TEAM POLYWHEEL

HPV 20" COMPOSITE DISC WHEEL DESIGN AND PRODUCTION SENIOR PROJECT

FINAL PROJECT REPORT

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1 Introduction/ Abstract

This project report will serve to describe the goals, objectives, and overall process of the Cal Poly Mechanical Engineering senior project team, PolyWheel, in the design and fabrication of a complete set of 20” composite disc wheels for use on a high-efficiency human powered vehicle (HPV). The project will include the manufacturing of durable and reusable molds to build the wheels in order for multiple wheel sets to be made in the future. The wheels will be designed and built to be compatible with the Cal Poly HPV Team’s 2012 race bike and by other streamlined recumbent bicycles requiring a 20” wheel. The wheels need to optimize weight, rigidity, crash survivability, and aerodynamics. Design requirements for the wheel sets are being provided by the Cal Poly HPV Team and George Leone. Funding for the materials is being provided by John Neilson.

2 Background

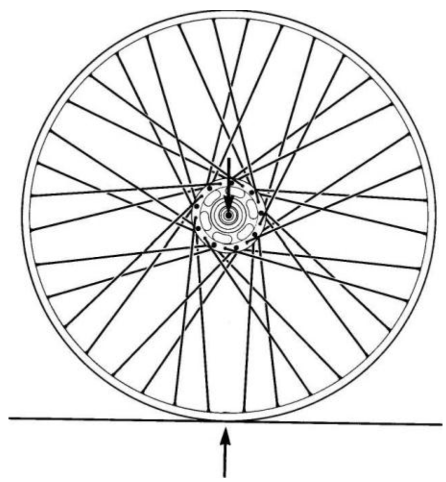


Figure 1: External Loads on a Bicycle Wheel

The bicycle wheel has not been altered in many ages since the turn from wood spokes to pre-tensioned steel spokes. The wheel is designed to withstand a combination of loads and a driving torque that is needed to transfer the force from the hub to the rim of the wheel which propels the bike forward. The rim of the wheel also supports a pressure vessel in the form of a tube and tire.

2.1 Respective Weights of Road Bike Wheels

With the advent of composite materials the total weight of bike wheels was significantly reduced. Today most of the weight lies in the actual tire itself rather than the composition that makes up the center of the wheel. A wheel that contains spokes outweighs a disc wheel made of carbon fiber in most cases. The spokes are being replaced by fewer spokes or composite materials that allow for less aerodynamic drag. The frame and spokes are being made with an aerodynamic factor in mind resulting in a frame with less sharp edges and more oval pieces allowing air to pass smoothly over the piece. The reduction in weight allows the rider to accelerate quicker due to a lower moment of inertia. The main drawback to carbon fiber wheels is their reduced durability. A layer of Kevlar or type of Kevlar weave is sometimes incorporated into the rim profile to improve wear resistance in the case of a flat. A lighter disc wheel may result in reduced rolling resistance, but the main advantage is reducing weight and drag. The rear wheel tends to be heavier in that it is the one driving the system forward and needs more parts to perform. The front wheel tends to have a smaller hub and less spokes, but a higher moment of inertia (thus heavier wheel) does help in turning the bicycle.

Table 1. Wheel Masses

Spoke				
Type	Front/Rear	Hub	Tire **T**ubular/ **C**lincher	Mass(grams)
24 Stainless Steel Clincher 700c	R	Steel Freehub	C	1,001
Spinergy Stealth FCC PBO 20 Radial/2-Cross 700c (6)	R	Custom CNC machined, hidden flange front, Force-10 rear	C	1,500

Disc				
Type	Front/Rear	Hub	Tire **T**ubular/Tubeless **C**lincher	Mass(grams)
Mavic Comete Track	R	Aluminum Fixed Cog	T	980
Zipp 900	R	Cassette Hub	T	936
Corima Disc C+ 2D (20% more rigid than CN version) 700c	R	Shimano 10 speed cassette	T	1,030

A rider will make up time mostly based on aerodynamics throughout a ride since this factor is always present, not just during acceleration like the moment of inertia. Another factor that is always present is the rolling resistance of the wheel. The key for a racing wheel is weight and aerodynamics compromising with cost and durability. The drag is mainly due to pressure drag. Pressure drag occurs when an area of low pressure forms behind the rider and the rider is literally being pushed backwards. The technology has rapidly progressed over the last 20 years leading to disc wheels that dramatically reduce the force of drag on the bike leading to greater acceleration and faster speeds of human powered vehicles.

Table 2. Bike Wheel Coefficients of Drag[8]

Wheel	**C_d in direction in which bike is moving with 0° yaw**
Conventional 36-spoke	0.0491
Specialized tri-spoke	0.0379
HED disk (lenticular)	0.0361

2.2 Wheel Weight Distribution

Some sources state a 55-60% distribution on the back wheel and a 40-45% on the front wheel gives a comfortable ride with least likely overuse of muscles. More weight on the front wheel increases turning ability and decreases the likelihood of shimmying. For recumbent bikes weight distribution tends to lean toward more weight on the front wheel, but this all depends on the build of the person and geometry of the frame. Weight also aids in braking power due to an increased normal force and friction force. The bike tire will deform under an increased normal force and the surface area contact with the road surface will increase allowing a larger area for molecular adhesive bonds to occur. There are also more sites for static, kinematic and sliding kinematic friction to occur. Rolling resistance is determined by the area of tread in contact with the surface (tire width), the thinness and fragility of the tread material, the different patterns on the tread and the radius of the tire. Rolling resistance increases with tire width and decreases with wheel radius.

2.3 Tubular/ Sew Ups and Clincher Bike Tires

Most high end track bike wheels have a tubular and clincher option with the tubular option being lighter. Tubeless clincher tires are becoming more popular as they are able to compete with the many advantages of tubular.

Figure 2. Tubular Tire

http://www.spadout.com/p/continental-grand-prix-4000-sr-tubular-tire/>

Tubular tires are a popular type of racing tire and are made of a rubber tube followed by layers of thread that are laid down diagonally. The diagonal layers are laid down perpendicularly to each other to form the carcass of the tire. The thinner the tread (the higher the threads per inch (TPI)) gives a more flexible tire. Some tires have a radial construction running underneath the plies to prevent puncture (such as the sub tread shown in Fig. 2). The carcass is then coated with a rubber/carbon blend which gives the black appearance. The carbon greatly increases the life of the tire. The sidewalls are not as thick as the tread area because they do not contact a surface and wear out. The tube is sewn to the inside of the carcass using a stitching method. The tube is then glued to the rim. The gluing process is very precise in that the glue needs to be worked up to the edge of the rim profile to prevent the tube from slipping off the rim around turns. The glue also needs a few hours to set for maximum performance, preferably longer.

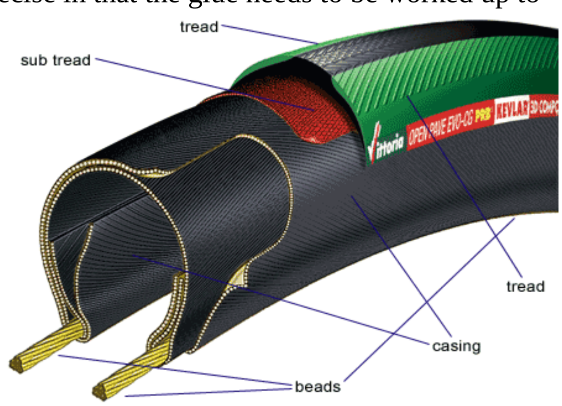


Figure 3. Clincher Tire

http://howtobuildyourownbike.blogspot.com/2009/02/how-to-build-your-own-bike-by-scott.html

A clincher tire consists of an inner balloon tube and 2 beads that run the circumference of the tire. The inner tube is inflated and the beads are pushed to the rim where they “clinch” the wheel. The beads hold the tire onto the rim. The beads can be made of steel cables, but Kevlar is being used today because it is lighter

A tubeless clincher tire works without a tube by using the tire pressure to seal itself to the rim. The valve used to inflate the tire is incorporated into the rim. Any debris or rough edges along the inside of the rim will defeat a proper inflation and may cause small steady leaks in the

future. Tubeless tires are mainly used for mountain biking applications in that the tire can have low inflation pressure without getting pinch flats.
In short, the biker community agrees on using clinchers for training and upgrading to a tubular for racing competition. Tubeless clincher tires are gaining in popularity and technology and they may surpass tubular as the tire of choice for race day.

Different advantages and disadvantages arise from the main two different tire fittings. PolyWheel is mostly concerned with the rim profile of tubular and clincher tires, the tubular tires being the simpler option. The debate amongst rolling resistance is highly debated. Most sources state a properly glued tubular tire has the least rolling resistance. Butyl rubber is widely used in carcass applications because it is light. Latex is sometimes used, but is very fragile and completely blows out when punctured.

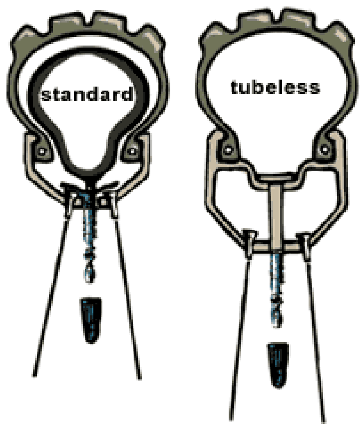


Figure 4. Standard and Tubeless Clincher Profiles

Figure 5. Rim Profiles

<http://lavamagazine.com/gear/zipp-announces-radical-new-rim-shape#axzz1DKGXU4IB>

Table 3. Tubular Advantages and Disadvantages

Tubular	
Advantages:	**Disadvantages:**
• Lighter tire and lighter rims	• Expensive
• Less prone to pinch flats	• Need to carry spare tubes
• Comfortable ride	• The glue needs to set a few hours for optimum performance

Table 4. Clincher Advantages and Disadvantages

Clincher	
Advantages:	**Disadvantages:**
• Quick turnover	• Heaviest
• Truer and rounder	• Installation difficult w/o tools
• Easy access to repair flats	• If tube blows, you can lose your tire

2.4 Bicycle Hubs

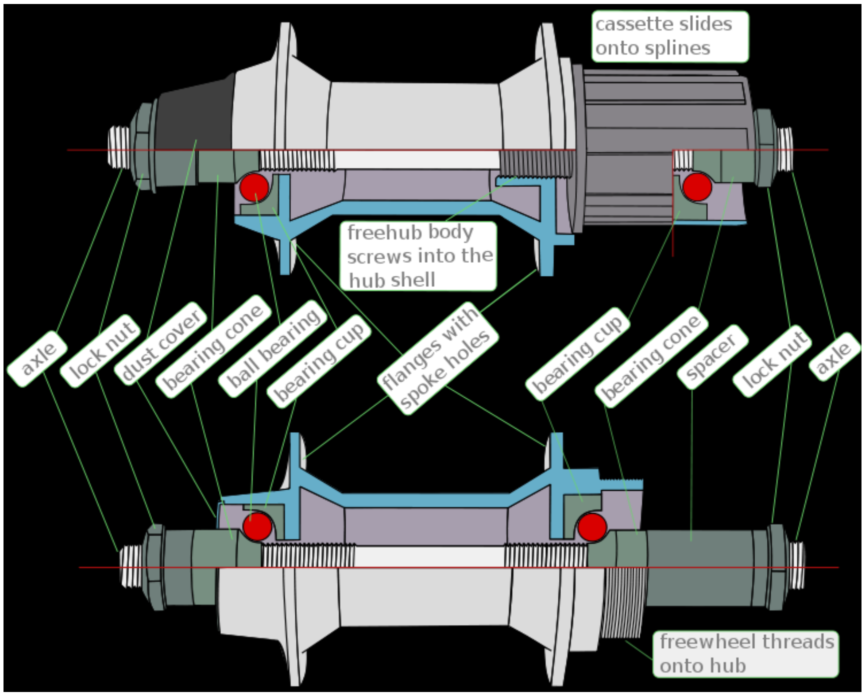


Figure 6. Freehub and Freewheel

<http://en.wikipedia.org/wiki/File:Labeled_Bicycle_Hub_Comparison-en.svg>

Bicycle hubs may be either the adjustable cup-and-cone type or the non-adjustable cartridge style. Both types can come in either the freehub type or the thread-on freewheel style. The freehub has the bearings and axle built into the hub whereas the thread on the freewheel fixes to a solid hub with no internal parts. Since all models of over the counter hubs are designed for spoked wheels, PolyWheel is also considering custom manufacturing the hub. This would allow for a more adjustable interface with the composite disk at the cost of an additional manufacturing process and limited compatibility. There exist documents specifying the geometry and parts of the internal workings of a hub. With this knowledge Team PolyWheel can manufacture our own hub casing and use the already existing internal components.

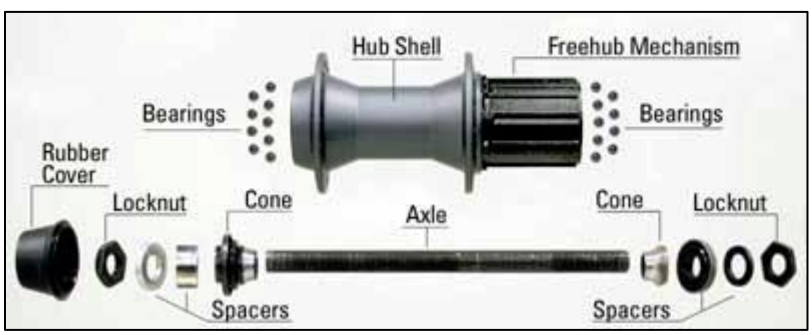


Figure 7. Cub and Cone Type Freehub

http://www.parktool.com/blog/repair-help/hub-overhaul-and-adjustment

2.5 Brakes

Braking systems can be divided into two major groups: hub and rim brakes. Hub brakes create a torque at the hub with a drum or disk brake. They generally function better in rough weather and in the case of a disk brake, have quick stopping times. Rim brakes apply pressure on the rim of the wheel with brake shoes. This means they have a larger braking surface with which to dissipate the heat generated during braking. They also weigh much less and apply less stress to the wheel and frame because of the smaller gripping force required on the longer moment arm.

