ME 493 Final Report
Year 2015

ASME Carbon Fiber Bike Process

Team Members:

Aaron Lovegren

Adrian Lahsene

Andrew Keith

Jessica Lindsey

Thomas Bergeron

Thomas Lindner

Advising: Evan Thomas, PhD, PE, MPH

Portland State University

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Executive Summary:

The PSU's ASME student group's carbon fiber bike frame capstone project places emphasis on the process and tooling to allow for carbon fiber bike frame production. This report discusses a review of key PDS guidelines; progress of design selections, including the frame jig, mandrels, and tube production equipment; design evaluations, including carbon fiber layup, initial FEA analysis, and frame testing; and, the post mortem analysis of the deliverables produced during the Capstone process.

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I. Introduction

Each year, the American Society of Mechanical Engineers (ASME) sponsors a student club at Portland State University. The club designs, builds, and competes with a human powered vehicle (HPV). For 2014-2015, the club proposed a carbon fiber bike frame capstone project. Several of the ASME HPV members are also on the capstone carbon fiber bike team; this allowed for a very open-ended project. The team decided to focus on the tooling and process of building carbon fiber bikes in a range of sizes as opposed to a focus on just the frame itself.

The tooling would allow a person, who is not experienced with carbon fiber but has basic shop experience, to easily and efficiently build carbon fiber bikes cheaply for personal use or for sale to customers. The bikes would be of medium quality (better than “homemade” carbon fiber bikes but not as good as high-end, super-light racing carbon fiber bikes), and the process would reduce the amount of required labor and skill level so the bikes could be produced at a lower cost. This would create a market of carbon fiber bikes that are more easily accessible to the general public. The tooling could be potentially sold to bike shops, start-up shops, and hobbyists.

All of the tooling is designed so that it is easy to adjust accurately and doesn’t require tools to adjust. The carbon fiber would have to be bought by the shop and they would have to have an oven. The tooling consists of a jig, mandrels, tube roller system, and vacuum and oven-safe bags.

II. Mission Statement

Our mission is to design the process and tooling for building carbon fiber bike frames of varying sizes and advance PSU’s knowledge and tooling in carbon fiber construction. The process and tooling will be targeted at any individual or company looking to get into carbon fiber bike frame construction. This includes, but is not limited to, bike shops, bicycle frame startups, amateur bike builders, and schools. For Portland State University, one of our deliverables will be a process documentation and tooling/fixture that future students, alumni, faculty, or even the public, through school programs, can build or have built a carbon fiber frame at cost. Our main performance criteria will be the ease of use and the ability to reuse our equipment to create quality carbon fiber bike frames which meet government regulations for street legal use. The target for completion of this project is the end of spring term, 2015.

III. Main Design Requirements

- Process must consist of steps to insure the safety of user; include Material Safety Data Sheet (MSDS) for materials used.
- Design must have comprehensive and comprehensible instructions to enable use by an individual with minimal training.
- Process must produce carbon fiber bike frames that adhere to government safety standards (code of Federal Regulations Title 16, Part 1512), specifically:
    - Requirements for Fork and Frame Assembly [1512.14]
    - Requirement for Seat: Adjustment Clamps [1512.15(c)]
    - Road Test [1512.17(a)]
    - Ground Clearance [1512.17(c)]
    - Toe Clearance [1512.17(d)]
    - The correlating Tests and Test Procedures [1512.18(k)(2); 1512.18(l); 1512.18(p)]
- Tooling and process must be robust enough to produce a minimum of 50 frames.
- Process must produce bike frames in varying sizes and geometries to allow for consumer customization.
- Completed design process must produce carbon fiber bike frames for only the cost of materials.
- Cost of project (i.e. materials, tooling, etc.) must be under the set $3,500 budget (this amount can be amended if additional funding is obtained).
- Process should require only basic maintenance (e.g. cleaning of tooling, etc.)

IV. Top-Level Alternative Designs

During the research and development stage several designs were investigated and evaluated based on the requirements of the product design specifications for the project. Not all of the process required initial designs to be explored. The major tooling components involved several design iterations which are listed in Table 1.

Table 1: Comparison of design iterations.

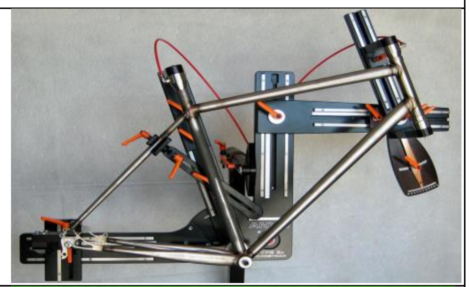
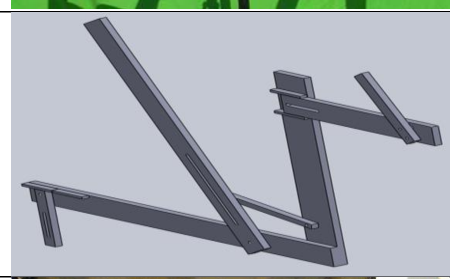
Design	Benefits	Issues	Figure
Jig			
Anvil	Very accurate and easy to use, looks professional	Expensive, requires a lot of precise machining	
Square Aluminum Extrusion	Easy to make, cheap	Hard to adjust, ugly	
Welded Bar Stock	Accurate	Requires machining	
Aluminum Extrusion	Cheap, easy to make, does not require much machining	Not as accurate as the other designs, somewhat hard to adjust	

Table 1 (Continued): Comparison of design iterations.

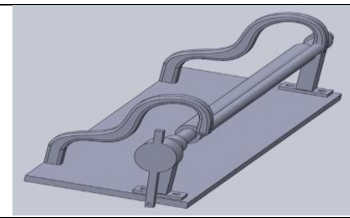
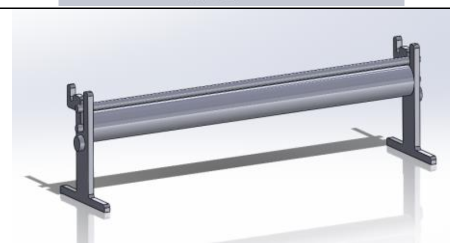
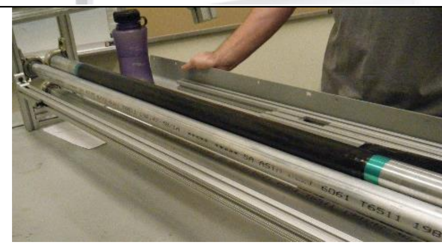
Design	Benefits	Issues	Figure
Mandrel Roller			
First		Complicated, hard to remove mandrel	
Second	Easy to remove mandrel, easy to add more weight		
Third	Comparable to rolling by hand, potential to make the process easier and faster than by hand		
By Hand	Works fairly well	Requires operator experience	

Table 1 (Continued): Comparison of design iterations.

Design	Benefits	Issues	Figure
Carbon Fiber Tube Removal			
Mechanical Jack	Quick reset	Requires precise machining	
Hydraulic Jack	Powerful, works	Very time consuming	
Grapeseed Oil / Mylar Liner	Works well, cheap, easy to use, easy to get, oil has high smoke point (can go in oven)		

The team decided that the aluminum extrusion jig, the third mandrel roller design, and the grapeseed oil/Mylar liner tube remover, were the designs that would be the most effective at meeting the maximum of our top requirements. The aluminum extrusion jig design was created and chosen as it is a middle ground between the expensive and machining intensive but accurate and easy to use Anvil jig and the hard to adjust but cheap and easy to make square aluminum extrusion jig.

At first the mandrels where rolled on a table surface by hand which initially produced tubes that were low quality including voids and folds, but as the operators became more experienced the tube quality increased dramatically with only occasional minor folding. The third mandrel roller design was chosen as our final tube rolling design. It produces tubes that are comparable to rolling by hand; the main benefits of the third design over rolling the tubes by hand is that it has the potential to make the process easier and faster than rolling the tubes by hand and also would not require the operator to be as experienced.

A wooden prototype was made of the mechanical jack carbon fiber tube remover. The benefit of the mechanical jack design was that it could be very quickly reset and that it could have a pushing rod long enough to push a whole tube out in one go. It was apparent however that the design was going to require a lot of precise machining. Next, a hydraulic jack design based on equipment already in the PSU machining lab was used to remove a full-size tube from a mandrel. The design provided the needed power but was very time consuming to use since the hydraulic jack only had a reach of about 6 inches and the tube was several feet long. After more research, grapeseed oil was used between the aluminum mandrel and the Mylar sheet before the carbon fiber was wrapped on the mandrel. The grapeseed oil acts as a lubricant to allow the finished tube to slide off the mandrel and has a high smoke point allowing it to go in the oven while the carbon fiber cures.

V. Final Design

The final design consists of several design components including the jig, tube roller system, mandrels, carbon fiber layup, tube compression, tube removal system, and mitering tooling. These will be individually discussed under the following sub-sections.

A. Jig

The bike frame jig is required to properly align the carbon fiber tubes for assembling the frame to the designed frame dimensions and geometry. The primary components of the jig were constructed using 80x20 extruded aluminum and aluminum L brackets as shown in Figure 1. Turned aluminum cones were used for retention of the head tube, seat tube and bottom bracket. The dropouts are secured by a machined aluminum "hub" section. Proper geometry is obtained by adjusting the height of the head tube cones, seat tube cone, bottom bracket cones, and drop out assembly as well as adjusting the distance and angle of the seat and head tube vertical supports. The proper angles are obtained by using an attached acrylic protractor and an inserted alignment indicator; the single protractor can slide and rotate to be used on both the seat and head tube supports. The design allowed for the jig to be securely attached to the tube roller system which provides a stable base while simplifying tooling configuration.

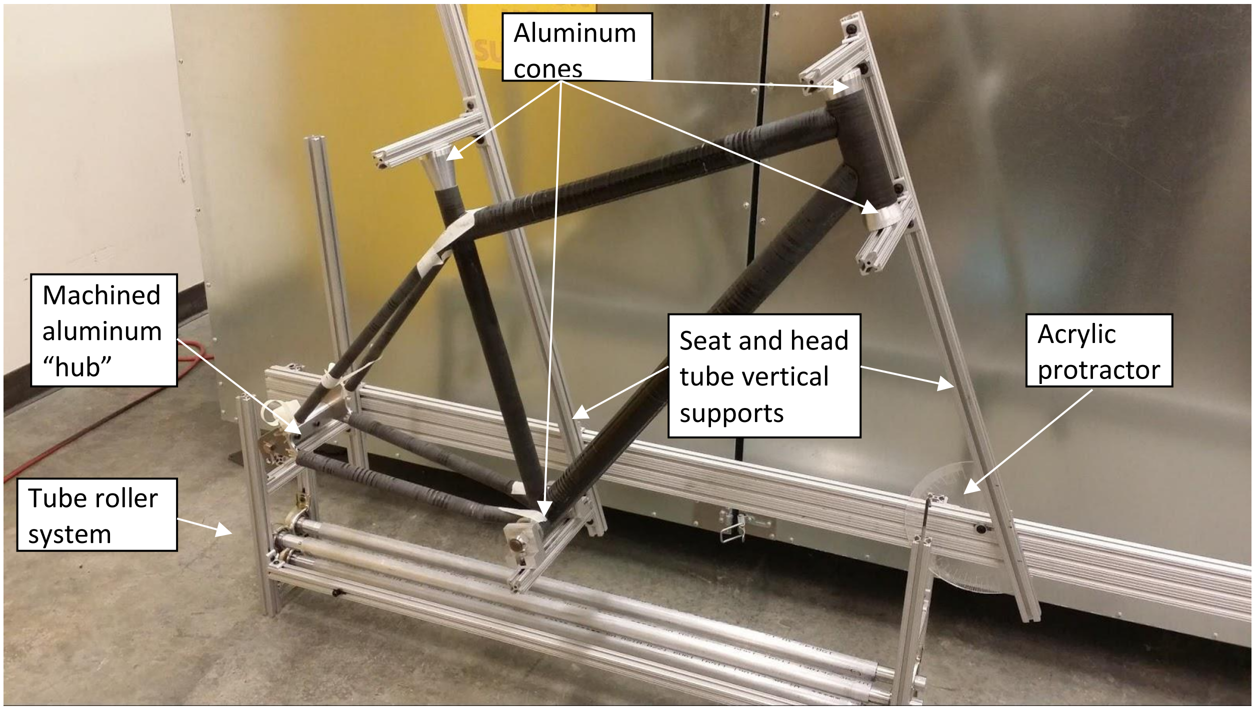


Figure 1 Bike frame jig constructed from extruded aluminum, aluminum L brackets, turned aluminum cones, and aluminum hub. The acrylic protractor is used to set the angles of the seat and head tube vertical supports. The tuber roller system acts as the jig stand and helps stabilize the system.

