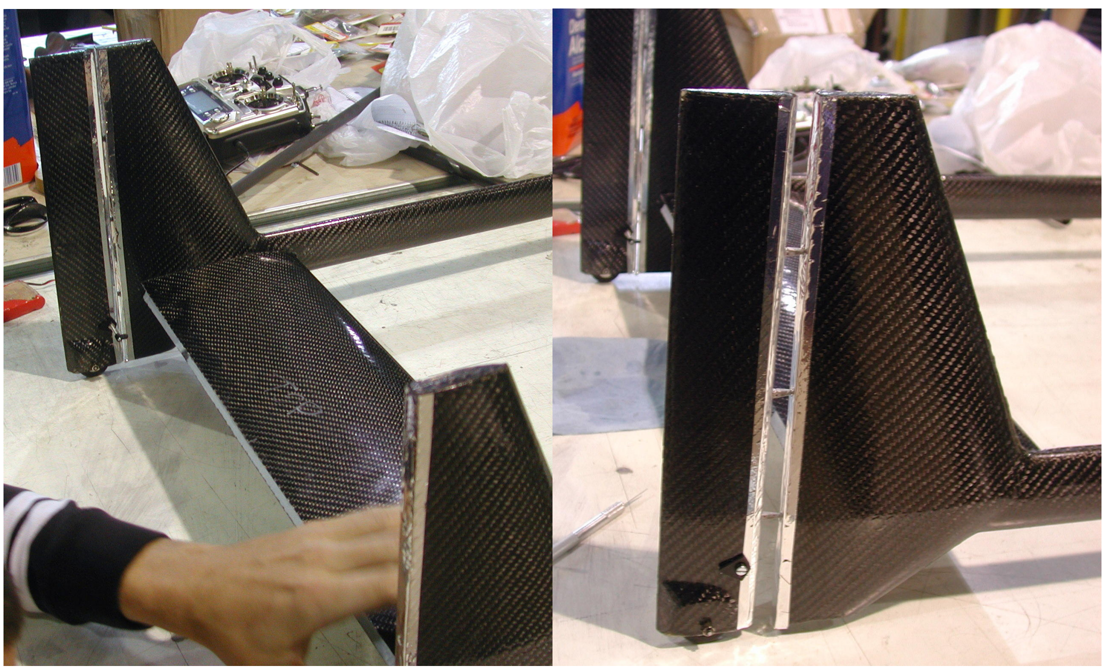


Figure 7.34. Rudder and Tail Wheel Installed.

The elevator was sized to fit in the span between the two rudders. Moreover, the elevator was trimmed so the rudders, when deflected either left or right, did not interfere with the elevator actuation. The control arm for the elevator servo was installed after the elevator was glued in place.

Figure 7.35. Almost Completed Aircraft – elevator not installed yet.

7.8 Final Integration

7.8.1 Propulsion Hardware Installation

The motor was fitted to the adjustable motor mount and secured (Figure 7.36). The motor was then installed to the firewall and connected to the speed controller. The main battery was secured to the rear-facing side of the firewall. Other minor electrical hardware was also installed like the main battery fuse holder and the main on/off switch. The propeller and spinner were secured to the motor shaft.