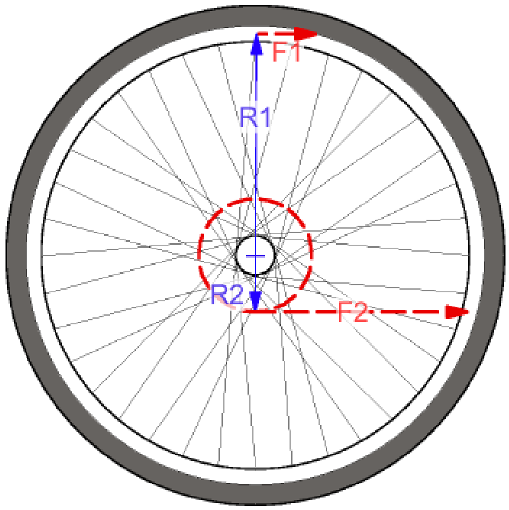


Figure 8. F1 is from a rim brake while F2 is from disc brake

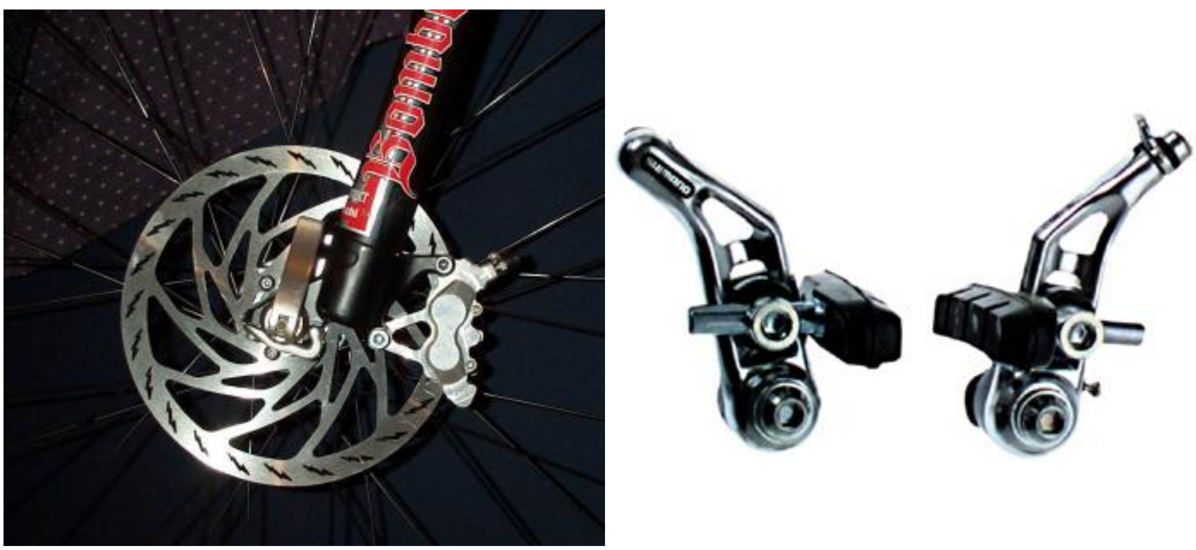


Figure 9. Disk and Rim Brakes

http://sheldonbrown.com/brakes.html

Caliper brakes are quite a bit heavier than rim brakes and their all-weather performance offsets this much more in off road cycling. Most road bikes use rim brakes for weight improvements. Ideally, PolyWheel will be able to interface with both types of brakes depending on the application.

2.6 Carbon Fiber

The high strength-to-weight ratio of composite materials makes them a very suitable and attractive option for many applications where minimizing weight is desired and/or critical without making sacrifices to the strength of the structure. Fiberglass and carbon fiber are two common types of typical composites. Of the two, carbon fiber has a much higher modulus of elasticity and a lower density making it the preferred choice of the two materials for a bicycle wheel application. There are many different types of commercial carbon fiber available each having unique properties and characteristics. The main difference is in how the carbon fibers are oriented. Since carbon fiber is very strong in tension (about 7 times stronger than mild steel), but is prone to failure when subjected to relatively low compressive loads, the orientation of the fibers with respect to the direction of the load is critical to ensure that the fibers are subjected to mostly tensile forces. Typically, carbon fiber sheets, known in industry as cloth, are woven so that the fibers meet at 90°. This allows the fibers to withstand a larger variety of loads than if the fibers were oriented all in the same direction. Other orientations commonly available are uni-directional and 45° cloth. Analysis of the load that the carbon fiber must withstand (including magnitude and direction) is very important in order to choose the proper cloth weave.

In addition to the orientation of fibers, there are also different types of weave patterns available for 90° cloth. With the various weave patterns, the carbon fibers are overlapped a varying number of times. This does not appreciably affect the ultimate strength of the sheet overall. The type of weave and number of carbon strands per bundle affects how easily the cloth can be draped around sharp corners and how resistant the cloth is to fraying at the ends. The three types of weaves commonly available are plain weave, twill, and harness-satin. Weaves are usually labeled using a notation that refers to how many times the fibers cross over and under one another. This is presented in a format such as 2X2. The first number in this set refers to how many strands are crossed "over" before going "under" the perpendicular strands. The second number refers to how many strands are crossed "under" before going back "over" the perpendicular strands. A plain weave is a 1X1 weave. This means that each fiber goes over one perpendicular fiber and then under the next. This pattern results in the tightest weave making it much less susceptible to fraying at the ends.

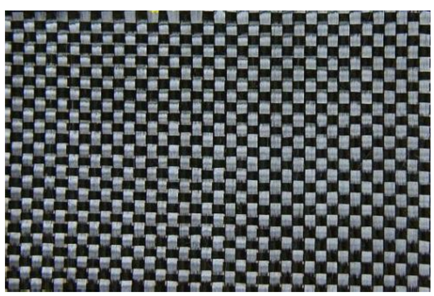


Figure 10. Plain Weave Cloth

A twill weave has an identical and even number of over/under weaves, primarily a 2X2 or 4X4 pattern. With this weave pattern, the cloth appears to have 45° lines running across it giving it an appealing surface finish. Being a much looser weave, twill cloth is easier to bend around complex curves. However, the looser the fabric, the more likely the strands will separate. This can create spaces in the fabric around corners which could lead to structure failure. This must be kept in check when having to use looser weaves.


Figure 11. Twill Weave Cloth

Lastly, a harness-satin weave cloth has a pattern where the over weave is greater than 1 and the under weave is equal to one. Typical patterns are 3X1, 4X1, and 5X1. This weave provides the highest versatility for laying cloth around complex contours. As can be seen in the picture below, it also provides one of the most appealing surface finishes.

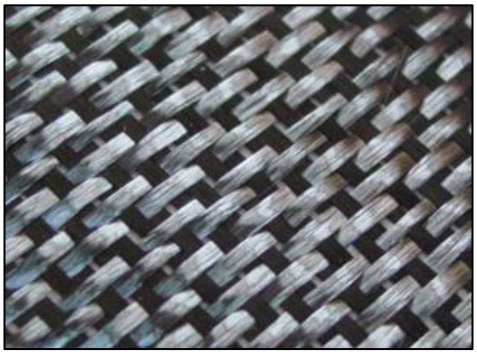


Figure 12. Harness-Satin Weave Cloth

In general, if complex curves and aesthetics are not important, a plain weave is the best option. But if the part being created is complex and a 'high-tech' look is desired, a twill or harness-satin weave is the preferred way to go.

Carbon fiber cloth is also referenced by the number of individual strands of carbon per fiber bundle (in thousands). Each fiber is made up of many small strands. Typical cloths are 1K, 3K, and 6K. For example, with a 3K fabric there are 3000 carbon strands in each carbon fiber.

Carbon fiber cloth alone is not extremely useful since it is very flexible. As mentioned earlier in this section, the cloth sheets can be folded and draped around contours (more or less easily depending on the weave). Resin is added to the cloth (this process will be explained shortly) and, once allowed to cure and harden, keeps the fiber cloth in the correct shape and direction. The resin itself does not add much strength to the structure. It is simply there to orient the cloth. Along with the different types of carbon fiber, there are many different types of resin that can be used. Resins differ in what curing process is required for them and how the resin is integrated with the carbon fiber. Some resins when mixed will begin to cure at room temperature (sometimes rather quickly) while other types of resins only cure when subjected to high heat, such as in an autoclave. There are advantages and disadvantages to using both types of resins depending on the type of part being created. When a long working time is necessary (for example with a very complex part), it is best to use resins that must be cured in an autoclave so that it does not begin to harden while the builder is still laying the sheets down. The main two ways to integrate the resin with the carbon fiber is by either using a process known as a wet layup or by using a product called carbon fiber prepreg. With a wet layup, the resin is poured and brushed onto the carbon fiber cloth.

The ratio of carbon fiber to resin must be kept in check by the builder along with ensuring that the resin gets evenly distributed throughout the cloth. This process can be very difficult to learn properly. With the second option, carbon fiber prepreg, the resin is already impregnated into the carbon fiber. This takes a lot of the guess work out of the cloth layup procedure since the ratio of resin to carbon fiber is already optimized. With this material, the carbon fiber cloth is simply laid down where it is needed in the mold and the prepreg is then left to cure depending on what type of resin is used in the cloth (either at room temperature or in an autoclave).

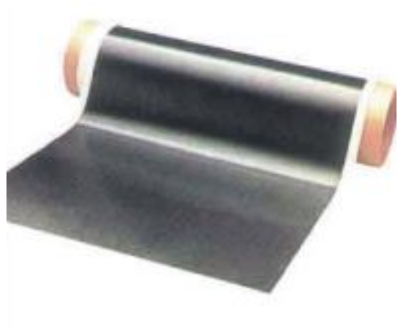


Figure 13. Prepreg Carbon Fiber

When laying carbon fiber cloth into molds, a product known as a vacuum bag is often used to ensure that the sheet remains flush to the contours of the mold. The vacuum bag is the last layer to place over the mold. After a wet layup is laid on the mold, a release cloth is evenly spread over the carbon fiber. Next is a layer of perforated plastic that allows the resin to escape evenly from the carbon fiber. Fleece is then usually laid over to absorb the excess resin. The vacuum bag is then sealed over the mold and connected to a vacuum pump which runs for however long is deemed appropriate to bleed off the excess resin and/or for the resin to completely cure.

Figure 14. A crude but effective vacuum bag

The vacuum bag keeps a constant pressure across the entire surface of the part and must be kept on the part for the entire duration of the resin’s curing time.

2.7 Existing Commercial Composite Disc Wheels

The use of composites in the bicycle industry is not new by any means. Composites have been used in bicycle frames and wheels dating back to the early 1990's. For this reason, a great deal of development and testing has gone into finding the best use of composite materials on bicycles. But even with the extensive use of composites in today's bikes, very few companies are willing to give out any information on the specific materials and layup procedures used to build their parts. There are many companies in existence today that manufacture high-tech carbon fiber bicycle wheels, both spoked and disc. The majority of wheels produced are 700c and 650c wheels and there are not any companies that commercially manufacture a 20" composite disc wheel made specifically for a bicycle.

Like mentioned previously, most information regarding the engineering specifications of composite wheels is considered proprietary. Most of these companies do not fully understand the extent of composites, but are able to build and test their own products using an empirical approach to optimization. The following subsections explain the existing designs of composite wheels, previous composite projects, and a reference literature overview.

Zipp Speed Weaponry is one of the leading manufacturers of 700C composite disc wheels for bicycles. The company focuses on producing wheels designed for highest level of competition, with weight and efficiency being the top two priorities. Zipp offers several models of composite disc wheels. One of the more noteworthy models is the Sub-9, a rear composite wheel that creates forward lift when subjected to a wind attack angle of 12-18 degrees. This is accomplished using a specific surface texture as can be seen in the following picture on the next page. While this specific aspect may not be feasible in our design and is not necessarily within the scope of this senior project, this example demonstrates the importance of aerodynamics in the design of composite wheels. The Sub-9 is made completely from composite with the exception of its aluminum hub. Details of the aluminum/composite integration are difficult to see from pictures and Zipp considers it a proprietary part of the wheel design making it hard to report any specific information. The Sub-9 is made for use with tubular tires. Also note that this wheel is designed for v-type scrub brakes, a type of rim brake. The braking surface, which is on the rim nearest the tire bead, is covered with a special (and proprietary) friction material. This friction material is necessary due to the poor heat dissipation and non-ideal friction coefficient of the composite. The claimed weight of the Sub-9 wheel is 998 grams. With a current MSRP of around $2500 (as of January 2011), this wheel is primarily reserved for only the top competitors in bicycle racing.

Figure 15. Zipp Sub-9 Wheel

Corima is another wheel manufacturer that is a close competitor to Zipp. They too produce a composite disc wheel designed for tubular tires. The general specs of the wheels are the same as those from Zipp with exception of the ‘forward lift’ surface texture design. Corima’s wheel weighs in at 985 grams.

Figure 16. Corima C+ Disc Wheel

The weights of both Zipp’s and Corima’s wheels are important, but their sizing numbers must be kept in mind. Both wheels are sized for standard road bikes (size 700C). The weight is also measured without the tire, tube, or any removable hub parts installed. Being that our wheel will be designed for a 20” tire, these numbers will only be used as an indirect reference. Strength and stiffness aspects of both wheels are not available to the public. The only way to find a definite answer to what these wheels can hold up to would be to buy a set and subject them to loads until failure. However, this process of reverse engineering is not within the budget scope of our project.

2.8 Supermileage Composite Wheel Senior Project

A past Cal Poly Senior Project titled "Supermileage Seat and Wheel Development and Production" took on the task of designing and manufacturing a set of carbon fiber wheels with an integrated aluminum hub. The wheels were designed to be used with the current Cal Poly Supermileage Team's competition vehicle which is a four wheeled car. The layup method and type of hardener and resin used in the project are on file. While the application of these wheels is quite different from a bicycle, the general concepts, layup processes, and lessons learned from the project can be adapted for use in the design and manufacturing of composite bicycle wheels.

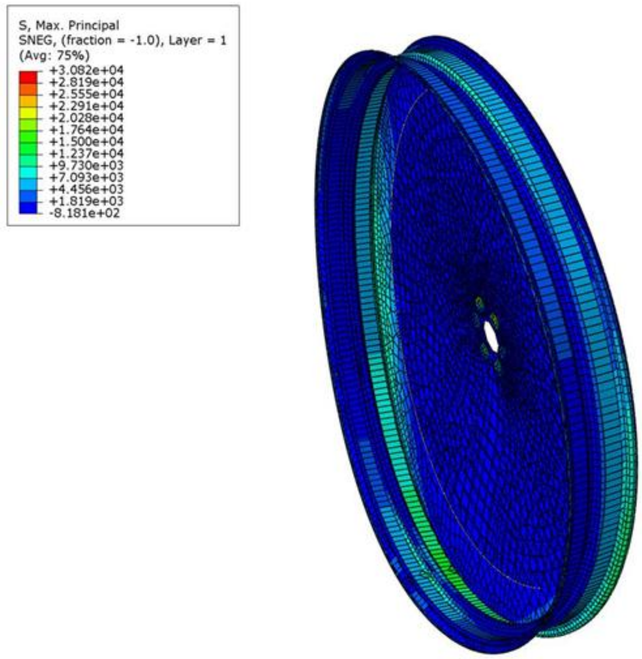


Figure 17. ABAQUS Simulation of Central Coast Composites Wheel

A major problem that the team ran into was with the different coefficients of thermal expansion for the carbon fiber and aluminum mold. The mold shrunk when cooled causing the carbon fiber to experience compressive stresses as it was pushed back to its original shape before being subjected to the curing process in the autoclave. The team suggested using carbon fiber for the molds since they would then have the same coefficient of thermal expansion. A second problem worth noting was the team's issue with the composite rim holding the pressure needed in the tires. It was suggested in the report that at least 10 plies should be used for the carbon fiber hoops to prevent the rims from blowing out when pumping up the tires to the operating pressure. This number will be analyzed thoroughly as it is a critical dimension and directly impacts the performance of the wheel. Many other aspects of the design and process from the report will be used to steer the design of our composite disc bicycle wheels.