B. Tube Roller System

The tube roller system is designed to restrict jostling of the mandrels and applies pressure while wrapping the carbon fiber around the mandrels. The system is comprised of 80x20 extruded aluminum, bar stock, and bearings as shown in Figure 2. The mandrel is free to rotate when placed between the top two bars; the precut carbon fiber sheets are applied to the mandrel and wrapped while applying a downward pressure and rolling the mandrel. This setup also allows for stable and even application of the final layers of shrink tape. The current setup only utilizes the top two bars while the bottom bar would be used with future modifications to allow for automated pressure application and motorized rotation.

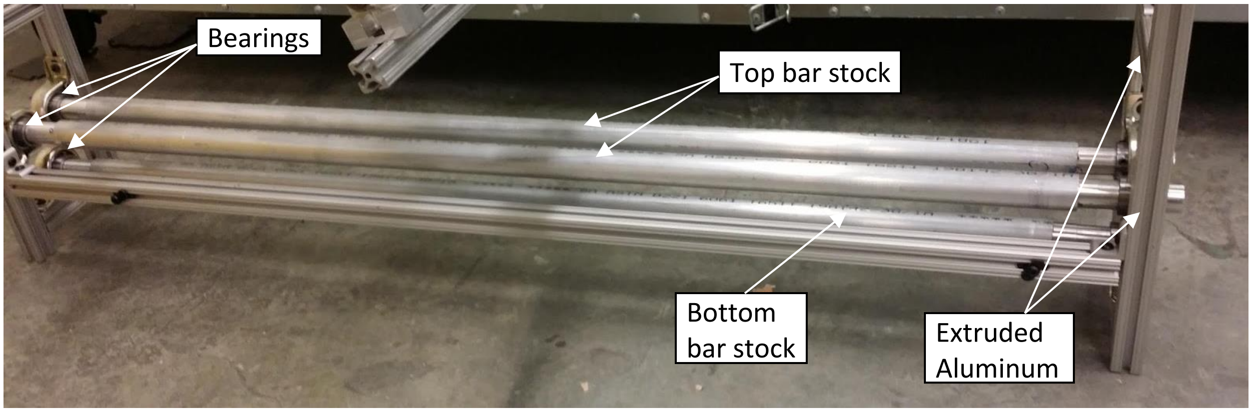


Figure 2 Tube roller system constructed with 80x20 extruded aluminum, aluminum bar stock and bearings.

C. Mandrels

The mandrels are bars/shafts that are used to wrap carbon fiber sheets for the formation of the carbon fiber tubes. Aluminum stock was primarily selected for its high level of thermal expansion coefficient which provides additional compression while curing the carbon fiber. The mandrels were cut and turned to satisfy lengths for larger bike frames and diameters to accommodate standard bike components. A total of seven mandrels were made with various diameters corresponding to each of the bike frame tubes.

D. Carbon Fiber Layup

Pre-impregnated carbon fiber sheets with carbon fibers running in the same direction (unidirectional) were selected for its ease of use and ability to control the fiber direction in layup. The design of the carbon fiber layup was determined based on industry documentation and experimental strain gauge testing to maximize the stiffness in tension, compression, bending, and torsion. See Appendix E for more about carbon fiber and layup design.

E. Tube Compression – Heat Shrink Tape, Vacuum and Bags

After the carbon fiber has been wrapped on the mandrel and before it is cured in the oven it is either wrapped with heat shrink tape or put in a vacuum bag. Both the vacuum bags and heat shrink tape apply pressure on the outside of the carbon fiber tube while the aluminum mandrel applies pressure on the inside of the tube as it heats and expands. This compression is very important to get a high-quality and strong composite as it compresses the layers of carbon fiber together so that they adhere to each other while curing.

Two types of tape were used to wrap the carbon fiber tubes. First a nonstick tape is applied to the rolled carbon fiber tubes. Next, thermal compression tape is wrapped around to compress the layers of carbon during curing. Once the mandrel is heated and the carbon is cured, the tape is removed and there is a glossy resin surface finish which often requires sanding.

The vacuum and bags are used after the tubes have been assembled into a frame and the joints have been wrapped with carbon fiber. The heat shrink tape is not effective to wrap joints so the whole frame is put in a vacuum bag for compression during curing.

F. Oven

The PSU rocket club's Rocket Airframe oven was used to cure the carbon fiber. It was set at a step rate of 1^{o}F/sec and a temperature of 270^{o}F with a hold time of 1 hour. (Note that the hold temperature was set at 230^{o}F to offset a 40 degree oven temperature setting error.) The carbon fiber that was used had different recommendations for the step rate but the oven control did not step any slower. The oven has a built in vacuum tube that was used with the vacuum bags when curing the joints of the frame.

G. Carbon Fiber Tube Removing System

To remove the cured carbon fiber tubes from the mandrels Mylar plastic is used as a barrier between the carbon and mandrel. Grapeseed oil is applied between the aluminum mandrel and Mylar plastic as a lubricant. This makes it easier to slide the carbon fiber tube off the mandrel. The tube typically can be pulled off by hand while other times the tube is wrapped with rubber and held in a vice to be pushed/tapped out. Grapeseed oil has a high heat tolerance with a smoke point of 420^{o}F – 428^{o}F (216^{o}C – 220^{o}C) and is cheap and readily available at grocery stores (Alfaro).

H. Mitering Tooling

The tube junctions on the frame were mitered using the Tube Shark Notcher, a tool used for mitering metal tubes and was adapted for our sanding application, as shown in Figure 3. Custom drum sanding bits were made to correspond with the base tube's outer diameter allowing a flush fit between the mitered tube and the base tube wall. Tubes to be mitered were fed into the Tube

Shark using self-centering right angle clamps into the sanding cylinders; the Tube Shark allows for easy adjustment of the sanding cylinders to the prescribed angles. The miters were cut by the tubes being fed against the revolving drum sander.

Figure 3 Tube Shark Notcher with custom dram sanding bits used to miter carbon fiber tubes.

VI. Product Design Specification (PDS) Evaluation

The criteria and evaluation for the elements of the project are shown in the following sections. All tooling was evaluated by constructing two different bicycle frames with different geometries in different sizes. Both frames were then built using standard components to evaluate tolerances and alignments.

A. Evaluation for Function and Performance

All tooling was made to accommodate bike frames of various sizes and multiple bike frame styles and geometries. Certain components of the tooling were not as accurate as we initially wanted; however, the process became more consistent during the iterations of tool design and tube making. The evaluation table and criteria are in Table 2.

Table 2: Evaluation for function and performance.

Evaluation for Function and Performance					
Requirements	**Priority**	**Metric**	**Target**	**Verification**	**Accomplished**
Custom Frame Size	***	Yes/No	Yes	Inspection	Yes
Custom Frame Geometry	***	Yes/No	Yes	Inspection	Yes
Tooling Consistency	***	Yes/No	Yes	Inspection	Yes
Tooling Accuracy	***	Yes/No	Yes	Inspection	No
Process Consistency	***	Yes/No	Yes	Inspection	Yes
Process Accuracy	***	Yes/No	Yes	Inspection	Yes

B. Evaluation for Structural Integrity

Large deflection and stress areas within the frame were analyzed using FEA software Abaqus (see Appendix F - FEA Analysis). The FEA model suggests that the areas of maximum stress are greatest in the upper tubes of the bike, especially on the top tube and the seat stays where they connect to the fixed head tube and rear drop outs. The maximum downward displacement occurs in the middle of the bike with the max at the top of the seat tube where the rider sits. A 250 pound rider performed a high-stress road test and impact test on the fully assembled bike frame and accessories including "bunny hops" and stepping on the bottom bracket to apply excessive torsion at the joint. The frame was ridden under more normal road conditions by approximately 20 riders in a row. During all testing the bike frame remained unaffected and did not show any signs of failure. The evaluation table and criteria are in Table 3.

Table 3: Evaluation for Structural Integrity.

Evaluation for Structural Integrity					
Requirements	**Priority**	**Metric**	**Target**	**Verification**	**Accomplished**
Seat Adjustment Clamps and Load Test (Gov. Reg.)	***	Pass/Fail	Pass	Inspection	Pass
Road Test (Gov. Reg.)	***	Pass/Fail	Pass	Inspection	Pass
Carbon Fiber Strain Testing	**	Yes/No	Yes	Testing	Yes
Carbon Fiber Strain Testing	**	Yes/No	Yes	Testing	Yes

C. Evaluation for Manufacturability and Assembly

All of the tools were made to be easy to assemble and to be easy to manufacture. All components of the tooling were made or were available on-site in the PSU engineering building. The evaluation table and criteria are in Table 4.

Table 4: Evaluation for Manufacturability and Assembly.

Evaluation for Manufacturability and Assembly					
Requirements	**Priority**	**Metric**	**Target**	**Verification**	**Accomplished**
Ease of Tooling Assembly	*	Yes/No	Yes	Inspection	Yes
Tool Manufacturing Facilities (PSU or "off-the-shelf")	**	Yes/No	Yes	Inspection	Yes

D. Evaluation for Cost and Financial Performance

The materials to build a standard road bike frame cost approximately $125/frame which is well within our target of $1500/frame. The total amount of money spent on the project was $2187.10 which was within our total budget of $3500. See Table 5 for the criteria and evaluation.

Table 5: Evaluation for Cost and Financial Performance.

Evaluation for Cost and Financial Performance					
Requirements	**Priority**	**Metric**	**Target**	**Verification**	**Accomplished**
Cost of Process Development	***	$	<3,500	Budget	Yes
End-Use Frame Manufacturing	**	$	<1,500	Bill of Materials	Yes

E. Evaluation for Safety and Ergonomics

All sharp corners on the tooling were rounded. Tools were designed to be stable and to rotate smoothly without pinch spots. Tooling was made considering ergonomics and ease of use, but fell short of our general goal in some components of the process. The jig requires one person to loosen up to four bolts at a time while another person holds the bracket so that the length or angle of the fixture can be adjusted. This causes inaccuracy in the adjustment of the jig and makes tolerancing and alignment more difficult. Another iteration of the jig using components that are more precise would solve this problem. See Table 6 for an evaluation of the safety and ergonomics.

Table 6: Evaluation for Safety and Ergonomics.

Evaluation for Safety and Ergonomics					
Requirements	**Priority**	**Metric**	**Target**	**Verification**	**Accomplished**
Easy to Follow Production Process	***	Yes/No	Yes	Inspection	Yes
Minimal Effort Tooling Adjustment	***	Yes/No	Yes	Inspection	No
Ergonomic Safety	***	Yes/No	Yes	Inspection	Yes
Frame Integrity (Government Regulations)	***	Pass/Fail	Pass	Testing	Pass
Fork and Frame Test (Gov. Reg.)	***	Pass/Fail	Pass	Testing	Pass

F. Evaluation for Material and Mobility

The only location on the carbon fiber frame that was directly near metal was where the chain stays and seat stays slid onto the aluminum dropouts. In these locations the aluminum was fully covered with epoxy and putty to protect the carbon fiber. The frame weighed 1081 grams which was 57 grams heavier than an industry standard monocoque carbon fiber frame (which are generally lighter weight). See Table 7 for the evaluation for the material and mobility.