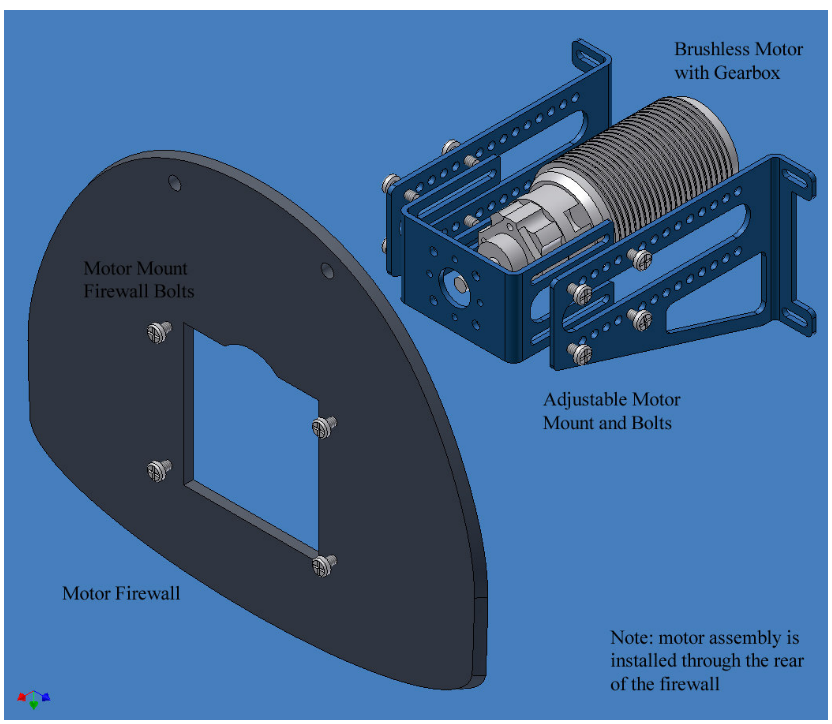


Figure 7.36. Motor Mount Assembly.

7.8.2 Final Wiring and Electronic Hardware Installation

The receiver was installed in the rear of the fuselage and its antenna ran outside the aircraft towards one of the vertical stabilizer. All of the servo extensions were connected to the receiver in their proper channels. Both the receiver and receiver battery were housed in foam and secured to the aft bulkhead.

7.8.3 Other Hardware Installation

The main landing gear struts were also screwed in place and adjusted such that the wheels were parallel the aircraft's longitudinal axis and to each. The hatch front alignment pins were glued and the rear hatch release was installed (Figure 7.35).

7.8.4 Spar Tube Screws/Tie-Down

The outboard wings were secured by means of a ¼-inch nylon bolt screwed at each end of the spar. A hole was made through the spar sleeve and half way through the carry-thru spar (Figure 7.37). The bolt threaded to the internal carry-thru spar and held the two outboard wings in place.

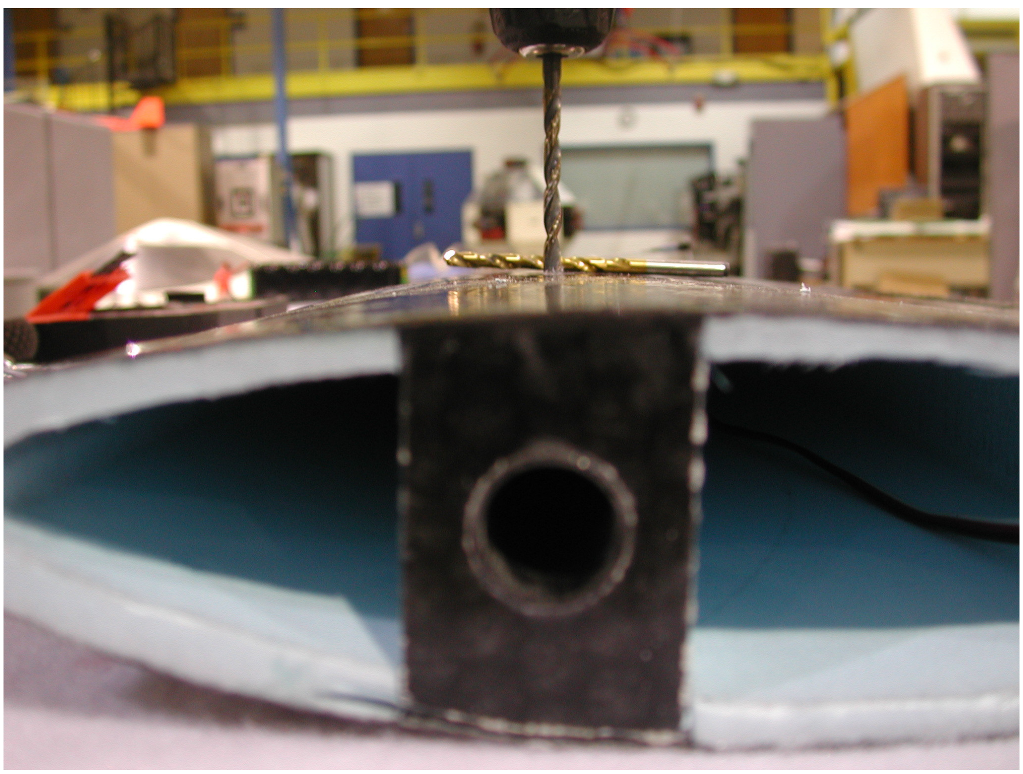


Figure 7.37. Wing Bolt Clearance Hole Made.