2.9 Bicycle Wheel Literature

There are several quality pieces of literature that have been written by engineers addressing the types of loading and the basic design behind traditional bicycle wheels. Bicycling Science by David Wilson and The Bicycle Wheel by Jobst Brandt are two books that explore the basic loads encountered in a bicycle wheel and how the wheel reacts to these loads. From the analysis done in these texts (specifically the finite element analysis done by Brandt in The Bicycle Wheel), it was determined that, for a standard wire spoked wheel, the hub 'stands' on the bottom spokes and does not 'hang' from the top spokes. At first glance, this seems counterintuitive and almost impossible since the thin steel spokes are designed to work in tension and will buckle under very low compressive loads. In actuality, the 'compression' in the bottom spokes used to support the hub is in fact just a reduction in tension. The bottom spokes are still subjected to a tensile force, it is just reduced which subjects the hub to an upward force equal to the weight bearing down on the wheel. This same concept is seen in some bridge designs. Concrete can be used as a tensile member by pre-compressing it and then subjecting it to a reduction in compression. In the bicycle wheel case, the spokes are pre-tensioned and are subjected to a reduction in tension thus acting as a compressive member. The top spokes of a traditional wheel are not affected when weight is added to the bicycle. Disc wheel forces are similar to this, however, since all of the material in the wheel is connected, the top, bottom, and sides of the wheel will feel some component of the force. Even with this difference, we can still begin to develop basic strength and stiffness criteria for our final composite disc wheel design by comparing it to the typical strengths of standard aluminum wheels. According to Zipp, uni-directional carbon fibers in the radial direction account for 85% of the loads experienced by the wheel (11). A carbon fiber weave is used near the hub and in the rim profile due to the changing geometry and different forces experienced in these areas. At the hub the torque is transmitted through the material that bonds the aluminum casing to the carbon fiber weave. A greater contact surface area, minimized sharp edges, many layered weave carbon fiber will help these forces transition smoothly.

3 Design Development

3.1 Conceptual Designs

PolyWheel's overall goal is to build a set of composite disc wheels. We will also manufacture the reusable molds. The wheel set will be tested and analyzed so that our design may be improved in the future.

Table 5. PolyWheel Formal Engineering Requirements (see Appendix A)

Specification Number	Parameter Description	Requirement or Target (units)	Tolerance	Risk	Compliance
1	Total Wheel Weight	1 kg	Max	M	A, I
2	Trueness Tolerance	0 in	±0.025 inch	H	I
3	Wheel Diameter	451 mm	±0.25 mm	M	S
4	Material Costs	$1000 USA	Max	M	A
5	Tire Pressure	140 psi	Max	M	T, I, S
6	Operate at design speed	100 mph	Max	H	A
7	Increased Aerodynamics	33% over standard spoke wheel	Min	M	T, S
8	Environment exposure	Wetness, humidity and sun exposure		M	T

A House of Quality included in Appendix A was constructed to develop engineering specifications based on customer, industry and team driven requirements. The customer needs 20" composite wheels which must be fulfilled in our final product.

Total Weight

Competition in industry creates a need for a durable wheel able to withstand high speeds while remaining lightweight. The total weight of a composite wheel was found to be less than 1 kg for most manufacturers. Even though total weight has a negative correlation with other specifications, PolyWheel needs to meet this criteria in order to be considered a factor among outside competition.

Trueness Tolerance/Wheel Diameter

The trueness of the wheel, or how straight it is in the vertical plane and how close the axle is to the center of the rim, is beneficial to other specifications. Meeting this criterion will increase our chances of meeting other engineering specifications such as durability, resulting in a high grade composite wheel. The flatness and concentricity of our mold will be extremely important in meeting this specification. The rim diameter of 451 mm needs to be held to a tight tolerance so that the tire will fit on the rim and can be inflated properly. The Supermileage senior project team from last spring ran into problems with their mold and discovered their rim was too large to hold a standard sized tire.

Tire Pressure
The pressure from a high performance racing tire is a very important design consideration at 140 psi, especially with tubular tires. We also must consider the possibility of the user overinflating the tire. The disc will need to be able to withstand the pressure of the tire acting from all sides while being ridden while overinflated to maintain reliability.

Design Speed
A set operating speed of 100 mph is just over what the fastest riders in the world achieve today. Our wheels may be used for this application so we must incorporate the technology needed to build a durable wheel that will withstand these speeds. Kevlar construction in the rim may be needed in order to absorb vibrations experienced by the road surface and distribute this energy evenly through the carbon fiber composite disc.

Exposure to Environment
Our wheel s will operate in adverse environmental conditions and must hold up to dirt, grime, UV rays and light rain. A wheel that performs differently or degrades under these conditions will not be accepted in the bike community.

3.2 Concept Selection

The first step in the selection process was to compare and contrast the options available for key design features of the wheel. These features include the hub style and design, rim profile, and the disc shape. We broke each of these key components into its own subsystem and analyzed them individually. We constructed three independent Pugh matrices to select an optimum concept for each subsystem of the wheel. The matrices are provided in the following tables.

Table 6. Pugh Matrix for Rim Designs

	Rim Concepts			
	Composite		Aluminum	
Criteria	Clincher	Tubular	Clincher (Ref)	Tubular
Weight	+	+	0	+
Strength	0	+	0	0
Stiffness	+	+	0	0
Concentricity	0	-	0	-
Ease of Manufacture	-	0	0	0
Rolling Resistance	0	+	0	+
Reliability	0	-	0	-
Sum	1	2	0	0
Rank	2	1	3	3

Our final choice for a rim profile is a tubular rim profile. This was selected most for ease of manufacturing. The clincher rim's complex profile would be difficult to layup with carbon fiber. Tubular tires are also very popular for high-speed sprint bicycle applications and would translate well to a high-speed HPV.

Table 7. Pugh Matrix for Disc Designs

	Disc Concepts		
Criteria	Flat Disc	Angled Disc	Steel Spokes (Ref)
Weight	+	+	0
Radial Strength	+	0	0
Lateral Strength	-	0	0
Stiffness	+	+	0
Hub Integration	-	-	0
Ease of Manufacture	0	-	0
Aerodynamics	+	+	0
Symmetry (F to B)	+	0	0
Sum	3	1	0
Rank	1	2	2

Our final choice for a disc shape was to use a flat disc. Again, the ease of manufacturing outweighs the small bending moment strength gained by using a tapered disc shape. Building a flat disc also makes the wheel design much more versatile. One wheel can be used for both front and rear applications without the need for dishing for a sprocket cassette.

Table 8. Pugh Matrix for Hub Designs

	Hub Concepts		
	Custom Made		
Criteria	One Piece	Two Piece	Store Bought (Ref)
Weight	0	0	0
Strength	+	0	0
Disc Integration	+	+	0
Ease of Manufacture	-	-	0
Adjustability	+	+	0
Sum	2	1	0
Rank	1	2	3

Our final choice for a hub design was to manufacture one piece custom hubs. This approach will allow us flexibility in the hub/disc integration for the wheel.

3.3 Proof of Concept

In order to test our idea and make sure our tire fits correctly on our final product we decided to make our final product out of MDF board. Purchasing a tire is a stressful ordeal because the numbers that characterize the diameter of the wheel are based on different standards. Our model will also allow us to test our hub design. We will cut out a hex mole in the MDF board and interface our hub casing. We can also use this mold to draw out the portions of carbon fiber that will be laser cut. The carbon fiber will need to overlap each other and will also overlap the sides of the hub hole and sidewalls of the rim.

4 Description of Final Design

4.1 Overall Description

The final design consists of two main components, one being the female carbon mold and the other being the final product. The carbon mold is a three piece set (three rim hoops and two different discs). The carbon molds will be made from three male MDF molds machined to size. Carbon fiber will be laid over this mold to make the female carbon mold. The final product will be made from the four female carbon fiber molds bolted together with one more mold to make the flat disc piece that will be glued onto the rim portion. The aluminum hub is made from existing internal components from a Shimano XT mountain bike hub. The casing is machined from 6061-T651 aluminum. A custom hub will allow us to dictate the interface geometry of the carbon fiber wheel to the aluminum. We also designed the flange overlap.

4.2 Detailed Design Description

The MDF molds are machined from 2 pieces of ½ inch thick MDF board glued together to make a 1 inch thick piece. The MDF board will be placed in a CNC mill and held by a special fixture. These MDF molds will then be used to make the female carbon fiber molds. We will proceed with a layup procedure with 6k carbon as a primary layer in order to fill all grooves and get a nice seat. Following layers will be used to add bulk to our carbon fiber molds. The molds will be vacuumed bagged and allowed to cure. The three carbon fiber rim hoop molds then have three holes drilled in each end allowing them to be bolted to each other forming a hoop and then bolting that hoop to the flush disc. Prepreg carbon fiber cut by the laser cutter will be placed in the mold paying close attention to overlap and orientation. This forms the bottom piece, rim profile and a portion of the sidewall of the final wheel, known as the rim. After vacuum bagging, the mold will be cured in the autoclave. The second piece to the wheel will be made from a flat mold, vacuum bagged, cured in the autoclave and glued onto the sidewall section of the first mold with epoxy. There will be no core material for our final wheel.

The layup procedure consists of unidirectional fiber oriented similar to the spokes in a bike wheel. The number of the spokes may vary from 16-22 pieces of fiber. Reinforcement of the rim profile may be needed to prevent the 200psi tube from blowing out the sidewalls. The thickness of the rim profile will be determined by comparing an existing tubular rim profile of a carbon fiber disc wheel and measuring the thickness. We can approximate the number of layers from this thickness. The disc section of the wheel is thin aero grade carbon fiber that will mainly serve to aerodynamically streamline the disc wheel.

The aluminum hub has stock hub internal components from a Shimano xt mountain bike hub. The hub casing is designed around the internal components, essentially removing the spoke flanges and adding a hex portion for the disc interface. This design allows us to optimize the material placement in the hub while not needing to build our own internal components.

Detailed drawings and assemblies for the above mentioned parts can be found in Appendix B.

4.3 Analysis Results

The forces, moments and torque experienced by the wheel will all be withheld by the carbon fiber matrix. Analysis to determine equivalent strength and stiffness will make sure our wheel matches that of a similar 20" spoke wheel. This analysis can be found in Appendix E.

4.4 Cost Estimation

At this point in the design, we have not specified exact material sizes, number of plies, etc. This makes an estimate for the costs for both the mold and the wheel rough approximations. We know the approximate surface area of the wheel for determining carbon fiber pricing, but without the number of plies in each location, we cannot pin down the number. Other components, such as the amount of MDF board used producing the mold, also have unknown volumes at this time and suffer from the same pricing issues. Single use items, such as the release ply and vacuum bag, are accurately priced.

Table 9. Estimated pricing for a single wheel mold

Estimated Mold BOM			
Line Item	Item	Quantity	Cost
1	Carbon Fiber Cloth	20-30 ft^2	$180-$270
2	MDF Board	4'x8'x½"	$26
3	1/4-20 Steel Bolts	1 box	$3.29
4	Vacuum Bag	1 yd	$4.25
5	Peel Ply	1 yd	$15
6	Sealant Tape	25 ft	$7
7	Perforated Release Film	1 yd	$5
8	Bleeder Absorber Cloth	1 yd	$4
	Total:		$250-$330

Table 10. Estimated pricing for a single wheel

Estimated Wheel BOM			
Line Item	Item	Quantity	Cost
9	Carbon Fiber Cloth	15-25 ft^2	$135-$225
10	Vacuum Bag	1 yd	$4.25
11	Peel Ply	1 yd	$15
12	Sealant Tape	25 ft	$7
13	Perforated Release Film	1 yd	$5
14	Bleeder Absorber Cloth	1 yd	$4
15	3" Aluminum Bar Stock	6 in	$28.70
16	Shimano Freehub	1	$120
17	20" Tubular Tire	1	$50
18	Adhesive	1 tube	$10
	Total:		$370-$470 (w/o core)

Labor times for the production of the mold and wheel have been roughly estimated, without knowing the exact experience level of the manufacturer it is difficult to estimate how long it will take. Our current estimates are for a team of three people working and are as follows:

- Mold: 30 hours
  - Foam Mold Modeling/machining: 5 hours
  - Sanding: 10 hours
  - Mold Prep: 5 hours
  - Cutting carbon: 2 hours
  - Carbon layup: 3 hours
  - Final adjustments: 5 hours
- Wheel: 14.5 hours
  - Cutting carbon: 3 hours
  - Carbon layup: 3 hours
  - Disc/Rim quality control: 4 hours
  - Hub machining: 0.5 hours
  - Hub quality control: 1 hour
  - Disc-Hub assembly: 3 hours

4.5 Material Selection/ Justification

As mentioned previously in this report, the material selected for the wheel discs as well as the wheel molds is a carbon fiber prepreg cloth. The cloth we have chosen to use is TC250 from the composite material manufacturer TenCate. This cloth is pre-impregnated with resin making it ready for immediate layup. Given the tight radius of the interior rim mold curvature, a prepreg composite cloth is the best choice since rolling or brushing resin onto dry cloth, as in a wet layup procedure, would be very difficult if not impossible to perform well. The selected composite is a 12K cloth which will give the wheel the needed strength but may cause issues with contouring the rim profile. This will be tested on the wheel prototype and from there a lower K-value cloth may be selected to make rim profiling easier. The same carbon fiber cloth will be used for the creation of the wheel molds. The primary justification for this is to keep the thermal expansion rates for the wheel and the mold the same to prevent buckling of the wheel during the curing process inside the autoclave. More specifications on the TC250 cloth are given in Appendix D.

The hub material selected is aluminum. Although carbon fiber-to-aluminum integration is complicated, aluminum is the best hub material choice for several reasons. Aluminum's low density in relation to its cost is a major factor in this selection. Other more advanced metals could conceivably be used, but the price of these metals increases exponentially. Aluminum is also very easy to machine. Since we are using a custom machined housing for our hub design, this property offers advantages over other types of metals. Our hub will be machined from a 1.5" hexagonal bar of 6061 T651 aluminum. This alloy of aluminum offers the best machinability and strength properties for its cost. Further information on the stock chosen for the hub is given in Appendix D. Figure 18 below shows some FEA results on the hub design chosen. Loads considered are a 200 pound load on the axle and a 175 N-m torque from braking. The FEA results showed a maximum deflection of just under .003" (pictured) and a safety factor of approximately 2.2 for maximum stress.

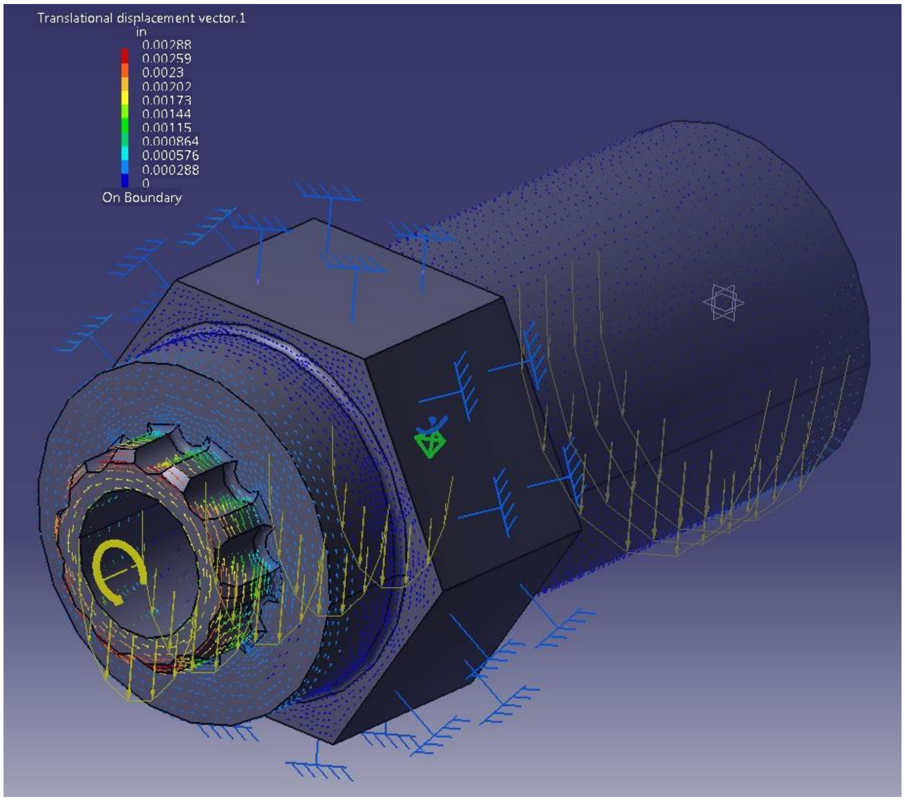


Figure 18. Hub FEA deflection results

4.6 Maintenance and Repair Considerations

Overall, the finished composite disc wheel does not require heavy maintenance to keep it operating properly. Once cured, composite disc wheels are not easily repairable. If structural damage, such as a crack, occurs to the composite material, the only option is to manufacture a new wheel. Continuous observation of the wheel is crucial to its performance to ensure that no cracks develop in the discs which could lead to catastrophic wheel failure. The hub, however, is designed for ease of maintenance. Since it utilizes all standard bicycle hub components (bearings, freehub, axle), the maintenance and replacement of these components is identical to that of a traditional bicycle hub. The casing itself can be repaired under certain circumstances such as slight freehub thread damage.