Table 7: Evaluation for Material and Mobility.

Evaluation for Material and Mobility					
Requirements	**Priority**	**Metric**	**Target**	**Verification**	**Accomplished**
Carbon Fiber	***	Yes/No	Yes	Design	Yes
Zero Direct Carbon Fiber to Metal Contact Points	***	Yes/No	Yes	Inspection	Yes

G. Evaluation for Maintenance

None of the tooling requires maintenance. Since lubricant, putty, and epoxy are used around the tooling and may splatter or drip on the tooling, routine cleaning will be necessary. Table 8 evaluates the maintenance criteria.

Table 8: Evaluation for Maintenance.

Evaluation for Maintenance					
Requirements	**Priority**	**Metric**	**Target**	**Verification**	**Accomplished**
Only Routine Cleaning	*	Yes/No	Yes	Inspection	Yes

VII. Conclusion and Recommendations

The project met all of the main PDS requirements and the tooling successfully made multiple, usable bike frames. The frames were comparable to industry carbon fiber frames in weight and were potentially very competitive in price. The main problems with the tooling and process were that certain tools such as the jig were not accurate enough which caused tolerance and alignment issues in the frame. If there were time to do another iteration of the jig, this problem could be greatly reduced by making a more precise jig requiring additional cost and machining. The tube roller design was comparable to an experienced work person rolling the tubes by hand on a table top. The benefit of the tube roller is that it allows for potential improvement that would make the tube rolling process more consistent and even. It would also allow the tube rolling process to be motorized. Again, additional time would have allowed the ability to experiment with design iterations and revisions to incorporate these improvements.

The project was very successful and the team was impressed with the structural integrity, lightness, and low cost of the frames. Each member of the team gained the knowledge and experience of composites, process design and improvement, teamwork, and problem solving. We hope that this project will inspire future students at PSU to use and improve upon our design and to incorporate carbon fiber into more projects to further build the knowledgebase of composites at PSU.

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VIII. Appendix

A. Detailed Description of Final Design (3D Assembly Figures)

The following are examples of 3D CAD drawings created in the design process.

Figure A.1 Road Bike Frame Design.

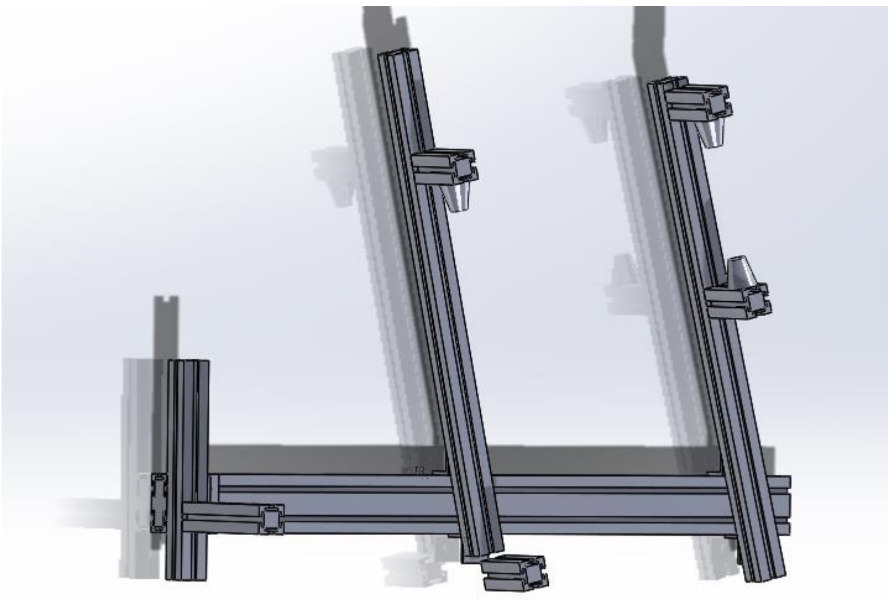


Figure A.2 Final bike frame jig design.

Figure A.3 Final carbon fiber tube roller system design.

B. Bill of Materials

Table B.1: Carbon fiber bike tooling bill of materials (BOM)

Part Number	Descritption	Vendor	Item #	Cost ($)	Units	Qty	Cost per unit ($)
CFB-00001-001	T-Slotted extrusion, 10S, 97 Lx1 in, 80/20	Grainger	2RCP9	$38.60	inch	97	$0.40
CFB-00002-001	Inside Corner Bracket, 2 Hole, for 10S	Grainger	2RCW6	$5.41	each	1	$5.41
CFB-00003-001	BHSCS & T-Nut, for 10S, PK15	Grainger	2UWP8	$11.19	each	15	$0.75
CFB-00004-001	Washer	Portland State University	NA		donated		$0.00
CFB-00005-001	Pillow Block Bearing, 1 in. Bore	Grainger	2X900	$20.16	each	1	$20.16
CFB-00006-001	AL 6061T6 plate, 0.190 in.	Metal Supermarkets	NA	$0.15	square inch	1	$0.15
CFB-00007-001	AL round 6061T6 0.625 in	Metal Supermarkets	NA	$0.18	inch	1	$0.18
CFB-00008-001	AL round 6061T6 0.875 in	Metal Supermarkets	NA	$0.34	inch	1	$0.34
CFB-00009-001	AL round 6061T6, 1.000 in	Metal Supermarkets	NA	$0.47	inch	1	$0.47
CFB-00010-001	AL round 6061T6, 1.250 in	Metal Supermarkets	NA	$0.73	inch	1	$0.73
CFB-00011-001	AL round 6061T6, 1.500 in	Metal Supermarkets	NA	$1.09	inch	1	$1.09
CFB-00012-001	AL round 6061T6, 1.750 in	Metal Supermarkets	NA	$1.48	inch	1	$1.48
CFB-00013-001	AL round 6061T6, 2.000 in	Metal Supermarkets	NA	$1.80	inch	1	$1.80
CFB-00018-001	Extrusion, T-Slot, 10S, 145 In L, 1 in W, 3 channel	Grainger	5JTC6	$146.00	inch	145	$1.01
CFB-00032-001	Unidirectional Carbon Fiber	Rockwest	14002-D	$37.99	roll	1	$37.99
CFB-00033-001	Epoxy, dp-420	Rockwest	1016	$30.99	ml	37	$0.84
CFB-00034-001	Free Form AIR	Amazon/Smooth-On Inc	Trial Unit	$25.00	lb	2	$13.89
CFB-00035-001	Stage 1 compression tape	Rockwest	1536-D	$14.99	roll	1	$14.99
CFB-00036-001	Stage 2 compression tape	Rockwest	1538-D	$19.99	roll	1	$19.99
CFB-00037-001	Breather fabric, resin sponge	Rockwest	3011-D	$7.99	square ft	15	$0.53
CFB-00042-001	Vacuum bag film	Rockwest	3014-D	$3.79	square ft	18	$0.21
CFB-00043-001	Teflon fabric release ply	Rockwest	3013-D	$18.99	square ft	15	$1.27
CFB-00044-001	Chromate tape	Rockwest	3009-D	$9.99	roll	1	$9.99
CFB-00045-001	3M high temp tape	Rockwest	8992-075	$10.99	roll	1	$10.99

Table B.2: Carbon fiber tube roller tooling bill of materials (BOM) and cost

Carbon Fiber Bike Roller							
Part Number	Descritption	Vendor	Item #	Cost ($)	Units	Qty	Cost per unit ($)
CFB-00002-001	Inside Corner Bracket, 2 Hole, for 10S	Grainger	2RCW6	5.41	each	8	$43.28
CFB-00003-001	BHSCS & T-Nut, for 10S, PK15	Grainger	2UWP8	$0.75	each	25	$18.65
CFB-00005-001	Pillow Block Bearing, 1 in. Bore	Grainger	2X900	20.16	each	6	$120.96
CFB-00014-001	18 in Vertical Support, 80/20 T-slotted extrusion	Portland State University	CFB-00001-001	$7.16	each	4	$28.65
CFB-00015-001	4.5 in Horizontal Support, 80/20 T-Slotted extrusion	Portland State University	CFB-00001-001	$1.79	each	4	$7.16
CFB-00016-001	6 in AL round 6061T6 1 in, bearing to roller press fit	Portland State University	CFB-00009-001	$2.83	each	6	$16.99
CFB-00017-001	42 in AL round 6061T6 1 in, roller	Portland State University	CFB-00009-001	$19.82	each	3	$59.47
						Carbon Fiber Roller Total	$295.17

Table B.3: Carbon fiber bike frame assembly tooling bill of materials (BOM) and cost

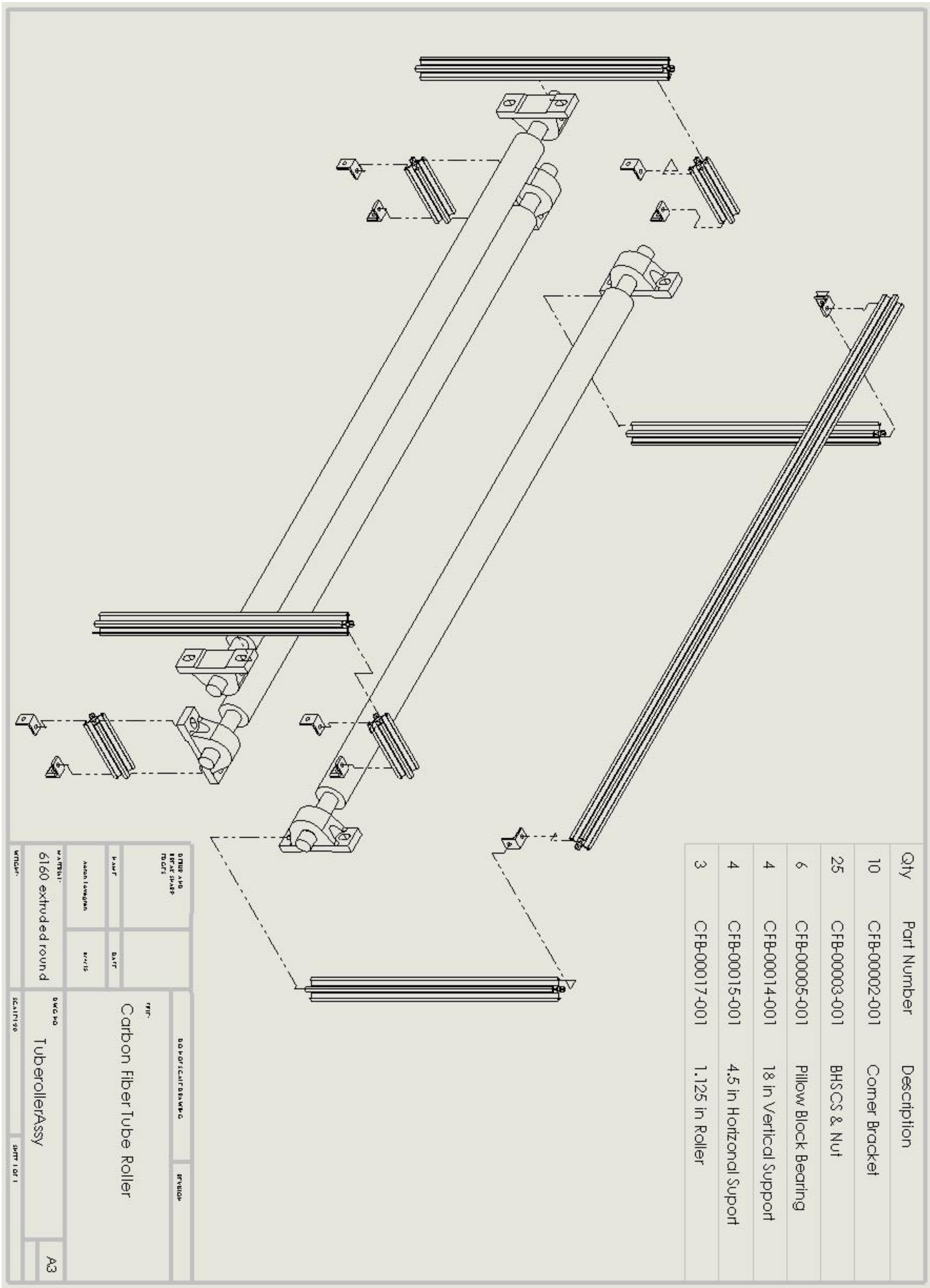
Carbon Fiber Bike Jig							
Part Number	Descritption	Vendor	Item #	Cost ($)	Units	Qty	Cost per unit ($)
CFB-00002-001	Inside Corner Bracket, 2 Hole, for 10S	Grainger	2RCW6	$5.41	each	20	$108.20
CFB-00003-001	BHSCS & T-Nut, for 10S, PK15	Grainger	2UWP8	$0.75	each	40	$29.84
CFB-00018-001	Extrusion, T-Slot, 10S, 145 In L, 1 in W, 3 channel	Grainger	5JTC6	$1.01	inch	72	$72.50
CFB-00019-001	10 in cross bar, 80/20 T-slotted extrusion	Portland State University	CFB-00001-001	$3.98	each	5	$19.90
CFB-00020-001	36 in vertical support, 80/20 T-slotted extrusion	Portland State University	CFB-00001-001	$14.33	each	2	$28.65
CFB-00021-001	25 in dropout vertical support, 80/20 T-slotted extrusion	Portland State University	CFB-00001-001	$9.95	each	1	$9.95
CFB-00022-001	Bottom Bracket alignment tool	Portland State University			Donated		$0.00
CFB-00023-001	Drop-out alignment tool	Portland State University			Donated		$0.00
CFB-00024-001	Vertical tube Protractor	Portland State University			Donated		$0.00
						Carbon Fiber Bike Jig Total	$269.03

Table B.4: Carbon fiber tube mandrel materials list and cost.