7.9 Advice

7.9.1 More on Labor and Task

The labor and tasks for this phase of the construction are interchangeable. From a project management point of view, three individuals can finish the project just as well as twenty can. The question is, how soon does the airplane have to be in the air?

The root branches in Figure 1.4 (Machining, Joining Parts and Internal Structure) can be developed independently. However, there is still some interplay between the different sections, but progress can be made in each branch. For example, while small parts are machined, trimming and trial fitting of vehicle parts can occur and fuselage internal structures can be manufactured.

In conclusion, the most efficient way to assemble the aircraft is to finalize each part independently and then piece them together in sequence. It is vital that all individuals understand what exactly he/she is working on and how it fits with the parts someone else is working on. The speed in which the assembly phases progresses depends on the number of skilled individuals working in various parts at the same time, communication between individuals and minimal operator/worker errors/mistakes.

7.9.2 Considerations Prior to Joining

Before committing pieces together, either in Part I or II, careful consideration must be given to ensure a (future) smooth assembly progression. The most important event that must occur *before* joining parts is the realization of what needs to be done prior to joining. One of the most damaging mistakes made during joining is the realization that parts that should have been embedded were not installed and "now it's too late". This kind of mistake can completely "kill" project momentum, cause on-the-spot design changes and/or junk entire vehicle subsection(s).

The only way to be truly immune to this problem is to have experienced workers. However, if this is not the case, then one has to settle for the next best option. If time is not too short, it is advisable to assemble the B-Grade vehicle first. In another words, chances are many parts were made in Chapters 5 & 6 and some parts are better in quality than others are. The variance in quality is there because of the learning curve involved, especially for first-timers.

The parts that are satisfactory, but otherwise not the best ones, can be used in the first go-around of assembly. This creates a safety net in case mistakes are made or issues overlooked. This kind of cautious approach to assembly alleviates the "zero mistake tolerance" mindset, thus, allowing the novice builder to learn the process and gain experience without jeopardizing the best-looking parts.

The approach mentioned in the previous three paragraphs was put to use in this project. Due to the wide-ranging variance in experience between group members, the first vehicle assembled was made up of parts that were somewhat less “gleaming”. To differentiate between the various parts, a non-permanent silver marker was used to label all of the pieces. The writing on the pieces is seen in various pictures in this Chapter.

7.9.3 Think First - Let the Solution Present Itself

The title of this section may seem innocent, but it speaks mountains. Another likely title for this section may have been “Fools Rush In”. The point here is that when a problem surfaces, it must be given adequate contemplation. At this stage in the construction, a misstep can ruin much of the work and delay the assembly process. During this project, when an undesirable event happened, often times the best solution was *not* the first solution that came to mind. The assembly of the airplane is connected to itself in many levels and solving one thing without thinking about the rest can, by far, be the least desirable course of action.

It is definitely exciting to see all of the pieces come together to form a final product. Although very close to the end, it is important to maintain quality control. The details, tirelessly given during the beginning of the construction, must be upheld down to the last screw. In general, once the aircraft is ready for flight it will look as good as the least detailed/finished part visible.

Chapter 8: Conclusion

8.1 Complete Aircraft

The completed aircraft is shown in Figures 8.1 to 8.5. The final product is *not* painted or coated with gloss. The reflective carbon composite skin is a result of the workmanship and attention given to the various manufacturing techniques described in previous Chapters. Decals were applied to airframe to enhance its appearance and aid the pilot's visual of the airplane during flight. Figure 8.6 is a team photo.

Figure 8.1. Completed Aircraft – nose close-up.

Figure 8.2. Completed Aircraft – Maryland flag reflection.

Figure 8.3. Completed Aircraft – runway access ramp.

Figure 8.4. Completed Aircraft – on take-off.

Figure 8.5. Completed Aircraft – flyby over runway.

Figure 8.6. Completed Aircraft – team picture.

8.2 Composite Construction Conclusion

The composite construction methods were customized to meet the needs of the individual parts of the aircraft. Each method utilized has its pros and cons. Furthermore, each method required different levels of care and skill sets.

However, the construction techniques developed in this document, when followed attentively, generated a product with superior quality given its cost.

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