5 Product Realization

5.1 HDF Mold Manufacturing and Preparation

The first step in our manufacturing process was to machine molds to layup our final carbon molds on. These are essentially molds to build molds. The male molds were originally CNC-machined out of MDF (Medium Density Fiberboard), but this proved to be a poor material choice. The fiberboard warped due to the changing weather conditions and it chipped very easily. We then went with our next choice, which was recommended by our project sponsor, George Leone: high density foam board. This material choice was superior to MDF as it held its shape much better and had a much lower risk of chipping. Its machinability was about the same as compared to MDF. We were quick to spray the molds with sealant soon after it was machined to prevent any possible warping or moisture absorption from occurring due to the outside elements. The sealant used was a medium-hard coat of Duratec sanding primer mixed with a pigment (to allow us to see the coverage area). Two layers of medium-hard Duratec coating were applied and each was sanded with subsequently higher grit sandpaper. The last layer added to the foam molds was a harder Duratec coating that was sanded to 800-grit to provide a smooth, hard release surface. Waxing the surface provided the final surface preparation of the molds. This initial mold preparation process lasted about a week and a half. This was due to the time it took for the Duratec spray to dry as well as the time to sand the surface. The extra time and care taken at this step helped to ensure a higher quality final product.

The drawings for the foam molds can be found in Appendix B in the 100 series drawings. Note that on the hoop pieces, the end caps were left off and the flanges were applied in a later setup.

Figure 19. 3-foam mold pieces coated in a first layer of Duratec

5.2 Carbon Mold Layup Process

In this section, we will go over the process of laying up carbon fiber. This section begins with a general overview of the process of carbon fiber layups along with specific steps that we implemented in our design.

The initial step in the process for laying up a mold surface with carbon fiber is to apply Frekote to all surfaces that will come in contact with the resin or carbon fiber. The Frekote layer prevents the resin from bonding to the mold surface and thus allows the part to be separated from the mold. Three layers of Frekote were applied to every mold surface before each layup to ensure complete coverage. Carbon fiber was then cut out from a roll attending to the various sizes and orientations needed. For our application, we used a twill (2x2 weave) 3K aero-grade carbon fiber orientated in the 0°-90° and 45°-45° directions. To begin the actual layup procedure, the fiber is first laid out between plastic sheets. A liquid resin/ hardener system is applied to the carbon fiber cloth in a mass ratio of 1:1 (carbon mass to resin mass) and spread by hand evenly over the carbon fiber allowing it to soak up the resin/ hardener system. The resin/hardener system is equal to the weight of the carbon fiber plus 10% to allow for losses in spreading. The system consists of 5/6 resin and 1/6 hardener, per the material directions. Once even resin coverage is obtained, the pieces of fiber can then be peeled off from the plastic and transported to the part. Another option is to leave the wet carbon between the plastic sheets and cut out the plastic around the carbon. Transporting in the plastic helps the carbon to maintain its shape and to prevent major weave distortion, especially with the 3K twill. With thinner cloth, weave distortion occurs easily and can make the carbon impossible to work with and layup properly. This distortion will also affect both the final look and strength characteristics of the final part. The fiber is laid in the mold and pushed up by hand into all the contours of the mold. Depending on the part, a different layup schedule was adhered to. Since these molds can have extra material in certain places, the carbon cloth was cut out in oversized rectangles to cover the mold. After curing, the excess carbon was cut off with a dremel or sanded down where needed.

Figure 20. Applying Frekote to mold surfaces

Once all the carbon fiber cloth is laid out on the mold, the vacuum bagging process begins. First, the carbon fiber is covered with a breather/release material that prevents all following layers from bonding with the carbon but allows excess resin to flow through it. This layer is then followed by a perforated plastic. This plastic sheet, with a pre-specified amount of holes, allows the correct amount of resin to stay in the fiber once the vacuum is applied. A layer of fleece is added next to absorb the excess resin that bleeds up through the perforated plastic. The whole mold is then covered with a vacuum bag sheet. Since our layups were done on a smooth, flat piece of glass, we were able to use this surface for a vacuum seal. Sealing tape was laid out around the parts and then stuck to the vacuum bag. A plug is inserted away from the mold to provide the means to pull the vacuum. As the vacuum is pulled using an electro-mechanical pump, the vacuum bag must be massaged into the more complex mold contours to ensure that the carbon fiber takes the mold shape properly. Once satisfied, the setup is left like this to cure overnight.

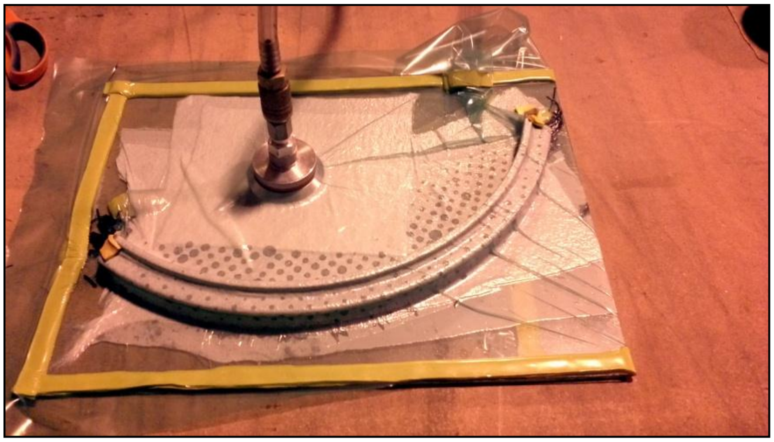


Figure 21. A rim profile piece curing in the vacuum bag setup

Initially only 2 layers of fiber cloth are applied in the layup. This was then allowed to fully cure and subsequent layups are then used to add bulk and strength to the part whether it was the carbon mold or the final wheel. These first two layers are meant to "capture" the geometry and curves of the part without making it too stiff. Once this initial layup is cured, the part can be popped off the mold. Since the Frekote is not perfect and the parts tend to stick a bit to the mold anyways, this ensures that the part will be able to release off the mold in later layups. After another application of Frekote to the mold surface is applied, again to prevent any possible mold-to-part bonding, the part is placed back onto the mold and the next bulking/strengthening layups take place. Essentially the process breaks the removal of the partial mold to part bonding and the geometric stiffness of the part coming off the mold into two operations.

Some parts of our carbon molds did not require the use of a vacuum bag. An example of this was the 'brackets' we designed to help hold the rim pieces together. The process is very similar to the one explained above, however, the part is simply left out in the air to dry and never has a vacuum applied to it. Figure 22 shows how this was done. Note the brackets lying down against the flat acrylic board.

A complete set of drawings detailing the desired carbon molds can be found in Appendix B in the 200 series drawings. Note again that the flanges to hold the hoop molds together were applied in a second process detailed below.

Figure 22. Flanges drying on hoop pieces after hand layup

After the entire process of creating the carbon molds was complete, the male hoop mold was still in fairly good shape. Most of the damage is on a non-part surface and the ends just needed to be filled in with a small amount of Bondo. The piece to create the flush disc, however, did not really survive the process. Since the final wheel layup requires a slight draft angle on the hub to release the part, a negative draft was required on the foam mold. In removing the carbon flush disc mold from the foam mold, the backside of the foam mold had to be excavated to allow for the release of the part. This destroyed the hex hole in the middle of the foam beyond the point of repair with Bondo.

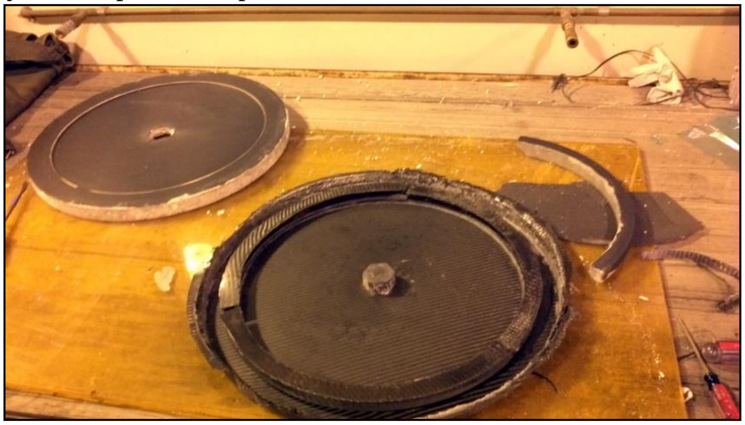


Figure 23. Female molds shown with the male plug molds

5.3 Final Wheel Layup Preparation and Process

For the final layup of the wheel, we needed a balanced, uniform wheel layout. In order to ensure we laid down uniform sheets of carbon in the correct orientations, we needed a way to provide repeatable cutout pieces of carbon fiber cloth. Utilizing a laser cutter provided the consistency we needed and saved a significant amount of labor time. After designing the shape of the layup pieces needed, we took the carbon to a laser cutter to cut the templates to the exact specifications. We laser cut the carbon while it was dry which gave us time to get ready to do the actual layup without worrying about the resin curing. The shapes cut and their layouts can be found in Appendix B in the 400 series drawings.

In the process of building fully carbon disc wheels, the most critical step in ensuring the final wheel is both concentric and true is to make sure that the mold is as perfect as possible. Since we do not want to sand past the outer layer of resin on the wheel because it destroys the fibers below, we can only do minimal post-process sanding to take down high spots on the wheels. Consequently, the final quality of the wheel is primarily determined by the quality of the mold it came from. The pieces of the mold, specifically the 3-piece rim molds, had to be fitted and held together to ensure an accurate final product. Bondo was used to help line up all the pieces. Once the pieces were set into a Bondo base to provide the correct offset from the flush disc, an inside micrometer was used to ensure an equidistant radius from the hub to the inside of the rim profile in 6 different places along the rim. The hoop sections were pressed into the Bondo and once the Bondo cured, it provided an imprint for the hoop piece to sit in and to stay aligned with respect to one another as well as to the bottom disc mold. Any remaining error in the alignment of the mold was corrected with Klean Klay, a non-drying modeling clay. Figure 24 shows the mold pieces assembled together and ready for layup preparation.

Figure 24. Carbon fiber disc mold with 3-piece rim mold attached and aligned

The hoop pieces were made to have a slightly larger radius than the flush disc to allow for adjustment in the alignment. The resulting gap was filled with Klean Klay along with any gaps in the adjoining hoop pieces along the rim profile. The hoop pieces were held together by clamping the flanges together to ensure they would not move outward from the center. Once all gaps were filled and the clay was smoothed to a satisfactory level, the layup procedure could begin. Since the vacuum bag would apply close to 14 psi over the entire mold, we wanted to make sure that the overhanging rim pieces would not be crushed by the vacuum bag. Therefore, after the breather, perforated plastic, and fleece were laid down, we wrapped small pieces of Klean Klay in fleece and inserted them into the rim to ensure both that the carbon fiber lied directly against the mold and to add support to keep the top of the rim profile from bending downward due to the vacuum bag. The flanges we added to the rim mold ended up being beneficial in more than one way. Besides for helping to keep the molds aligned, which was their primary purpose, they also provided an opposing moment once a vacuum was pulled to keep the hoop pieces from warping downward. The carbon fiber layup process was similar to the process described for the carbon mold layup.

The side of the wheel with the rim consisted of the flush disc with the hub centerpiece and the three hoop pieces. With this side we employed the 90°/45°/90°/45° orientation of the cloth pieces with 12 strands of uni-directional tape in a radial orientation to mimic the design of traditional wheel spokes. These spokes were placed parallel to the edges of the hub, two coming from each edge straight out to the rim. As described in this report, the uni-directional fiber is used to meet equivalent strength and stiffness parameters for a 20" spoke wheel. Analysis for this can be found in Appendix E. Since these parameters are met with just the use of the uni-directional there is no need to add more than one layer of fiber to form a disc, but we added four to ensure our design would function if the uni-directional layup failed to perform as expected. The extra discs added also contributed to the stiffness of our final wheel in planes not parallel with the disc. In order to allow for the carbon to wrap around the rim profile we used triangles that extended from the hub out along the bottom, and then up around the rim profile. The triangles were cut in 50° and 70° wide angles to prevent the seams of the two triangle layers to coincide which would become a potential weak spot in the final product. Rectangles were also cutout and were laid up in the rim profile, using 6 to cover one layer of the inside of the rim. See Figure 25 for a detailed schematic of the layout schedule. The plies were applied from bottom to top in the figure. Note that in order to achieve the 90°/45°/90°/45° pattern required, half of the laser cut pieces must be oriented with the fibers running straight up and down with respect to the drawing view and the other half must be rotated 45° from the drawing view.