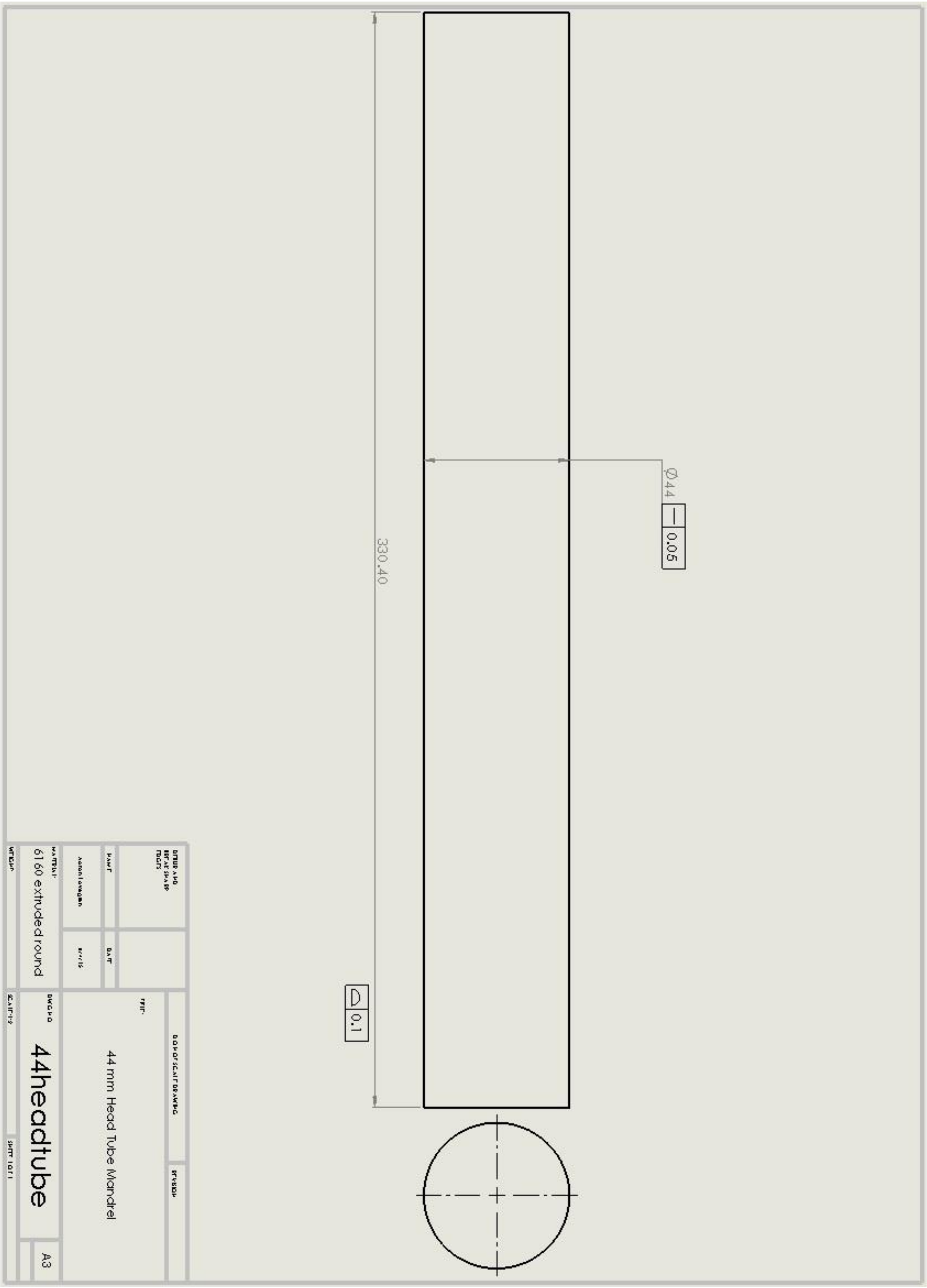
Carbon Fiber Tube Mandrel							
Part Number	Descritption	Vendor	Item #	Cost ($)	Units	Qty	Cost per unit ($)
CFB-00025-001	Seat Stay Mandrel, 0.6325 in AL round extruded 6061T6	Portland State University	CFB-00007-001	$0.18	inch	30	$5.48
CFB-00026-001	Chain Stay Mandrel, 0.875 in AL round extruded 6061T6	Portland State University	CFB-00008-001	$0.34	inch	30	$10.12
CFB-00027-001	44 mm Head Tube Mandrel, AL round extruded 6061T6	Portland State University	CFB-00013-001	$1.80	inch	13	$23.46
CFB-00028-001	41 mm Bottom Bracket Mandrel, AL round extruded 6061T6	Portland State University	CFB-00013-001	$1.80	inch	16	$28.88
CFB-00029-001	31.5 mm Seat Tube Mandrel, AL round extruded 6061T6	Portland State University	CFB-00012-001	$1.48	inch	42	$62.03
CFB-00030-001	Down Tube Mandrel, AL round extruded 6061T6	Portland State University	CFB-00018-001	$1.80	inch	40	$72.19
CFB-00031-001	Top Tube Mandrel, AL round extruded 6061T6	Portland State University	CFB-00012-001	$1.48	inch	40	$59.07
						Carbon Fiber Mandrel Total	$261.23