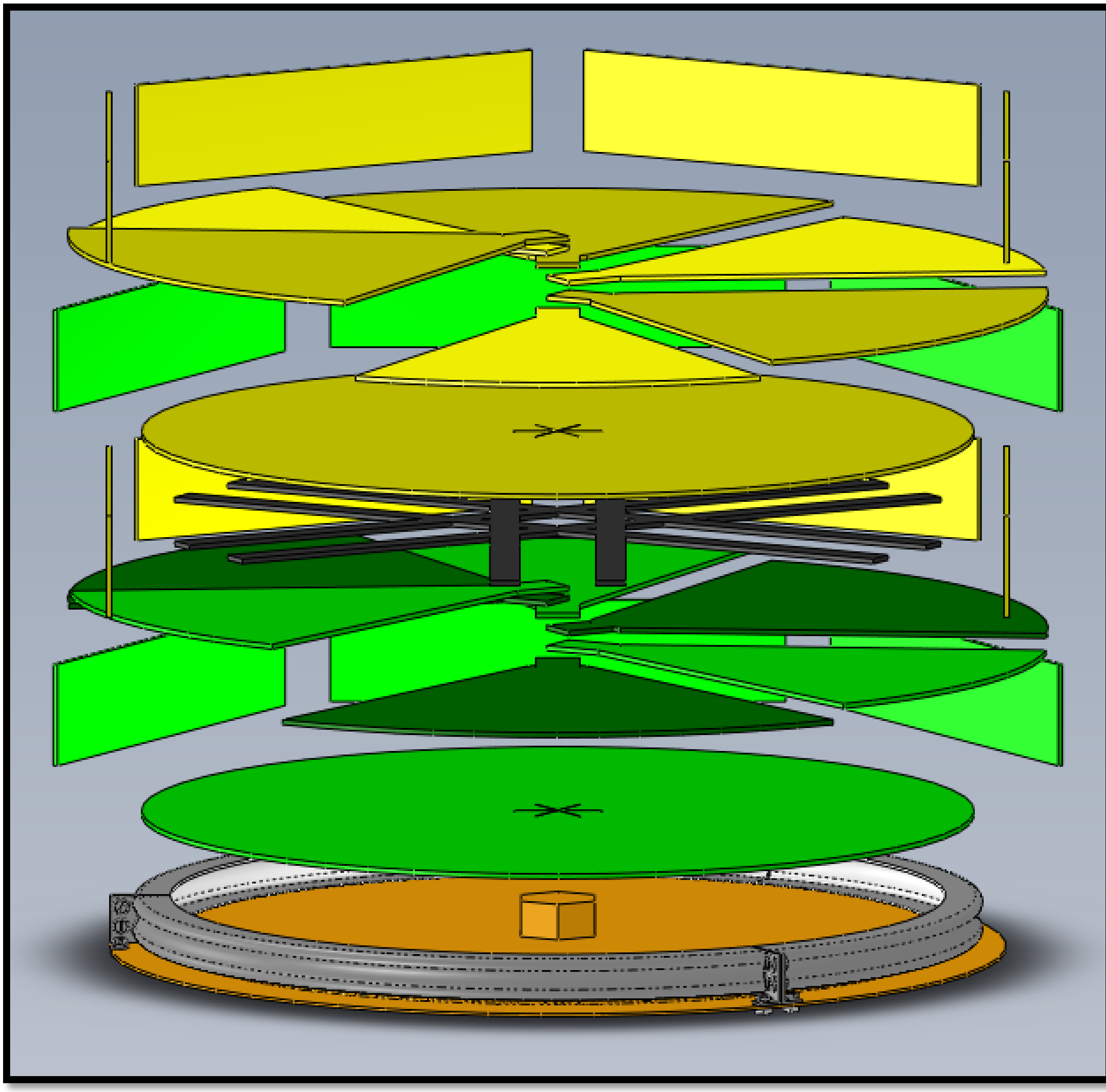


Figure 25. Wheel layup schedule

The colors in Figure 25 represent the orientation of the fibers. The green pieces are cut in the 0-90° orientation and the yellow in the 45-45° orientation. The black is the unidirectional tape. The slight color difference in the triangle pieces highlights the wider and narrower pieces and their orientation to the each other, note that the wide 45-45° gets placed on the narrow 0-90° degree piece and vice versa. Also note that while only three or four of the rectangular pieces are shown in each layer, six are actually included in in each layer, the missing ones are removed for clarity. All of these pieces, with the exception of the rectangular ones, are oriented by the hub. By cutting them out of the cloth in the correct orientation, nothing more is needed to ensure that the two orientations are canceling each other. The disc pieces have small triangular bits cut out from the star pattern in the middle, these push up to form straight edges along the edge of the hub with the leftover triangular bit forming onto the hub. The triangle pieces have a rectangular tab, the base of this tab lines up with the bottom edge of the hub and the tab forms the wall of the hub.

The opposing side of the wheel is merely a flat disc with a hexagonal hole in the middle. This was done by cutting a hexagonal hole in four circles of the correct diameter, two of which that are rotated 45° to provide the two orientations. These are layed up one after the other onto the original foam mold with the hexagonal nub in the middle for orientation. The foam mold was used because it did not suffer from the bridging of fiber and resin at the corner of the hub and because it was actually sturdier as well.

5.4 Custom Hub

As described earlier in this report, our hub was custom CNC-machined from hexagonal aluminum stock to properly interface with our composite wheel as well as have a standard interface with both the bicycle and with standard hub internals such as the bearings, axles, and free hub. All of the internal components of a Shimano Deore XT mountain bike hub were used and inserted into our custom hub design. The following figure shows what our final hub design looks like compared to a standard bicycle hub. The detailed drawing for hub manufacturing can be found in Appendix B with drawing number 303.

Figure 26. Custom hub design side-by-side with a standard bicycle hub

5.5 Assembly

The final pieces were trimmed, sanded, and cleaned up to allow for easy assembly, detailed drawings of them can be found in Appendix B in the 300 series drawings. Six lb/ft^3 foam core was inserted in between the discs to provide more rigidity to the final wheel. The addition of a foam core will prevent the discs of the wheel from buckling under axial and radial wheel loads. The foam was glued into the disc side with the integrated rim profile. The flat disc was then glued onto the top of the foam to complete the wheel.

Figure 27. Components ready for assembly

Figure 28. Sanding down the foam core before gluing the flat disc on

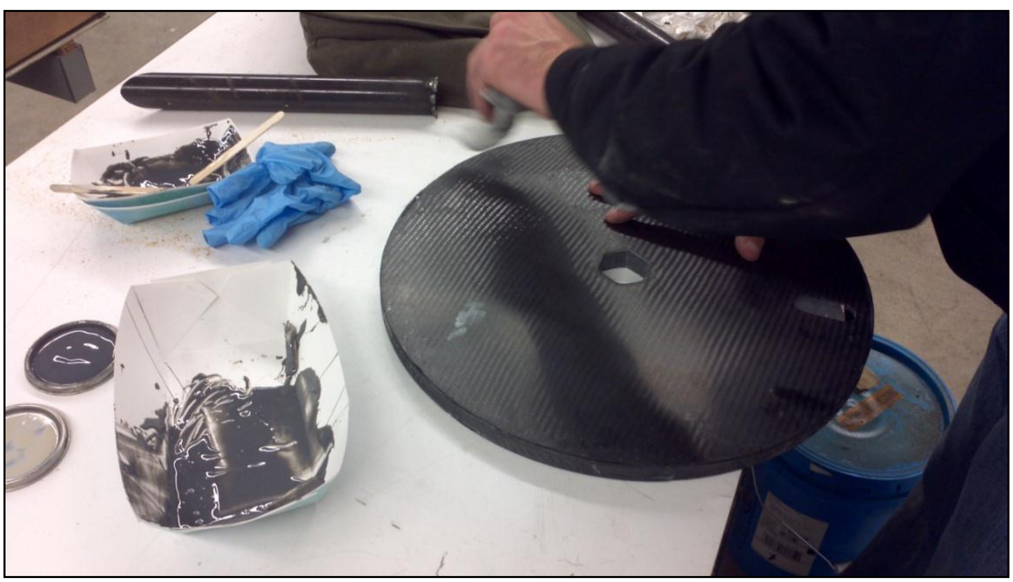


Figure 29. Wheel Assembly, note the Presta valve access hole

Once the glue was cured to hold the wheel together, an ovular through-hole was made in the discs and foam to allow access to the tire's valve stem. A hole was drilled radially into the rim profile to allow the stem to stick through. The hub was then acid etched and epoxied into the hexagonal hole in the wheel. All of the other components, such as the bearings and axle, were assembled into the hub in preparation for installation of the wheel onto a bicycle. The final step in assembly was to glue the tubular tire to the rim and allow it to dry before inflating or using the wheel.

All together, the prototype wheel weighed in at 1170 grams before the wheel. This is 10.7% higher than our design goal, but we believe that 1 kg can be achieved with a lighter foam core. A weight breakdown of each component can be found below in Table 11.

Table 11. Wheel component weights

Component:	Disc	Rim/Disc	Hub (assembled)	Foam Core
Weight (g)	154	300	460	256

5.6 Differences in Prototype and Planned Design

PolyWheel began this project with very limited knowledge about carbon fiber and the process that goes into building carbon parts. We learned a significant amount by actually going through the process of building this wheel. Consequently, some planned design aspects of our wheel changed as the manufacturing process of the project commenced.

One major change made in our physical prototype was the addition of a foam core. We originally planned to build a wheel with a hollow core which would save on complexity and weight of the final product. Upon inspection of our final discs, we determined that a core piece would be necessary to keep our final wheel as stiff as we expected it to be. This was because large sheets of carbon fiber, such as the sides of the disc, are very strong with respect to in-plane forces, but easily twist and bend. The foam core turns the two individual sheets of carbon into a box section that resists torsion and bending. The actual addition of a foam core was simple and only added a small amount of labor time to the overall manufacturing of the wheel.

Material selection for our prototype was also different than what we had planned. Initially, we wanted to use a pre-preg cloth that would need to be cured in an autoclave for the final wheel. Both the scheduling of autoclave time and the addition of other materials in the carbon molds (such as Bondo) that would not expand with the same thermal coefficient in the autoclave led us to change to a wet layup. We don't believe the final strength of the wheel was compromised. The only real change to our wheel was that is became quicker to produce at the expense of working with wet cloth which is a little more difficult to manage.

Another aspect of our planned design that changed with our actual prototype dealt with the strength of the rim profile molds while in a vacuum bag. The rim profile in the final wheel bowed inward due to the vacuum bag pushing downward. We corrected as much as possible by bulking up the mold more and by adding clay filler into the rim profile before a vacuum was pulled. As can be seen in the hole where the valve stem is located, the rim profile does not lie flush against the flat disc, but points downward. This allows a smaller area of bond surface on the rim profile for the flat disc to glue to. Consequently, the flat disc is mostly held in place by the foam in the prototype.

5.7 Recommendations

The quality of our prototype wheel came out great considering the learning process we all had to go through to build both the molds and the wheels. That being said, there are several recommendations we would make to change some aspects of this manufacturing process if this same wheel design was done in the future. These changes would help to improve the final quality of the wheel as well as make the overall process a little less complex.

The first recommendation we would make is to use a lower density core material. This could be in the form of a different type of foam or possibly Nomex. The foam we used in the prototype was readily available to us and gave us a good basis for building a prototype; however, it is not as light as it could be. Since the foam core is essentially only used to hold the carbon discs in place, the strength of it is not critical. Therefore, lower density foam would not adversely affect the strength of the wheel. The foam core could also be slot drilled to take out excess material not needed. As long as the slots are done in a uniform fashion, the wheel will remain in balance.

The wheel can be made in an autoclave, but more extensive molds would need to be manufactured. A different type of system would have to be designed to keep the rim molds aligned with one another. If this is the case in future mold designs, all jigs and attachments would need to be made out of carbon fiber unless the thermal expansion of the specific jig part would not affect the final part. This will prove more expensive than a wet layup where the jigs can be manufactured from cheaper materials. The jigs, however, could provide geometric benefits ensuring the final product is more easily made concentric, balanced, rigid, and uniform.

The molds themselves can be improved greatly now that we know how the process works and we believe a few more iterations will provide a superb wheel. The rim profile pieces need extra support to prevent them from bowing downward as they are curing after a vacuum is pulled over them. Stiffer flanges are needed between the pieces to hold them in position relative to one another. Making the mold as stiff as possible in the future is the best way to improve the quality and look of the final product.

Another major aspect of this project that we uncovered as we got further into it was that the use of an autoclave makes the mold design much more complicated and is not absolutely necessary in the design of high quality carbon fiber disc wheels. Our design in this project incorporated the manufacturing of carbon molds to allow the final wheel layup to be put into an autoclave. Knowing what we know now about wet layups and the intricacies behind them, we would recommend opting out of the use of an autoclave to build the final wheel as we did in the prototype. If we had the chance to go back to the drawing boards again and re-design the molds, we would recommend them to be made out of fiberglass. This would be much cheaper and added layers could easily be added to stiffen the molds.

6 Design Verification

6.1 Testing Setup

Due to time constraints, final testing has not been performed on the prototype wheel. What follows is the recommended testing procedure that has already been performed on a standard spoked wheel for a baseline comparison. Results for this testing can be found in Appendix C.

The data collection system for these tests involves the use of strain gages and a small, portable data acquisition board capable of being mounted to the wheel. For the spoked wheel test a SWOOP board provided by Professor Ridgley was used and is suitable for use with the disc wheel as well. Two strain gages are to be single direction strain gages placed in a radial fashion on the surface of the disc, one near the hub and the other near the rim along the same radial line. Figure 30 shows the placement of the strain gages on the spoked wheel below, the placement on the disc wheel should mimic this. More reliable results could be found by placing this setup on two or more separate locations of the disc to ensure the behavior of the entire wheel was being adequately measured.

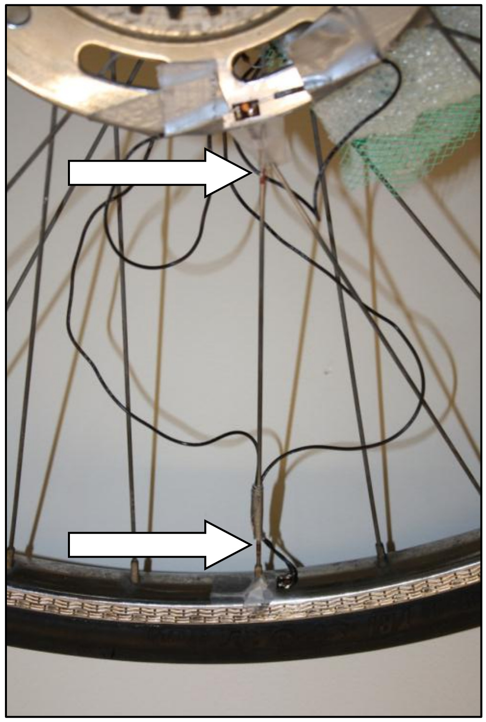


Figure 30. Strain gage placement on spoked wheel

The strain gages used in the spoked wheel were very small to fit onto the spokes, this is not the case for the disc wheel. Since the carbon fiber is an anisotropic material, a larger strain gage is needed to capture a larger area of the disc to get an average result for the behavior. The two strain gages get wired into opposite arms of a Wheatstone bridge circuit to amplify the signal to make it easier to record. This has the side effect of having no temperature compensation, however. In the very small gages on the spoked wheels this meant having to wait approximately forty seconds for the temperature change from the circuit current to level out before recording data. This can be remedied with two solutions: wiring both on the same arm of the circuit and losing the amplification of the signal, or getting two more gages to either act as dummy gages on a non-stressed portion of fiber or wired along the same radial path as the previous two. Figure 31 below shows the wiring diagram for the first, two gage setup.

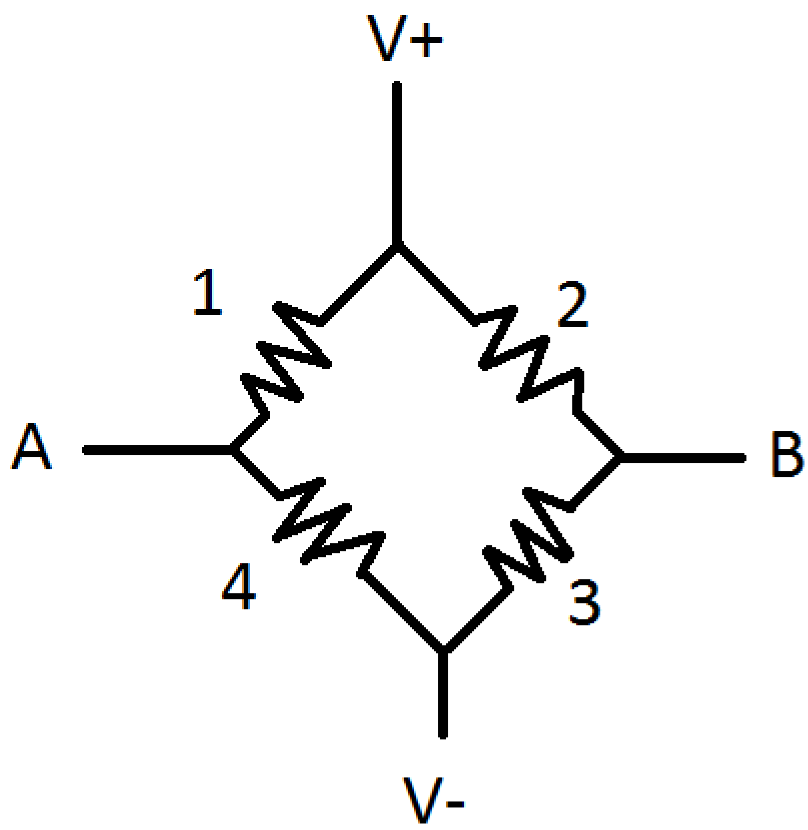


Figure 31. Wheatstone bridge wiring diagram

The two gage setup is placing the gages at locations 1 and 3 while filling 2 and 4 with resistors that match the nominal resistance of the gages used. V+ and V- are provided by the SWOOP board or whatever data acquisition system is being used, and V_A-V_B is what is used to determine the strain seen by the gages.

The SWOOP board could be placed conveniently between the spokes on the spoked wheel, but it will need to be attached to the surface of the disc wheel. This should not be an issue if it can be attached near the hub because the disc wheel is much narrower than the spoked wheel in this area so it should clear the rear stays of the frame. The only setting on the SWOOP board that can affect the results is the data sampling rate. We found that the maximum sampling rate the board could reliably operate at was 100 Hz. If a data acquisition system with a higher sampling rate could be found to work with the setup, faster riding speeds would be possible for dynamic data acquisition.

6.2 Testing Procedures

The procedures used to measure the strains in the wheel can be divided into two main subsets: static and dynamic testing. For static testing both the radial and lateral stiffness of the wheel is analyzed. Radial strain is measured by mounting the wheel to a bicycle frame and having a person sit on the seat or by loading the axle equally on both sides with a comparable force pointing straight down. Establishing a line pointing straight down from the hub and perpendicular to the ground as 0°, the strain is measured by aligning the strain gages from -30° to 30° and taking measurements at one or two degree increments. This allows a plot to be generated showing the displacement of a location on the wheel as it passes through the loading zone.

The lateral strain measurements are taken without mounting the wheel to a bike frame, but by laying it on its side and supporting two opposite sides of the rim and applying a vertical load at the hub. A schematic showing this setup for the spoked wheel is found below in Figure 32, the disc wheel setup looks exactly the same except without the spoke lines.

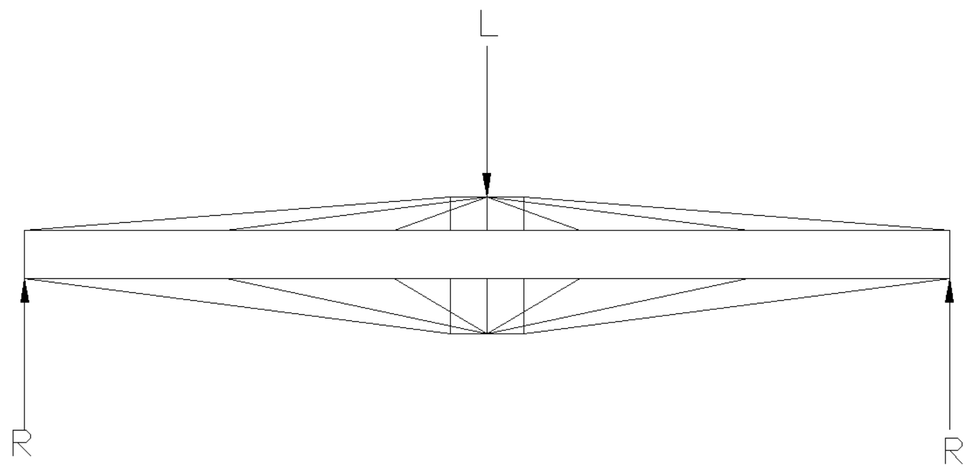


Figure 32. Loading schematic for lateral stiffness

The load L applied at the hub is increased in increments of five pounds to approximately 25 lbs with a data point being recorded at each load. The goal in this setup is to measure the lateral (vertical in Figure 32) displacement of the hub for a given load. Using the strain gages is somewhat of a geometry problem to calculate this from radial strain. An alternative to using the strain gage setup would be to place a dial indicator on the hub that directly measures the lateral displacement without any calculations.

The dynamic testing is limited by the sampling rate of the data acquisition system being used, in the case of the SWOOP board it is 100 Hz. This allowed for a maximum speed of approximately 135 rpm (10 mph for a standard 27” wheel) to ensure complete data collection. This provides a reasonable representation of the behavior of the wheel during dynamic operation, but higher speed tests would be very desirable. With a high speed data acquisition system, testing could be run at speeds closer to those found in the actual HPV competitions and if a very quick system could be used, impact testing from dropping off a curb or hitting a small obstacle such as a 2x4.

7 Conclusions and Recommendations

Overall, we believe that the mold setup we have created can be used to make parts that meet the specifications set by George Leone and the HPV team. Our prototype suffers from the rim being slightly bent inwards which greatly lowers the amount of glue surface to the flat disc piece, but this can be corrected by added more plies of carbon to the rim pieces. A more permanent offset than Bondo between the flush disc and the hoop pieces would improve the consistency of the layups and would also shorten the setup time ensuring concentricity. Even if it determined that the prototype wheel is not strong or stiff enough after ride testing, our mold setup allows for the addition of more plies of carbon wherever needed without changing any of the functional geometry of the wheel.

References

1. Alvernaz, James C., Verent Chan, Brian Hamstrom, David Lewis, and James Sciaini. *Supermileage Seat and Wheel Development and Production Final Report*. Rep. San Luis Obispo: Central Coast Composites, 2010. Print.

2. Brandt, Jobst, and Sherry Sheffield. *The Bicycle Wheel*. Palo Alto, Calif., USA: Avocet, 1993. Print.

3. Comète Track - Wheels - Track - Mavic." *Mavic | Mavic Is a French Manufacturer of High-end Bike Systems and Rider's Equipment.* Web. 04 Mar. 2011. <http://www.mavic.com/en/product/wheels/track/wheels/Comète-Track>.

4. "DISC Wheels Carbon Carbon Wheels CORIMA." *Corima Roue Carbone Roues Carbone Jante Carbone Selle Carbone Cadre Carbone*. Web. 04 Mar. 2011. <http://www.corima.com/gb/produits/roues/default.cfm?family=roues_para>.

5. "Road Wheel Weights." *Town & Country Real Estate - Traverse City Real Estate - Traverse City Homes*. Web. 04 Mar. 2011. <http://www.tc-homes.com/bike/features/wheels/cover.htm>.

6. *Spinergy*. Web. 04 Mar. 2011. <http://www.spinergy.com/catalog/product_info.php?products_id=89>.

7. "Tubeless Wheels." *Weight Weenies*. Web. 04 Mar. 2011. <http://weightweenies.starbike.com/listings/components.php?type=ustwheels>.

8. "Wheel Performance Discussion_Disc." *Analytic Cycling, Interactive Methods for Estimating Cycling Performance Parameters. Tom Compton*. Web. 04 Mar. 2011. <http://www.analyticcycling.com/WheelsConcept_Disc.html>.

9. *Wikipedia. 'Bicycle Wheel'. 3/2/11. <http://en.wikipedia.org/wiki/Bicycle_wheel>.*

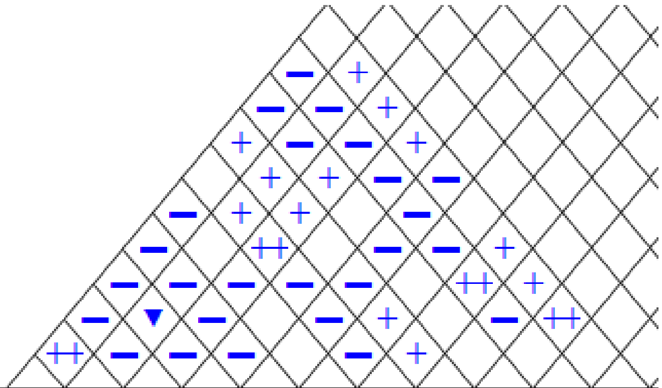
10. Willett, Kraig. "Wheel Performance." *Bike Tech Review*. Web. 3 Mar. 2011.

11. Wilson, David Gordon, Jim Papadopoulos, and Frank Rowland. Whitt. *Bicycling Science*. Cambridge, MA: MIT, 2004. Print.

12. *Zipp - Speed Weaponry*. Web. 25 Jan. 2011. <http://www.zipp.com/>.

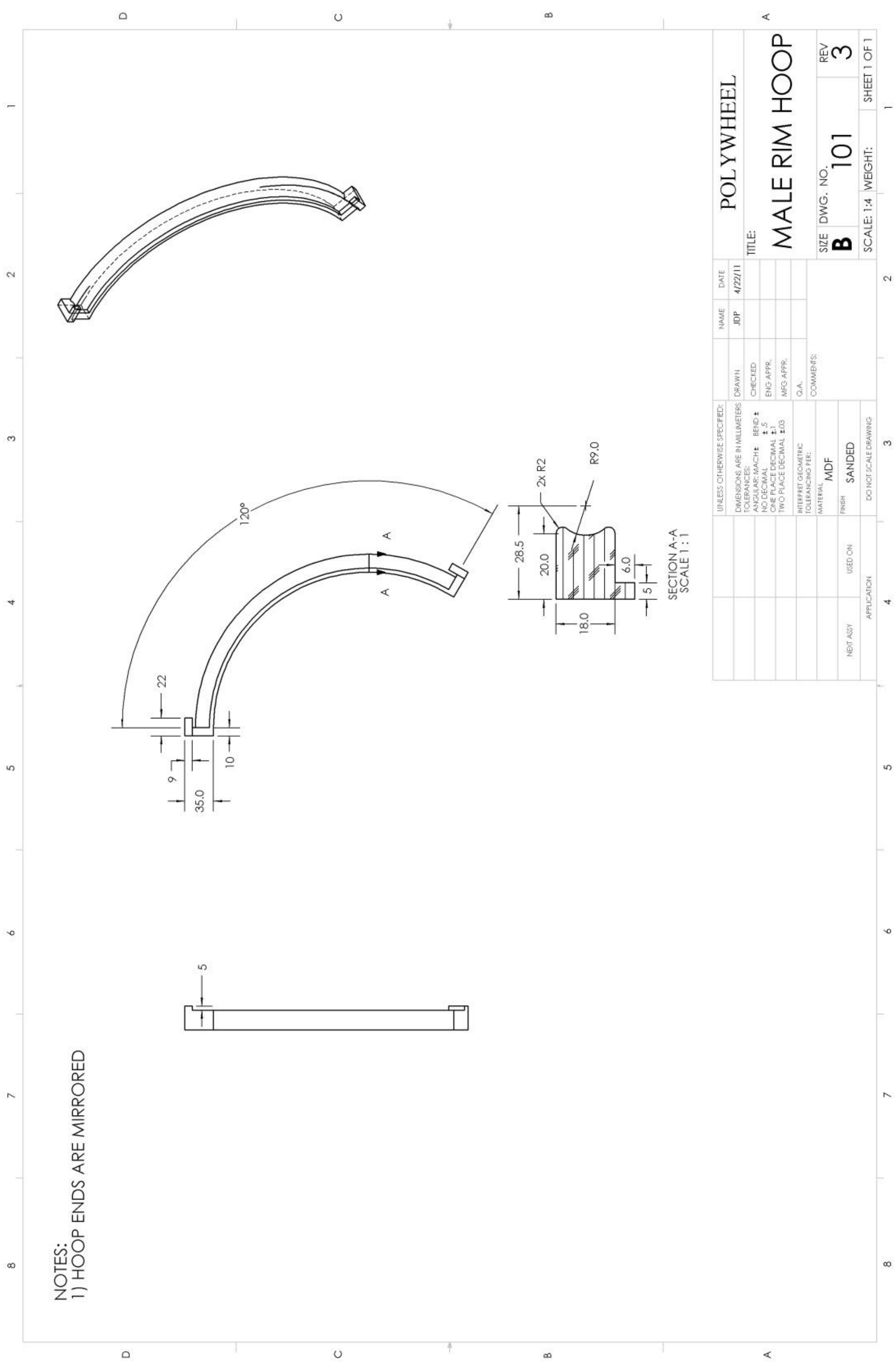
Appendix A - QFD

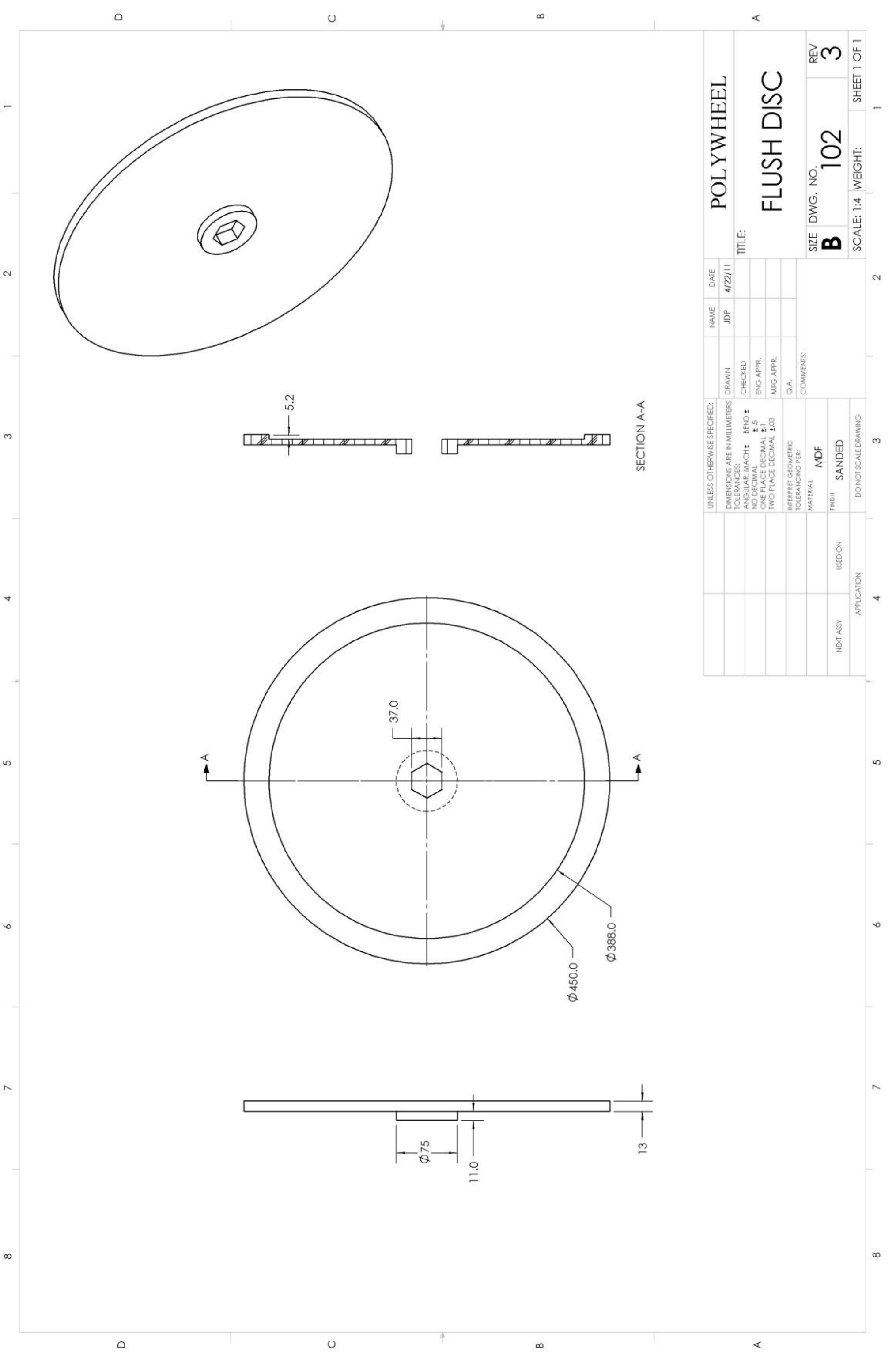
Legend		
⊙	Strong Relationship	9
O	Moderate Relationship	3
▲	Weak Relationship	1
++	Strong Positive Correlation	
+	Positive Correlation	
—	Negative Correlation	
▼	Strong Negative Correlation	
▼	Objective Is To Minimize	
▲	Objective Is To Maximize	
x	Objective Is To Hit Target	