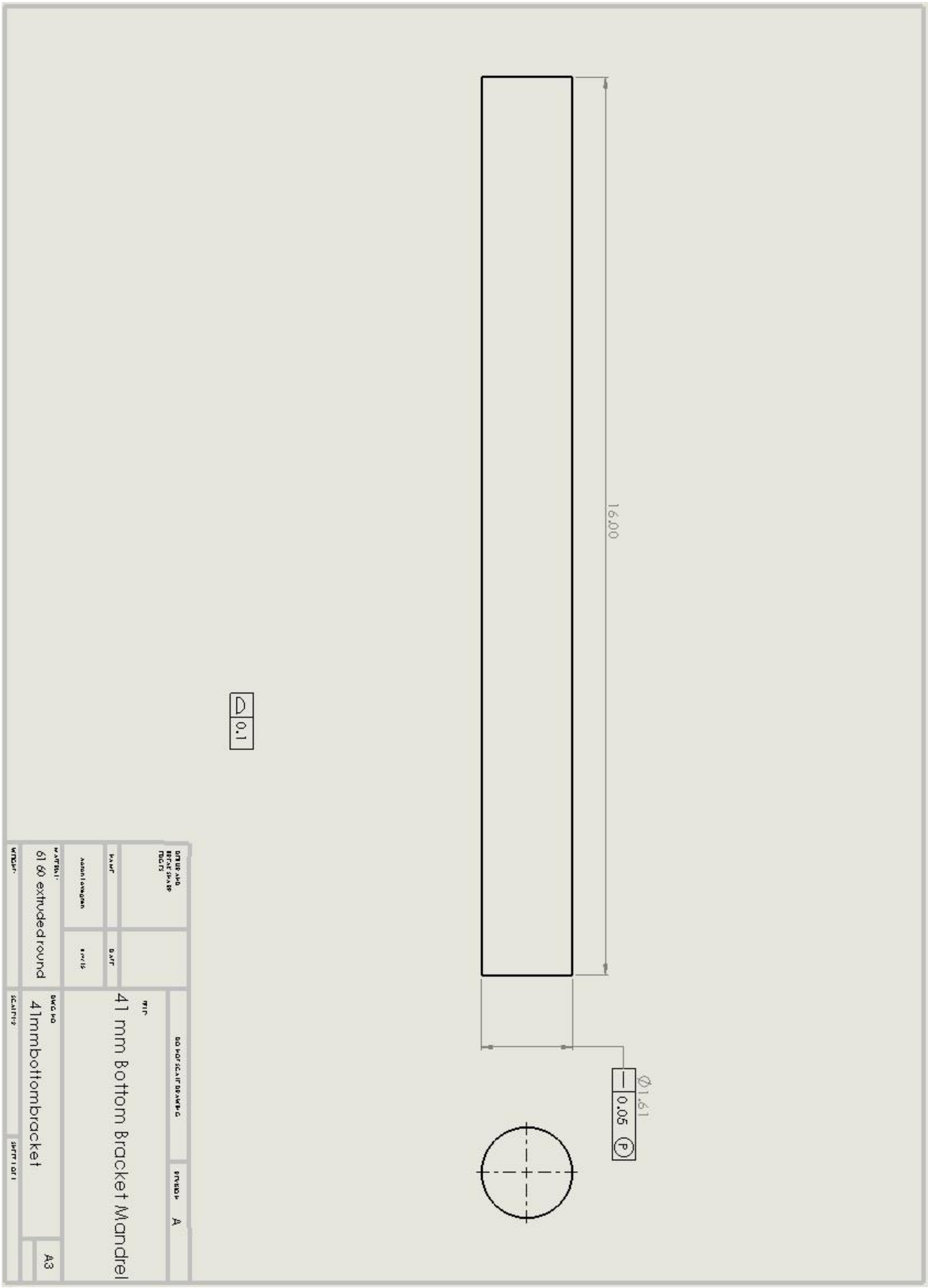
C. Production Drawings

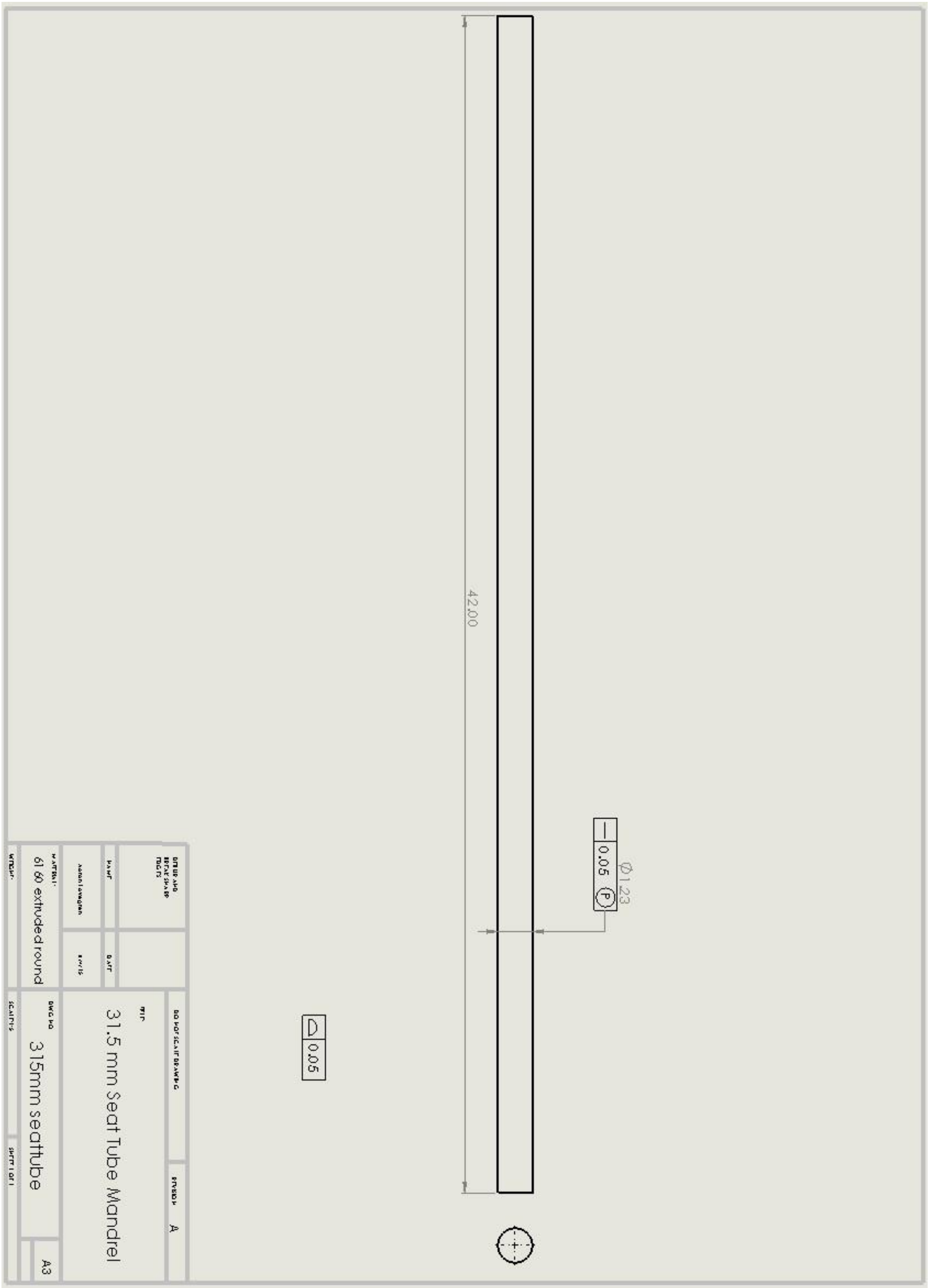
a. Carbon Fiber Tube Roller Assembly



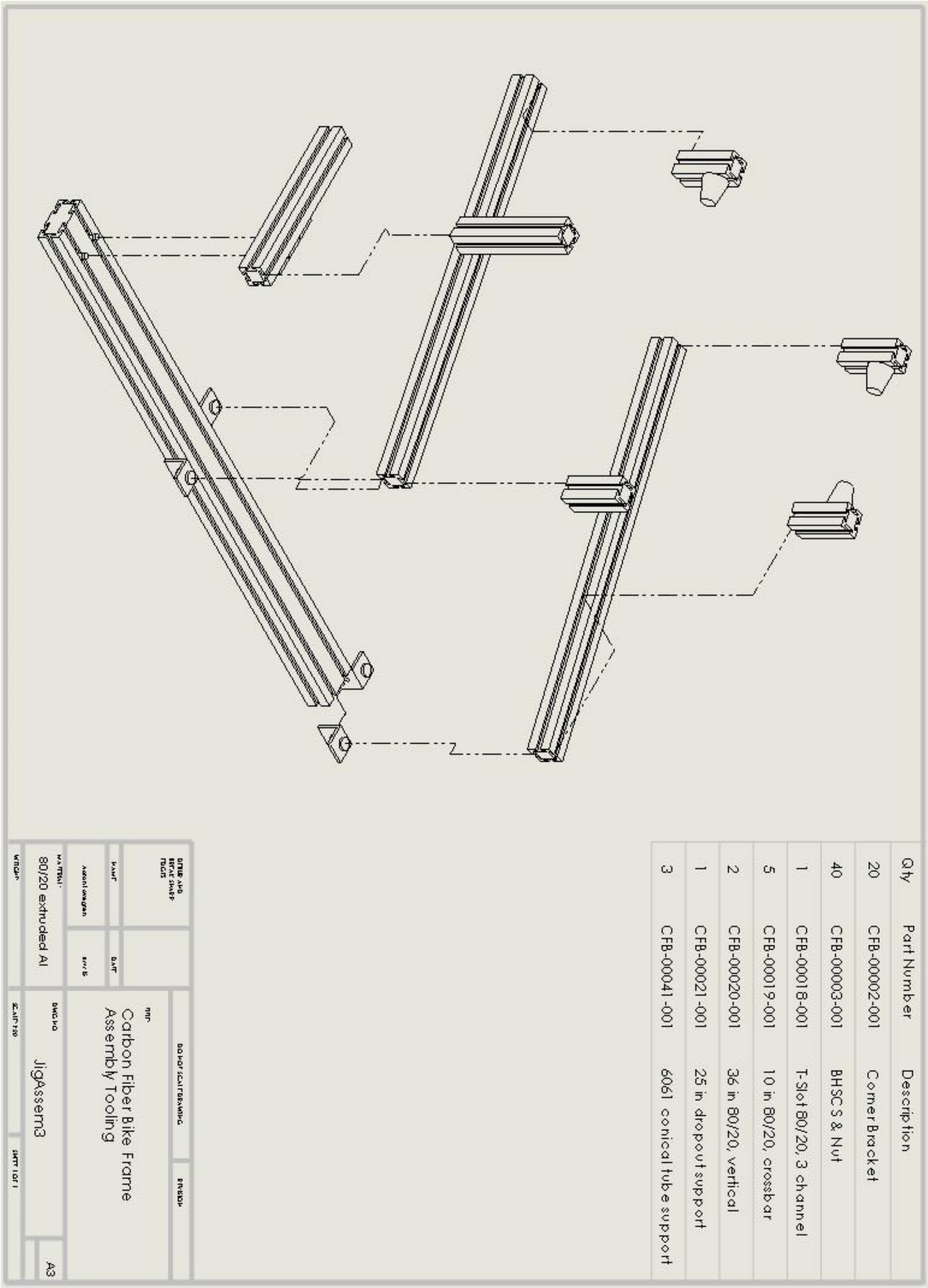
b. Mandrels


330.40
Ø44
0.05
0.1
6160 extruded round
44 mm Head Tube Mandrel
44headtube
A3


16.00
Ø1.61
0.05
0.1
41 mm Bottom Bracket Mandrel
41mmbottombracket
6160 extruded round
A
A3


42.00
Ø1.23
0.05 P
0.05
31.5 mm Seat Tube Mandrel
315mm seattube
6160 extruded round
A
A3

c. Carbon Fiber Tube Assembly Tooling



D. Equations

a. Volumetric thermal expansion:

The volumetric thermal expansion of a material is determined by

$$\frac{\Delta V}{V} = \int_{T_i}^{T_f} \alpha_V(T)\, dT$$

where α_v is the volumetric thermal expansion coefficient. The thermal expansion coefficient of the aluminum mandrels was an important factor in contributing to the compression of the carbon fiber during the curing process. The actual value, however, was not necessary to obtain as the compression forces of the shrink tape on the outer layer where unknown therefore the actual expansion of the aluminum could not be determined.

b. Carbon fiber cut dimensions:

Each of the tubes require individual calculations to determine the total length and width of carbon fiber sheets dependent on the desired tube length, mandrel diameter, and angle of wrap needed. The sheet and cut geometry is shown in Figure D.1.

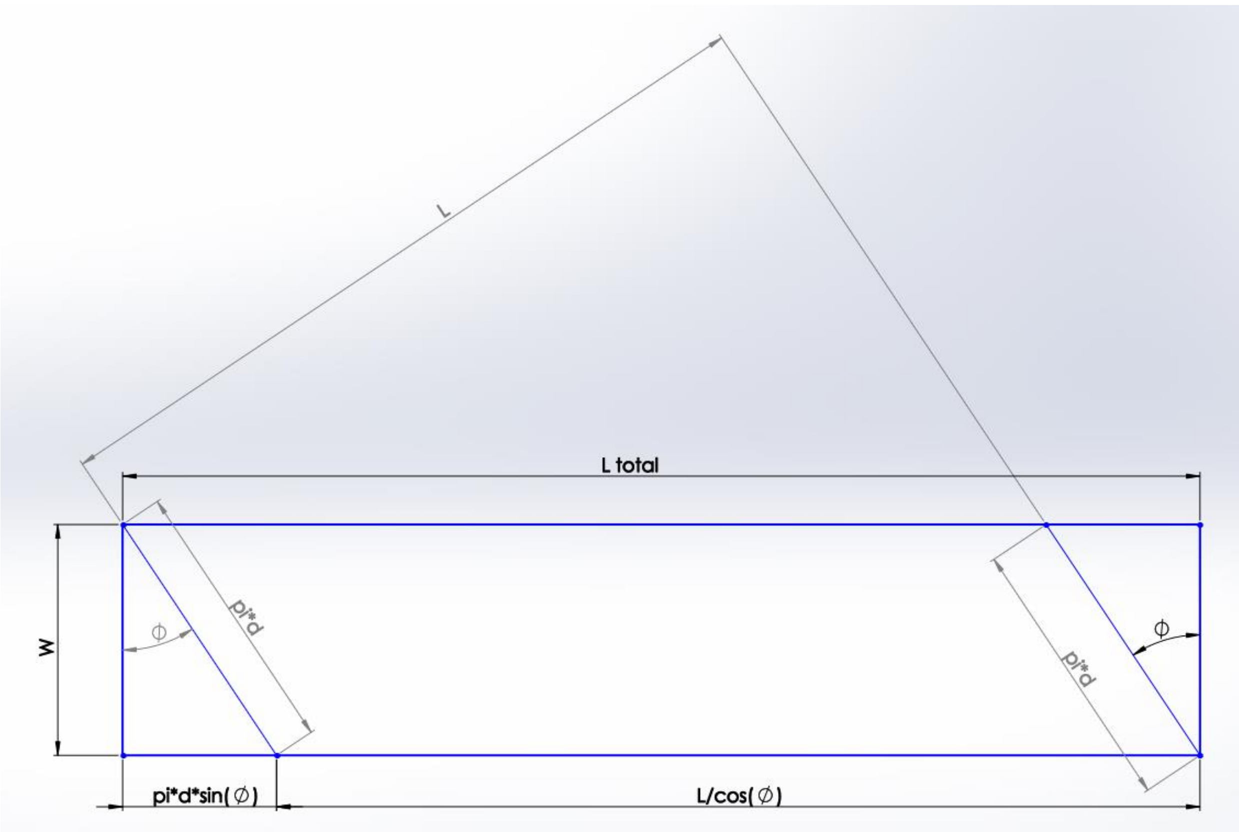


Figure D.1 Sheet and cut geometry for various tube lengths, diameters, and wrap angles.

The total length *L total* and the width *W* for the various sheet dimensions are calculated by

$$L\ total = \frac{L}{\cos(\emptyset)} + (\pi d)\sin(\emptyset)$$

$$W = (\pi d)cos(\emptyset)$$

where

$$L = desired\ tube\ length$$

$$d = mandrel\ diameter$$

$$\emptyset = wrap\ angle\ (i.e.\ 22.5° \ or\ 45°)$$

Examples of dimensions used accommodate most bike frame sizes are shown in Figure D.2. Based on mandrel sizes manufactured at Portland State University, dimensions are calculated and shown in Table D.1. An additional 20 mm of added material to the widths accounts for diameter growth from additional carbon fiber layers and to ensure complete wrapping around the mandrel for each layer of the tube.