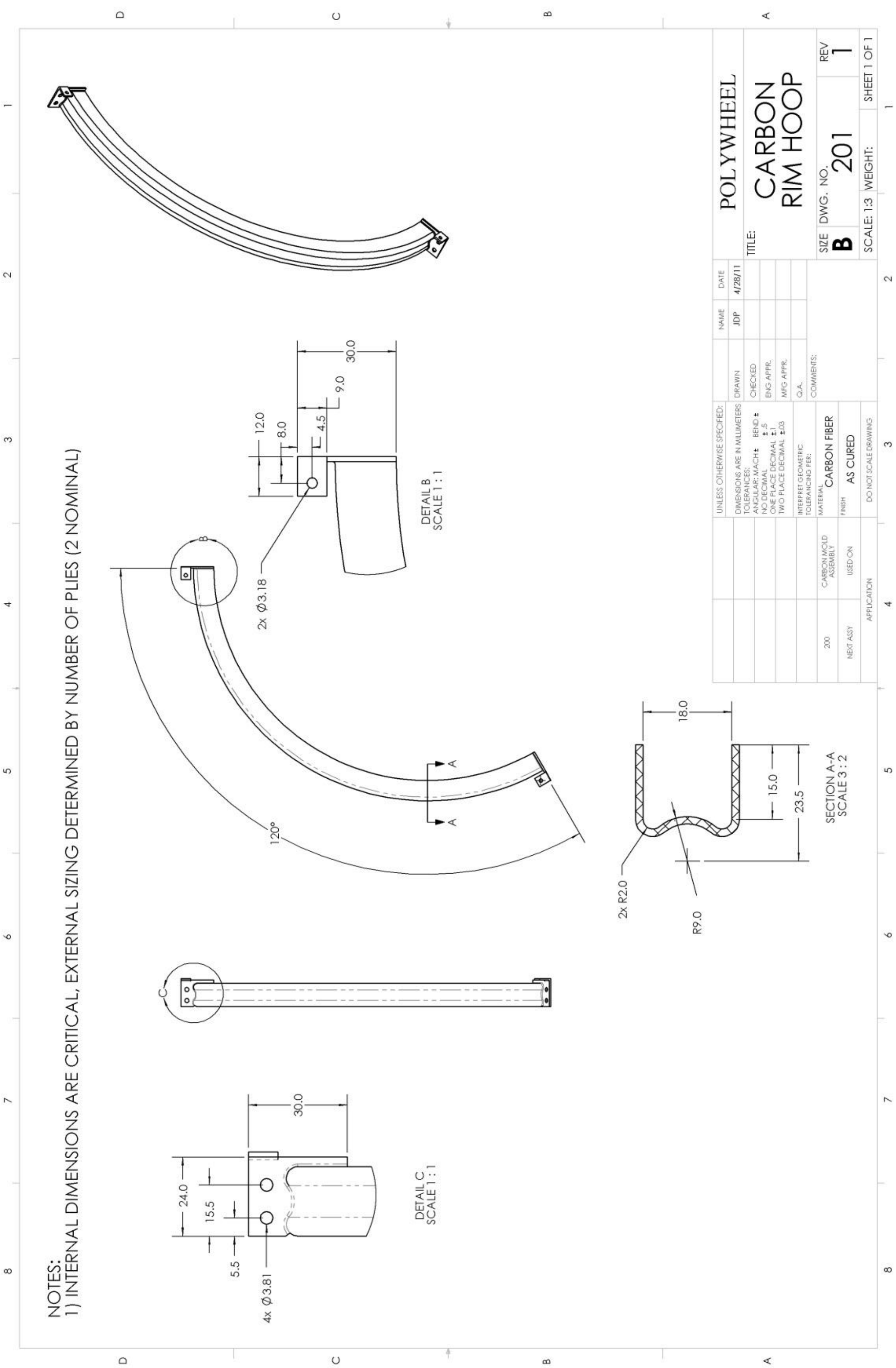


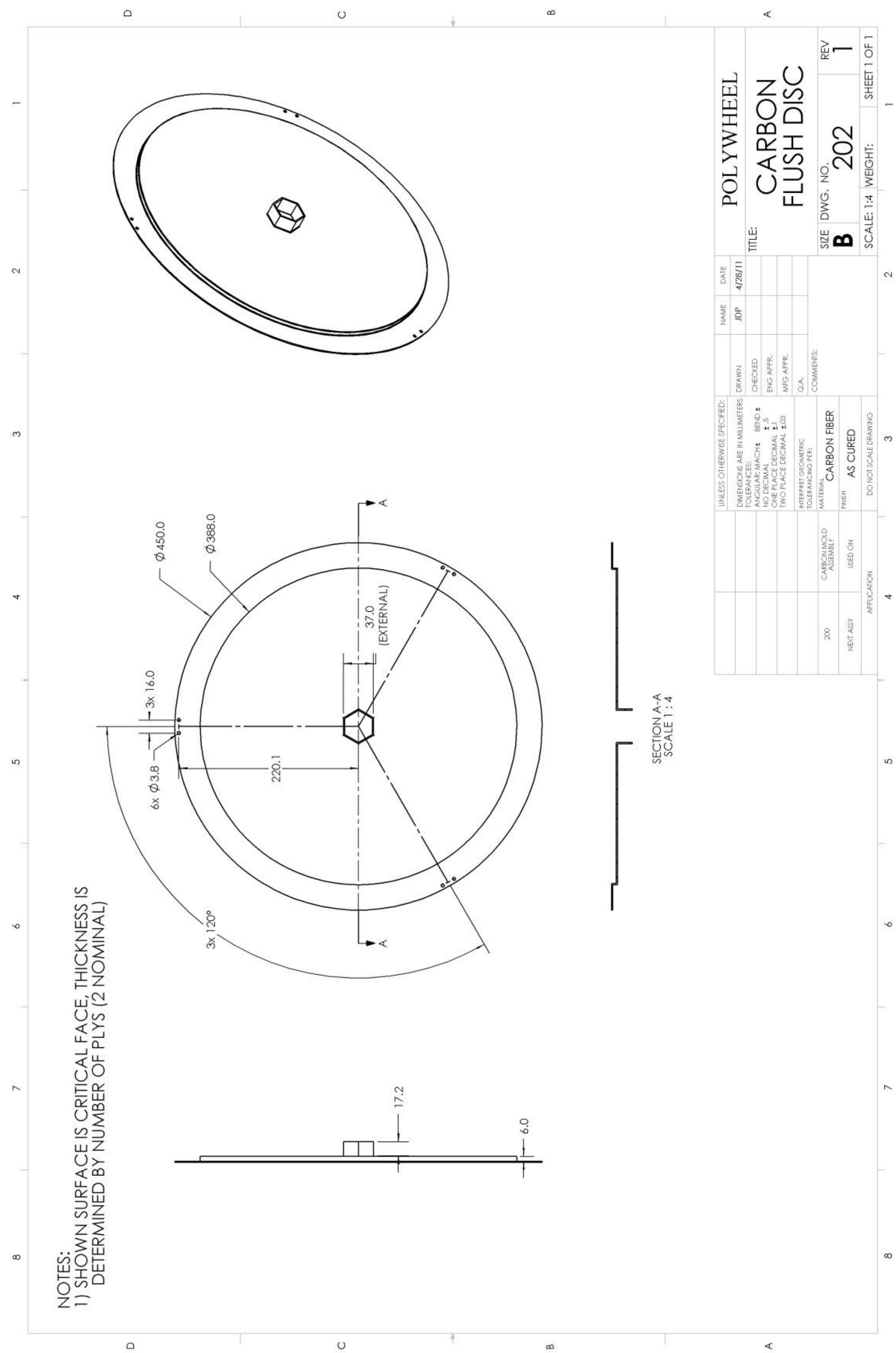
Row #	Max Relationship Value in Row	Relative Weight	Weight / Importance	Column # → / Demanded Quality (a.k.a. "Customer Requirements" or "Whats") ↓ / Quality Characteristics (a.k.a. "Functional Requirements" or "Hows") →	1 Hold tire pressure	2 Must Hold a static load radial load	3 Increase Aerodynamics over standard wheel	4 Total Weight	5 Cost	6 rim diameter	7 Max. operating speed	8 True to within +/-	9 Suffer no long term consequences from environment	10 Can withstand a lateral load	11 Makes people go WOW
				Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x)											
1	9	10.3	8.0	Lightweight*	▲	▲		⊙							
2	9	11.5	9.0	Sturdy/Durable*	⊙	⊙		▲			⊙			O	
3	9	12.8	10.0	Reliable*	⊙	⊙			▲		⊙	O		O	
4	9	6.4	5.0	Easy Installation	▲			▲		⊙					
5	9	6.4	5.0	Low Price				O	⊙			O			
6	9	2.6	2.0	Attractive Looks								▲			⊙
7	9	9.0	7.0	Aerodynamic			⊙				▲	▲			
8	9	10.3	8.0	Efficient			⊙	⊙			O	▲			
9	1	10.3	8.0	Common Tire Sizes				▲		▲					
10	9	7.7	6.0	Weatherproof									⊙		
11	9	12.8	10.0	20" Wheel*						⊙				▲	

Appendix B – Drawing Packet

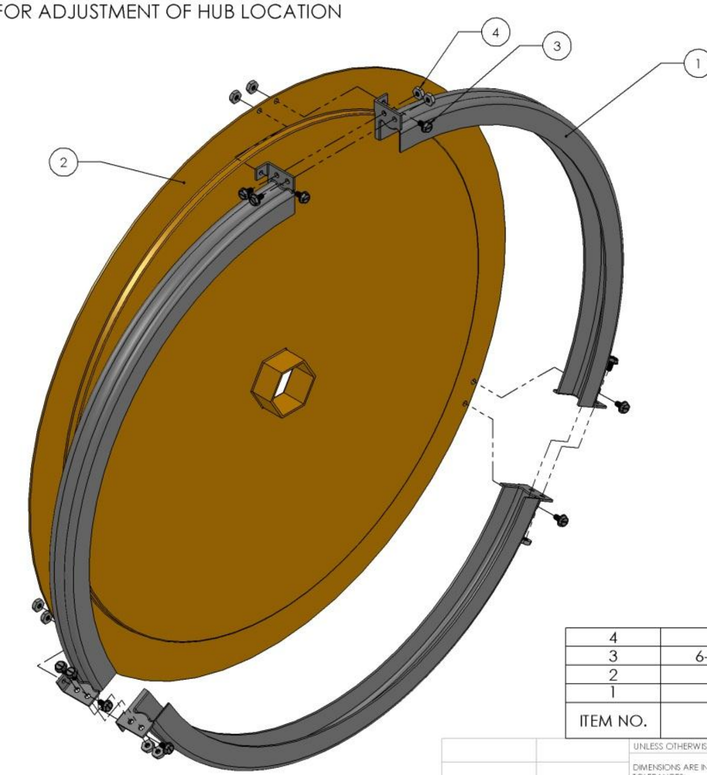



POLYWHEEL
TITLE:
FLUSH DISC
SIZE
B
DWG. NO.
102
REV
3
SCALE: 1:4
WEIGHT:
SHEET 1 OF 1
NAME
DATE
DRAWN
JDP
4/22/11
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
ANGULAR: MACH ± BEND ±
NO DECIMAL ±.5
ONE PLACE DECIMAL ±.1
TWO PLACE DECIMAL ±.03
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
MDF
FINISH
SANDED
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
SECTION A-A
5.2
37.0
Ø450.0
Ø388.0
Ø75
11.0
13
A
B
C
D
1
2
3
4
5
6
7
8


NOTES:
1) INTERNAL DIMENSIONS ARE CRITICAL, EXTERNAL SIZING DETERMINED BY NUMBER OF PLIES (2 NOMINAL)
DETAIL B
SCALE 1 : 1
DETAIL C
SCALE 1 : 1
SECTION A-A
SCALE 3 : 2
2x Ø3.18
4x Ø3.81
12.0
8.0
4.5
9.0
30.0
24.0
15.5
5.5
120°
18.0
15.0
23.5
2x R2.0
R9.0
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NAME
DATE
JDP
4/28/11
MATERIAL
CARBON FIBER
FINISH
AS CURED
DO NOT SCALE DRAWING
200
CARBON MOLD ASSEMBLY
NEXT ASSY
USED ON
APPLICATION
POLYWHEEL
TITLE:
CARBON
RIM HOOP
SIZE
B
DWG. NO.
201
REV
1
SCALE: 1:3
WEIGHT:
SHEET 1 OF 1


NOTES:
1) SHOWN SURFACE IS CRITICAL FACE, THICKNESS IS DETERMINED BY NUMBER OF PLYS (2 NOMINAL)
Ø450.0
Ø388.0
3x 16.0
6x Ø3.8
220.1
37.0 (EXTERNAL)
3x 120°
A
A
SECTION A-A
SCALE 1 : 4
17.2
6.0
POLYWHEEL
TITLE:
CARBON FLUSH DISC
SIZE B
DWG. NO. 202
REV 1
SCALE: 1:4
WEIGHT:
SHEET 1 OF 1
DRAWN JDP 4/28/11
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
MATERIAL CARBON FIBER
FINISH AS CURED
DO NOT SCALE DRAWING
200
CARBON MOLD ASSEMBLY
NEXT ASSY
USED ON
APPLICATION

NOTES:
1) PLAY IN SCREWS ALLOWS FOR ADJUSTMENT OF HUB LOCATION



ITEM NO.	DESCRIPTION	PART NUMBER	QTY.
4	6-32 HEX NUT		12
3	6-32 MACHINE SCREW		12
2	Carbon Flush Disc	202	1
1	Carbon Rim Hoop	201	3

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
ANGULAR: MACH ± BEND ±
NO DECIMAL ±.5
ONE PLACE DECIMAL ±.1
TWO PLACE DECIMAL ±.03
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	JDP	4/28/11
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