UNITS	SIZE	TTH	STA	HTA	RC	FC	WB	FL	OF	BBH	SO	HT	BBS	FD	STACK	REACH
inches	16	22.5	74°	68.5°	17.3	26.2	43.3	19.9	1.9	12	30.7	4.3	73mm	34.9mm	24.3	15.5
inches	18	23.5	74°	70°	17.3	26.6	43.8	19.9	1.9	12.2	32.1	4.7	73mm	34.9mm	24.8	16.3
inches	19	24	73°	70°	17.3	26.7	43.8	19.9	1.9	12.2	32.7	5.1	73mm	34.9mm	25.1	16.3
inches	20	24.5	73°	71°	17.3	26.8	43.9	19.9	1.9	12.2	33.4	5.5	73mm	34.9mm	25.7	16.6
inches	22	25.5	73°	72°	17.3	27.4	44.5	19.9	1.9	12.2	34.8	6.3	73mm	34.9mm	26.6	17.4

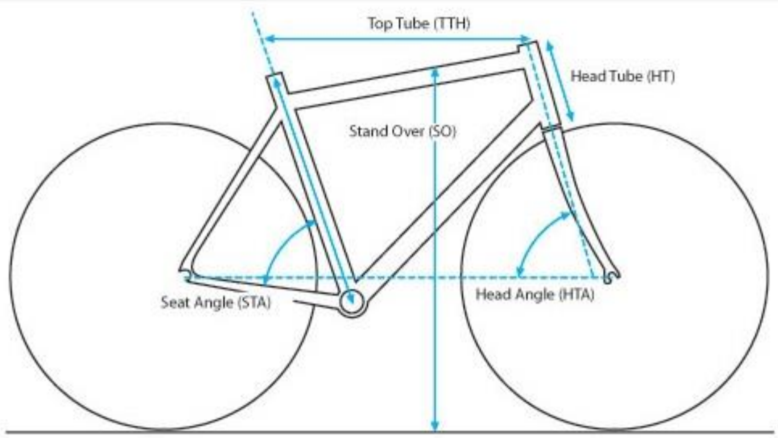


Figure D.2: Bike frame tube size and geometry shown is one possible configuration. Setups will vary based on bike use.

Table D.1 Example of calculated dimensions for sample lengths and diameters.

		total length = length/cos(angle)+pi*d*sin(angle)					
						w = pi*d*cos(angle)	
	dimensions		**cuts**				
			qty	**angle**	**total length**	**width**	**width**
top tube						(must add ~20 mm)	(w/ 20 mm)
length	700		1	90	700.0	124.1	144.1
Diameter	39.5		3	0	700.0	124.1	144.1
			2	45	1077.7	87.7	107.7
			2	22.5	805.2	114.6	134.6
Seat tube							
length	700		1	90	700.0	101.8	121.8
Diameter	32.4		3	0	700.0	101.8	121.8
			2	45	1061.9	72.0	92.0
			2	22.5	796.6	94.0	114.0
Down tube							
length	900		1	90	900.0	142.0	162.0
Diameter	45.2		3	0	900.0	142.0	162.0
			2	45	1373.2	100.4	120.4
			2	22.5	1028.5	131.2	151.2
Seat Stay							
length	700		1	90	700.0	50.2	70.2
Diameter	15.99		3	0	700.0	50.2	70.2
			2	45	1025.5	35.5	55.5
			2	22.5	776.9	46.4	66.4
Cain Stay							
length	700		1	90	700.0	70.0	90.0
Diameter	22.28		3	0	700.0	70.0	90.0
			2	45	1039.4	49.5	69.5
			2	22.5	784.5	64.7	84.7
Head Tube							
Length	250		4	90	250.0	137.3	157.3
Diameter	43.7		4	0	250.0	137.3	157.3
Bottom Bracket							
Length	150		4	90	150.0	127.9	147.9
Diameter	40.7		4	0	150.0	127.9	147.9

E. Carbon Fiber Information

When considering carbon fiber, three criteria are the most critical: the weave, the resin, and the type of carbon fiber. Each were deemed equally important. Consideration was given to the focus of the Capstone project: design tooling to produce a low cost carbon fiber bike frame. The tooling to develop a bike frame being the primary deliverable it was agreed the simplest and most repeatable carbon fiber layup process should be considered. No resin application meant pre-impregnated carbon fiber. Unidirectional fibers would allow the layup of the frame to be controlled more precisely. Each layer of carbon fiber could be rotated in a direction for greatest strength. The type of carbon fiber would simply need to be the cheapest, strongest available on the market; selection options for carbon fiber selection based on strength and modulus are shown in Figure .

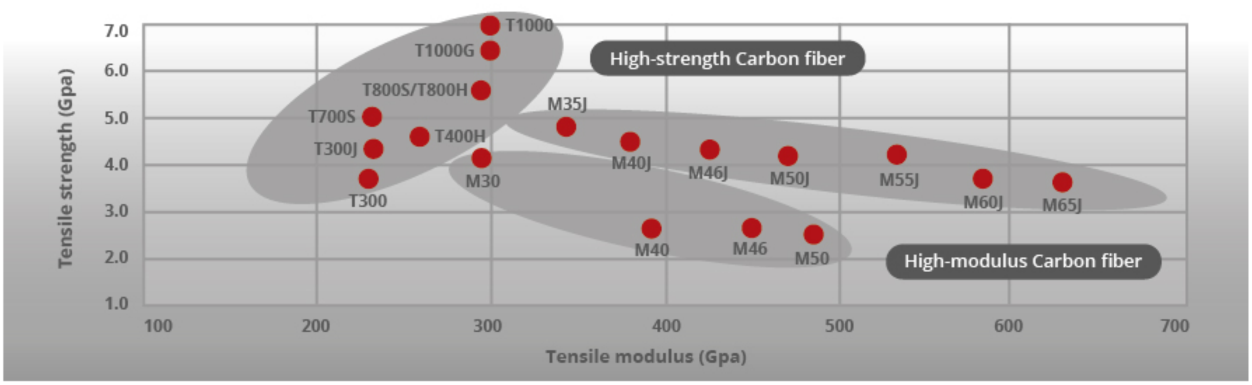


Figure E.1: Carbon fiber tensile strength comparted to tensile modulus; various carbon fiber options are shown based on strength and modulus. Units are in GPa.

Carbon Fiber and Bike Frame

When considering the strength of a bike tube in compression, bending, and torsion the layup of the carbon fiber is the most critical criteria; an example of carbon fiber layup is shown in Figure E.2. Each layer adds strength in the axis of fiber orientation. For this Capstone project we are testing and considering two layups for each frame part both were acquired from Basso Bike technical specifications of their Leguna Frame (Racing, 2015). The head tube and down tube will use a 1x0°, 1x22°, 2x45° layup; the seat tube and top tube will use 2x0° and 3x45° layup. Testing will be done on tubes four inches in length that are subjected to axial, bending, and torsional stresses.

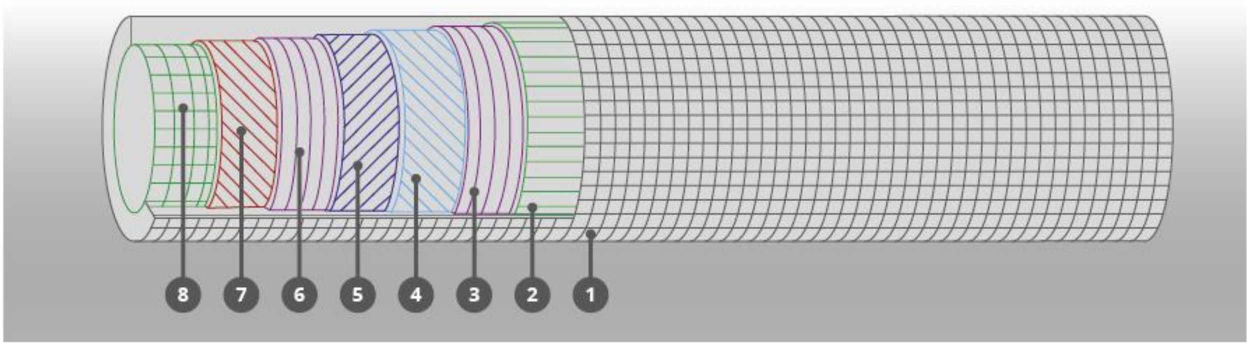


Figure E.2: Carbon fiber layup example showing orientation of layers. The image shows a total of 8 layers of varying carbon fiber directional layup. Image from Velocite (Velocite, 2015).

F. FEA Analysis

A simple model of a bike frame has been made in the finite element analysis software Abaqus. The Von Mises stress on the model are shown in Figure . Loads were applied to the top of the seat tube, the head tube, as well as the bottom bracket. The head tube and both rear dropouts were fixed by containing them in the x, y, and z translational directions. Thus far the model suggests that the areas of maximum stress are greatest in the upper tubes of the bike, specifically on the top tube and the seat stays where they connect to the fixed head tube and rear drop outs respectively.

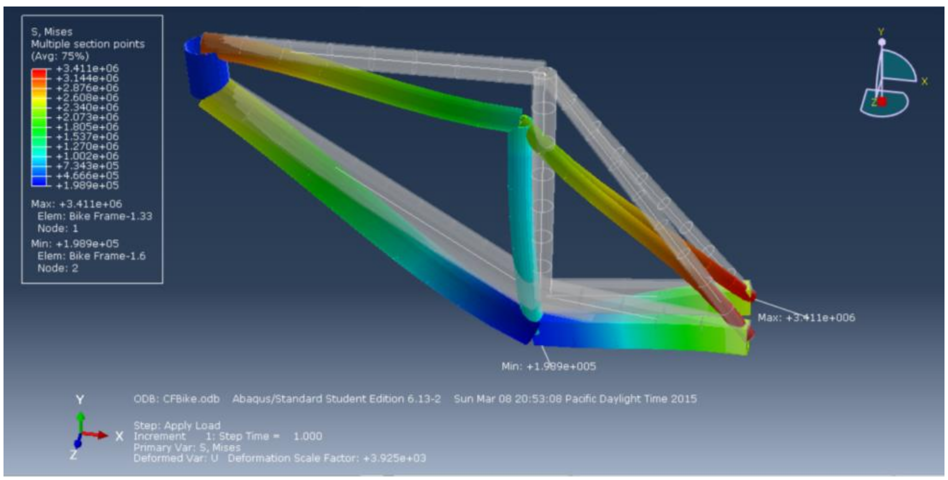


Figure F.1: Simple model of Von Mises stress contours plotted on deformed bike frame and non-deformed bike frame using finite element analysis software, Abaqus.

The deflection in the y-direction (U2) is plotted on the non-deformed frame and compared to the deformed shape as shown in Figure F.2. The maximum downward displacement (minimum magnitude) occurs in the middle of the bike (blue) with the max at the top of the seat tube where the rider sits.

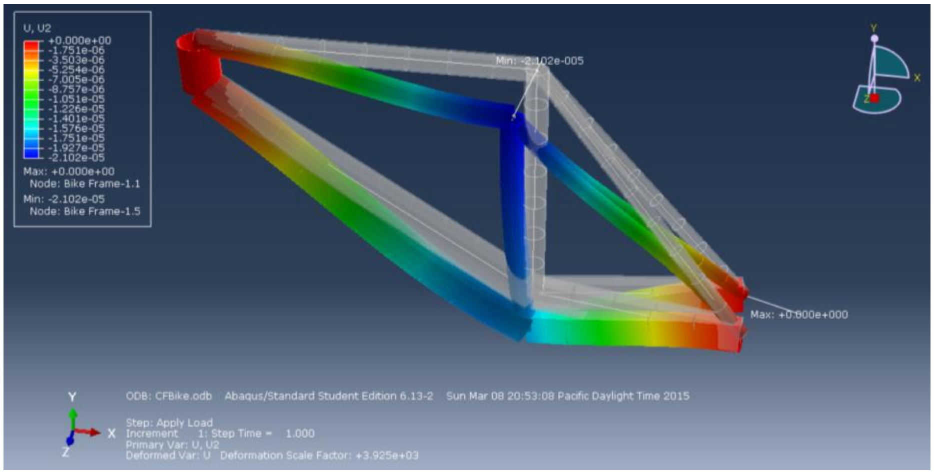
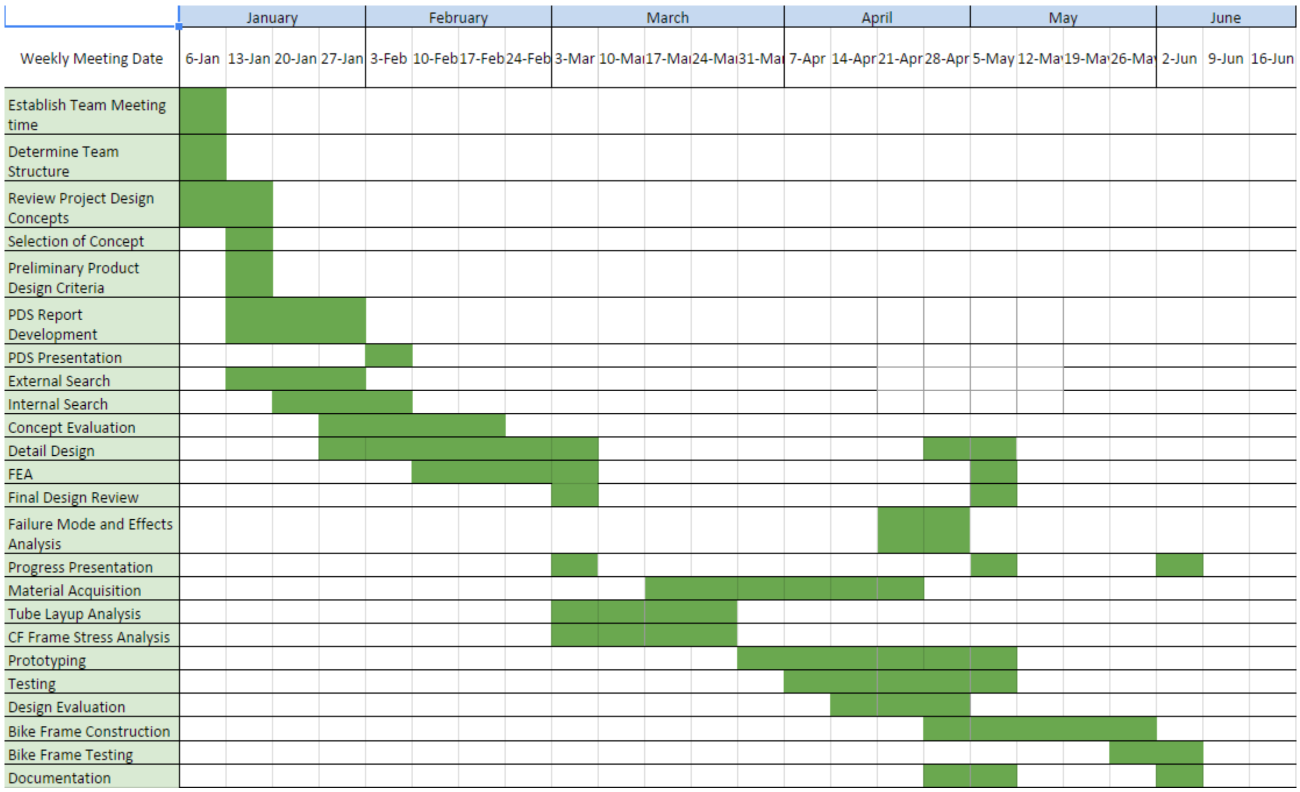


Figure F.2: Simple model of y-direction (U2) displacement plotted on deformed bike frame and non-deformed bike frame using finite element analysis software, Abaqus.

Areas to improve the model include assigning a different modulus of elasticity for each layup direction as opposed to one modulus elasticity for the 0^{o} angle direction, and determining more accurate magnitudes of force to apply to the frame. The model can be altered to test the difference in stress and deflection for different tube diameters, lengths, and angles.

G. Project Gantt Chart



H. Equipment Manual

ASME PSU Carbon Fiber Frame Capstone Group

Work Instructions Carbon Fiber Frame

How to use tooling developed at PSU to build a carbon fiber bike frame

Revision A
6-4-2015

Purpose

This section provides instructions for making tubes with the tube roller.

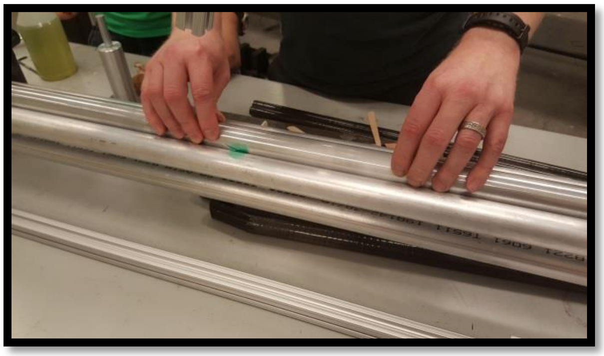
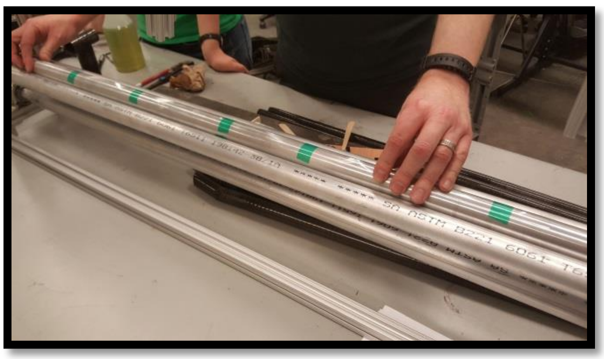
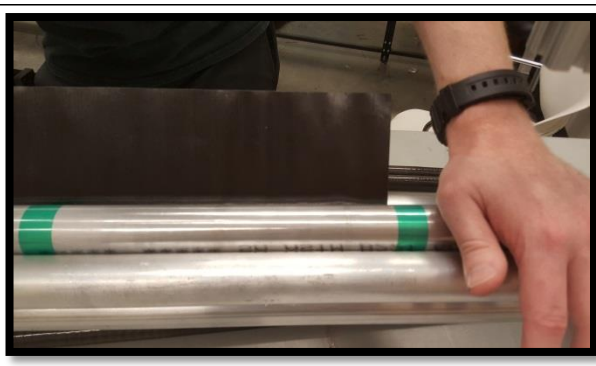
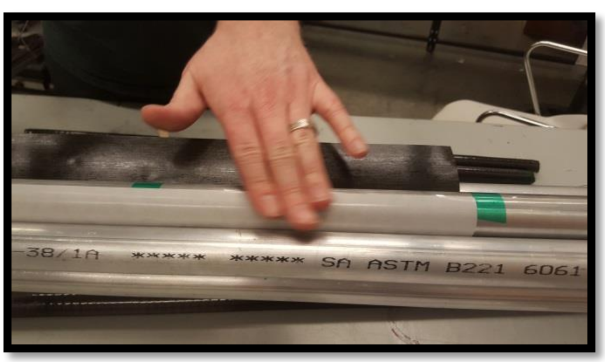
Tools, Fixtures, Material

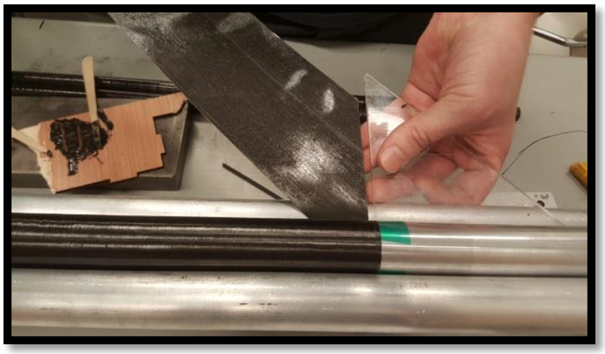
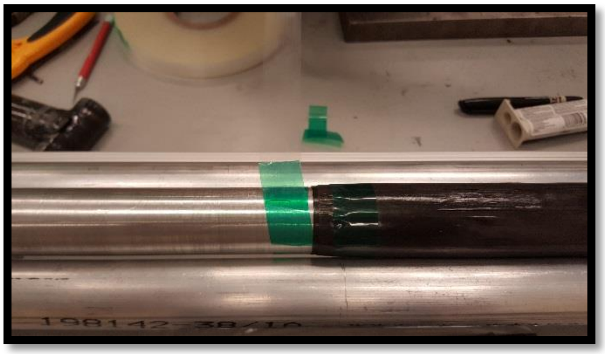
- Pre-Impregnated Carbon Fiber
- Cutting Tool
- Stencils
- Tube Roller
- Mylar
- High Smoke Point Oil (Example: Grapeseed Oil)
- Tape
- Release Tape
- Heat Shrink Tape

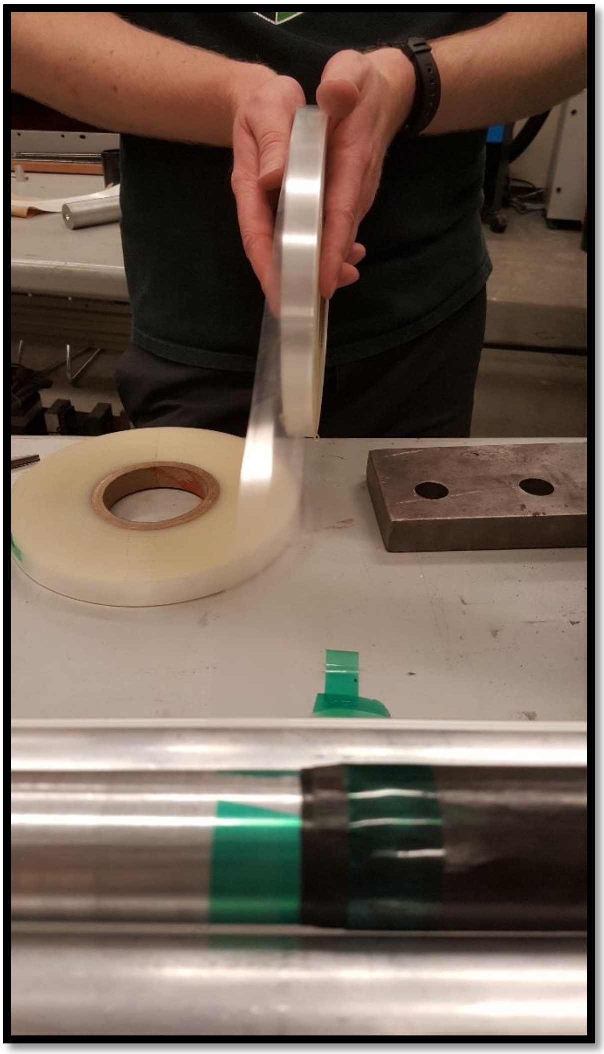
Safety Requirements

- Nitrile gloves (Optional)

Instructions

See Table	1. Cut the layup using 2. Table as a length guide for your tube and using the appropriate stencils.
See Table 2	3. Cut Mylar using Table 2 for lengths.
	4. Place the Mylar on the tube roller, and the mandrel on the Mylar.
	5. Oil the mandrel/Mylar contact surface, and wrap and secure the Mylar with tape. Note: Avoid getting oil on the outside of the Mylar
 	6. Wrap the layup around the mandrel. Note: Avoid poor contact with the mandrel and carbon fiber by pressing and messaging the carbon fiber onto the mandrel.

	
	7. On the roller, tape and wrap release tape around the carbon fiber. Tape both ends to secure it. Note: Release tape doesn't have the yellow hue that heat shrink tape has. 8. On the roller, tape and wrap heat shrink tape around the release tape. Tape both ends to secure it. Note: Maintain light tension, and ensure tape is overlapping while wrapping. Additional photos on the next page.



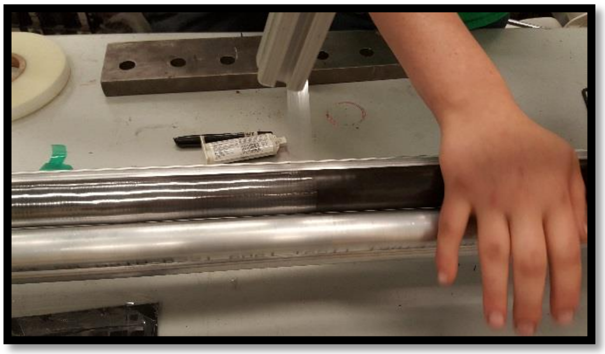
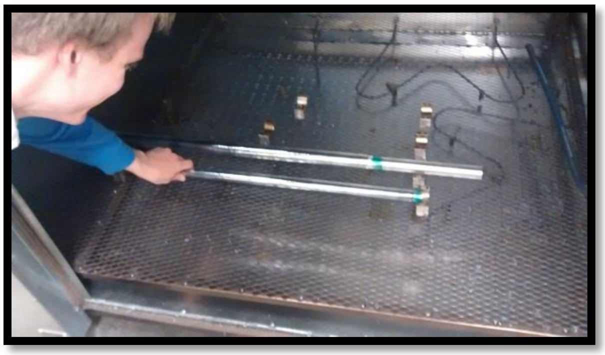
	
	9. Cure the wrapped mandrel in an oven at the suppliers recommended temperature and time. Note: PSU students have an oven available in the engineering building room 480.

Table 1: Layup Lengths for Each Tube

Top Tube

Layup Angle	Length in Fiber Direction	Length Perpendicular to Fiber
0	700 mm	144.1 mm (Stencil TT-0-90)
90	144.1 mm (Stencil TT-0-90)	700 mm
45	1077.7 mm	107.7 mm (Stencil TT-45)
22.5	805.2 mm	134.6 mm (Stencil TT-22.5)

Seat Tube

Layup Angle	Length in Fiber Direction	Length Perpendicular to Fiber
0	700 mm	121.8 mm (Stencil ST-0-90)
90	121.8 mm (Stencil ST-0-90)	700 mm
45	1061.9 mm	92.0 mm (Stencil ST-45)
22.5	796.6 mm	114.0 mm (Stencil ST-22.5)

Down Tube

Layup Angle	Length in Fiber Direction	Length Perpendicular to Fiber
0	900 mm	162 mm (Stencil DT-0-90)
90	162 mm (Stencil DT-0-90)	900 mm
45	1373.2 mm	120.4 mm (Stencil DT-45)
22.5	1028.5 mm	151.2 mm(Stencil DT-22.5)

Head Tube

Layup Angle	Length in Fiber Direction	Length Perpendicular to Fiber
0	200 mm	157.3 mm (Stencil HT-0-90)
90	157.3 mm (Stencil HT-0-90)	200 mm

Bottom Bracket		
Layup Angle	**Length in Fiber Direction**	**Length Perpendicular to Fiber**
0	300 mm	147.9 mm (Stencil BB-0-90)
90	147.9 mm (Stencil BB-0-90)	300 mm

Seat Stay		
Layup Angle	**Length in Fiber Direction**	**Length Perpendicular to Fiber**
0	700 mm	70.2 mm (Stencil SS-0-90)
90	70.2 mm(Stencil SS-0-90)	700 mm
45	1025.4 mm	55.5 mm (Stencil SS-45)
22.5	776.9 mm	66.4 mm (Stencil SS-22.5)

Chain Stay		
Layup Angle	**Length in Fiber Direction**	**Length Perpendicular to Fiber**
0	700 mm	90.0 mm (Stencil CS-0-90)
90	90.0 mm (Stencil CS-0-90)	700 mm
45	1039.4 mm	69.5 mm (Stencil CS-45)
22.5	64.7 mm	84.7 mm (Stencil CS-22.5)

Table 2: Mylar Lengths for Each Mandrel

Mandrel	Length (mm)	Width (mm)
Top Tube	780	164.1
Seat Tube	780	141.8
Down Tube	980	182
Head Tube	280	177.3
Bottom Bracket	380	167.9
Seat Stay	780	90.2
Chain Stay	780	110

Purpose

This section provides instructions on mitering the tubes.

Tools, Fixtures, Material

- Sanding Drum
- Sand Paper
- Marker
- Carbon Fiber Tubes

Safety Requirements

Use the following safety equipment and use caution with moving components (aka the sander in operation).

- Respirator
- Gloves
- Goggles

Instructions

 	1. Apply sand paper to the appropriate sanding drum. Use Table 3 when choosing which drums will be needed
	2. Mark on the tube where the miter is to end.
	3. Set the sanding drum to the appropriate angle and miter the joints to the miter end mark. Repeat all these steps for all miters needed. Note: PSU students can use the Tubeshark®, located in the Engineering Building room 480, to miter the joints.

Table 3: Sanding Drums for Each Tube

Tube	Miter End 1	Miter End 2
Top Tube	Seat Tube Drum	Head Tube Drum
Seat Tube	Bottom Bracket Drum	N/A
Down Tube	Seat Tube and Bottom Bracket Drum	Head Tube Drum
Chain Stay	Bottom Bracket Drum	N/A
Seat Stay	Seat Tube Drum	N/A

Purpose

These instructions show how to join the tubes using epoxy to make the bike frame

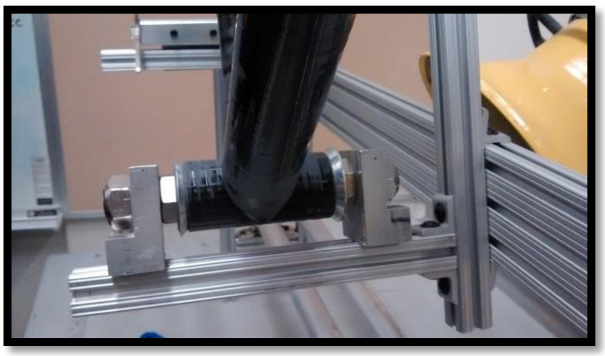
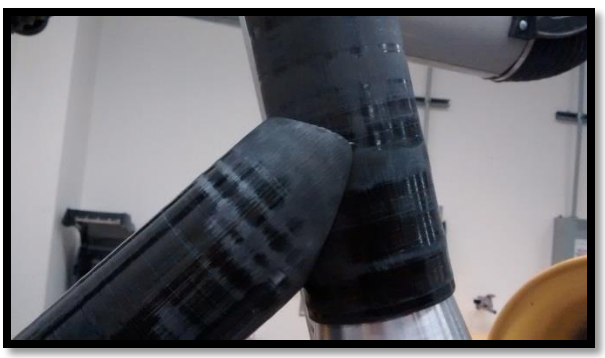
Tools, Fixtures, Material

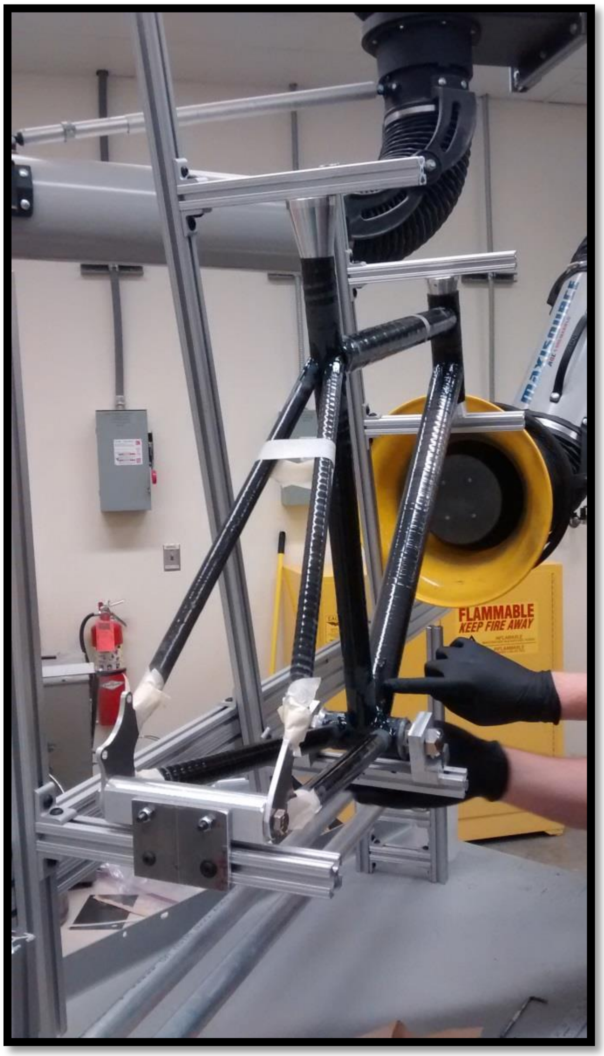
- Sand Paper
- Mitered Carbon Fiber Tubes
- Frame Fixture
- Epoxy

Safety Requirements

- Respirator
- Gloves
- Goggles

Instructions

	1. Set the frame fixture to the desired angles and distances. 2. Sand the tubes to create a surface for everything to stick to. Note: Wipe the tubes down afterwards so there is no dust left on the tubes.
	3. Place the bottom bracket in the bottom bracket mount first.
	4. Put the frame together without glue, and check the tubes for a flush, tight fit, and make sure the bike frame is straight.
	5. Epoxy the joints using product instructions. Only a small bead is required under the joints. Note: The tubes have to be taken off and reattached after the glue is applied.

 	6. Let the frame sit for the required hardening time, as required by the product instructions. 7. After the epoxy has hardened, check that the frame is still properly sized and aligned. If it is not, break the joints and redo all steps.

Purpose

These instructions show how to shape the joints using Smooth-On Free Form® Air (Sculpting Epoxy Dough) and wrap the joints

Tools, Fixtures, Material

- Sculpting Epoxy Dough
- Sand Paper
- Pre-impregnated Unidirectional Carbon Fiber

Safety Requirements

- Respirator
- Gloves
- Goggles

Instructions

	1. Apply sculpting epoxy dough around the joints to create a smooth curved surface. Let the sculpting epoxy dough dry for as long as the product specifies.
	2. Sand the dried sculpting epoxy dough to remove and smooth any imperfections. 3. Clean the frame with alcohol and cloth to remove any dust.
 	4. Cut the layup for the joints. Reference: Patent located at http://www.google.com/patents/US4900048 Note: Use scrap carbon fiber if you have it. 5. Apply the layup to the joints.

Purpose

These instructions show the final processes for curing the joints and finishing the bike.

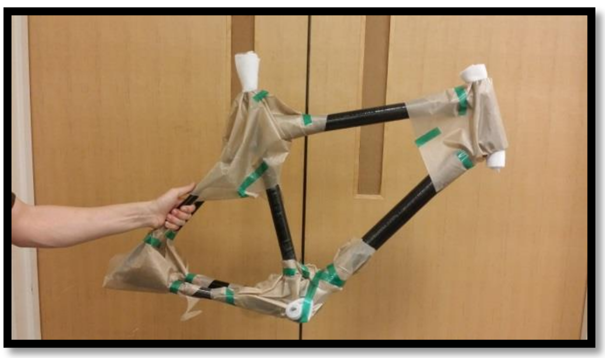
Tools, Fixtures, Material

- Release Paper
- Vacuum Bag
- Vacuum
- Oven
- Sand Paper

Safety Requirements

- Respirator
- Gloves
- Goggles

Instructions

	1. Wrap the release paper around the uncured joints.
	2. Vacuum bag the entire bike frame.

	3. Use the vacuum to suck the air out of the bag. Note: At PSU the vacuum generator is located with the oven.
	4. Keeping the vacuum on, cure the bike frame joints in the oven at the required temperature and time for your material. 5. After curing the joints, sand the bike to prep the frame for a protective coating.