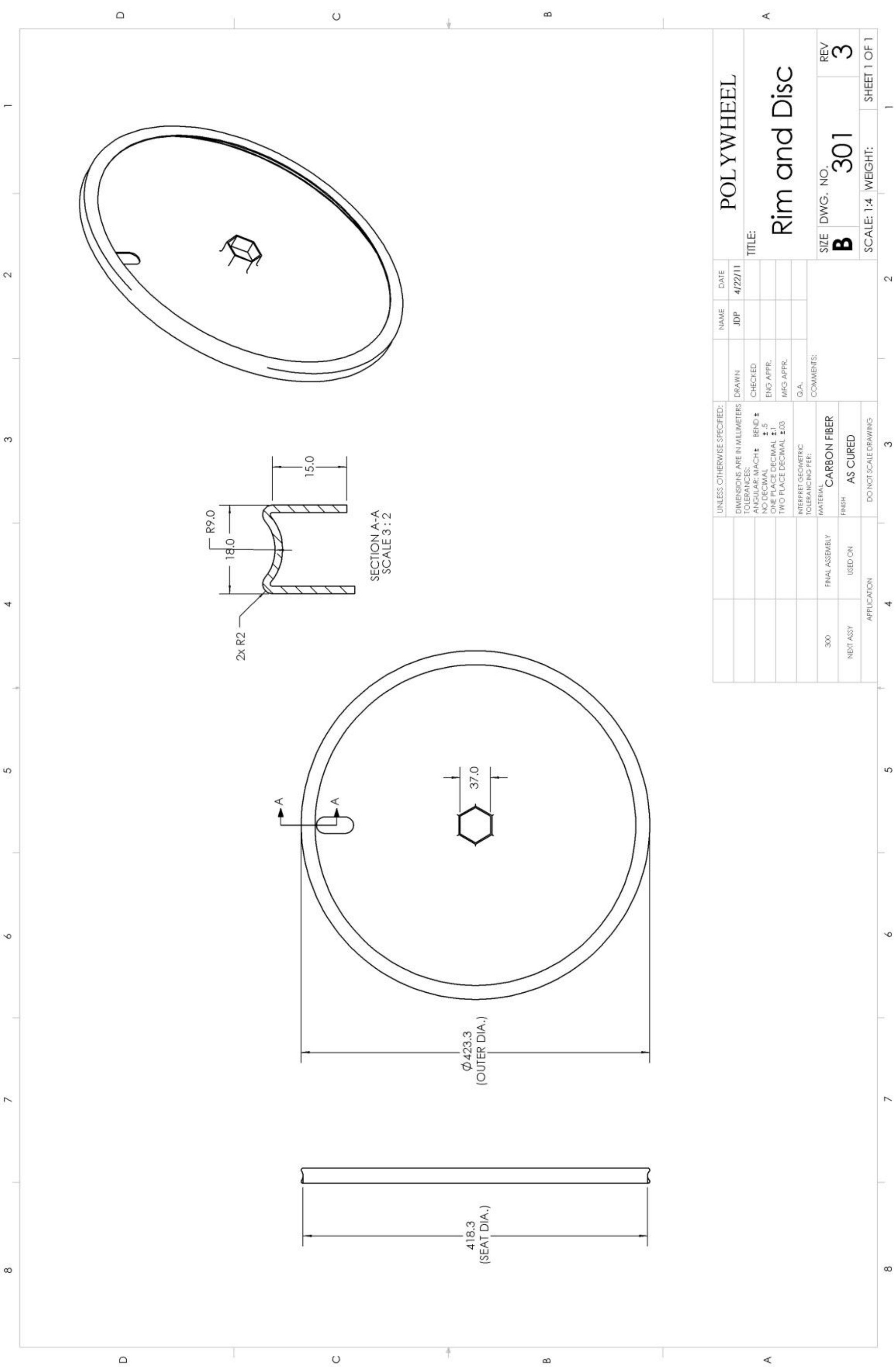
NEXT ASSY | USED ON
APPLICATION

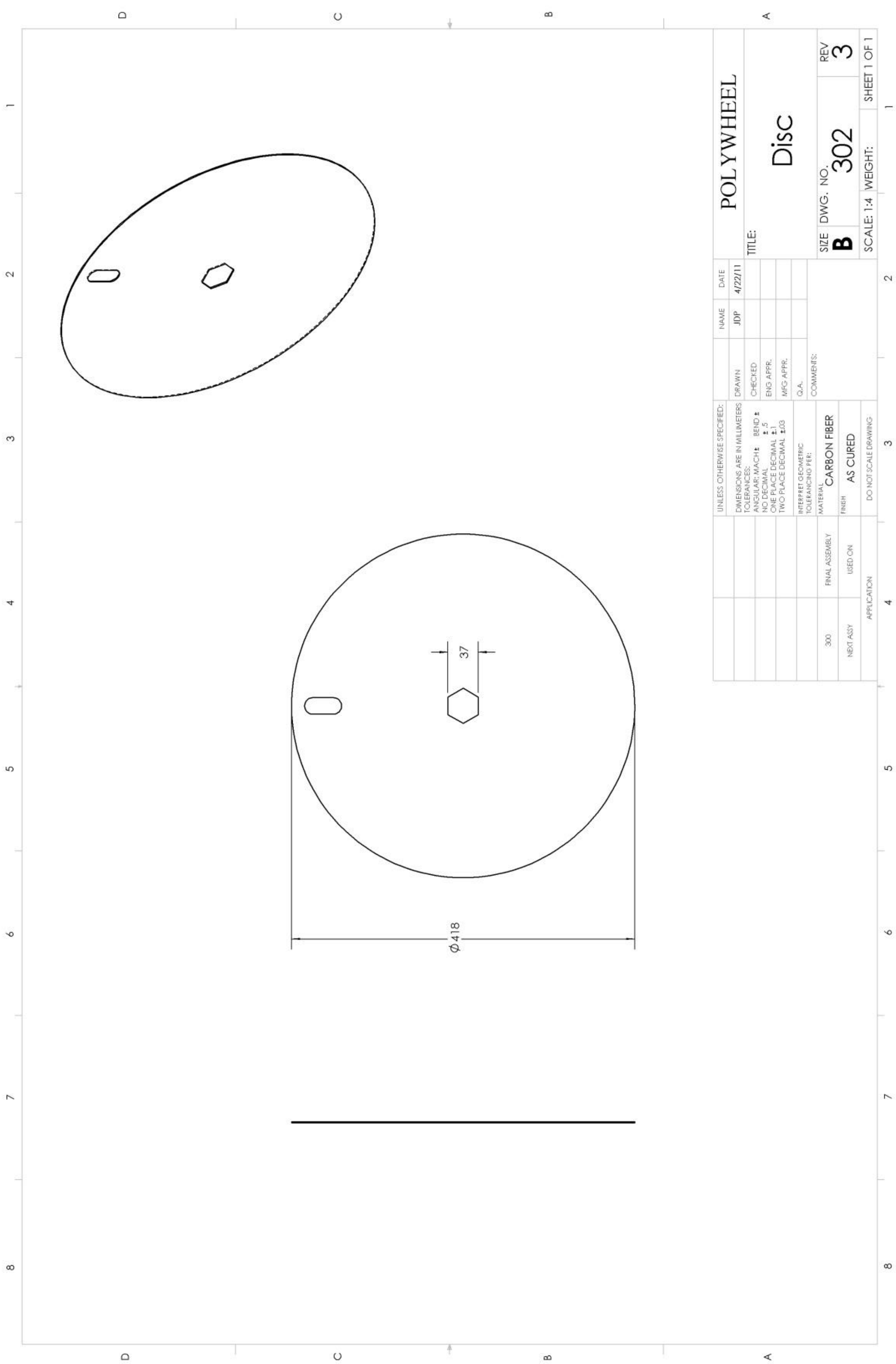
POLYWHEEL

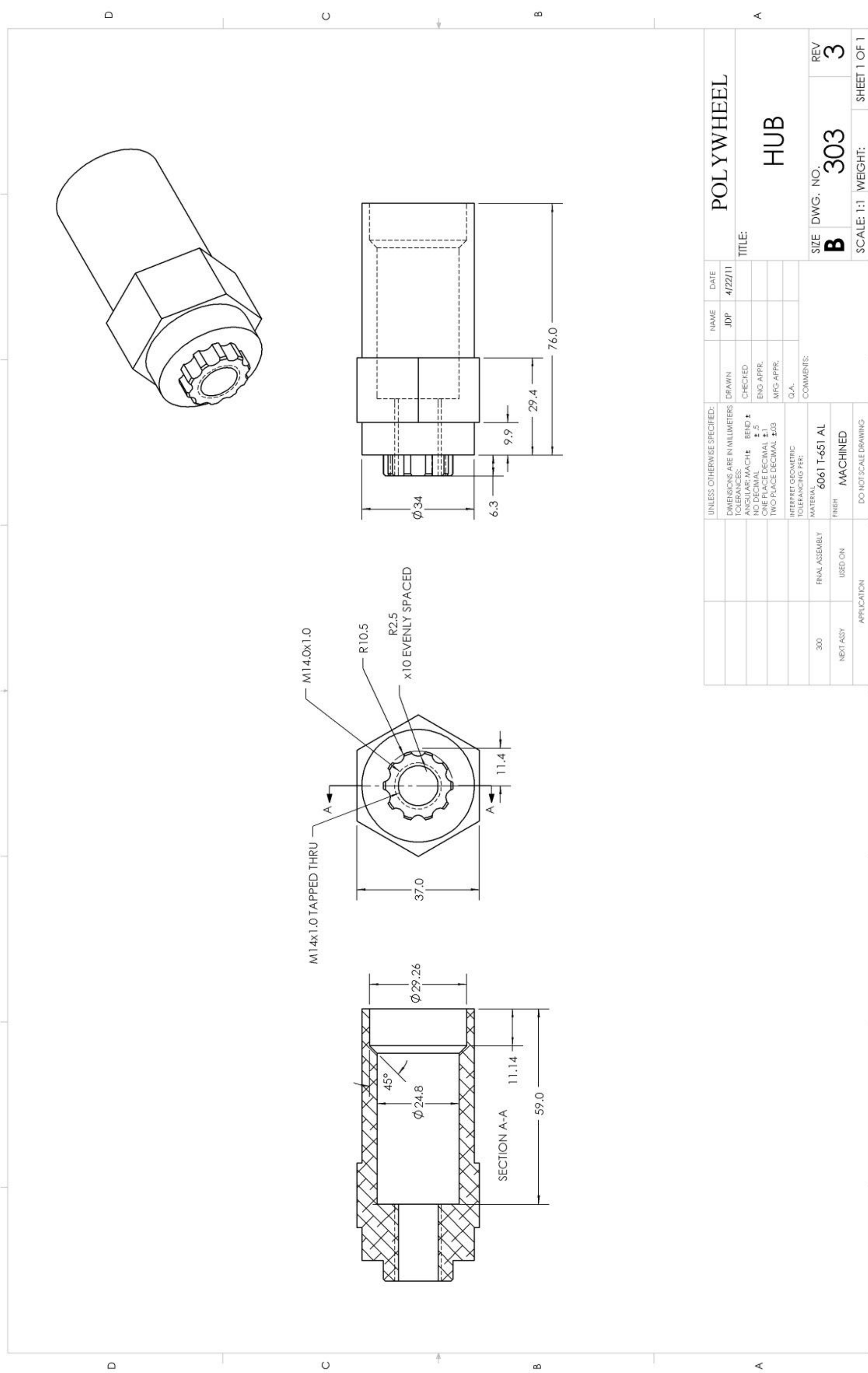
TITLE: CARBON MOLD ASSEMBLY

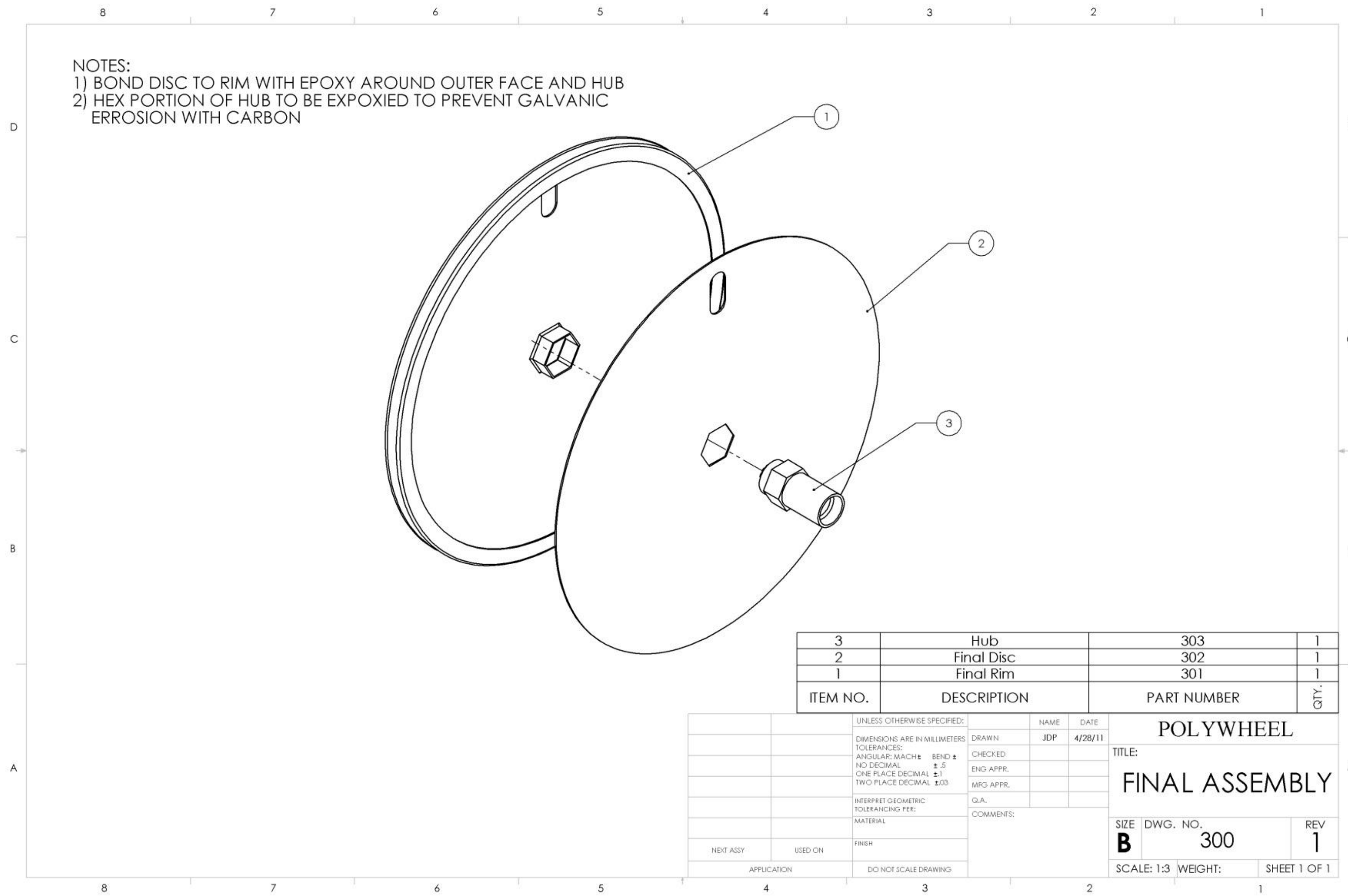
SIZE B | DWG. NO. 200 | REV 1

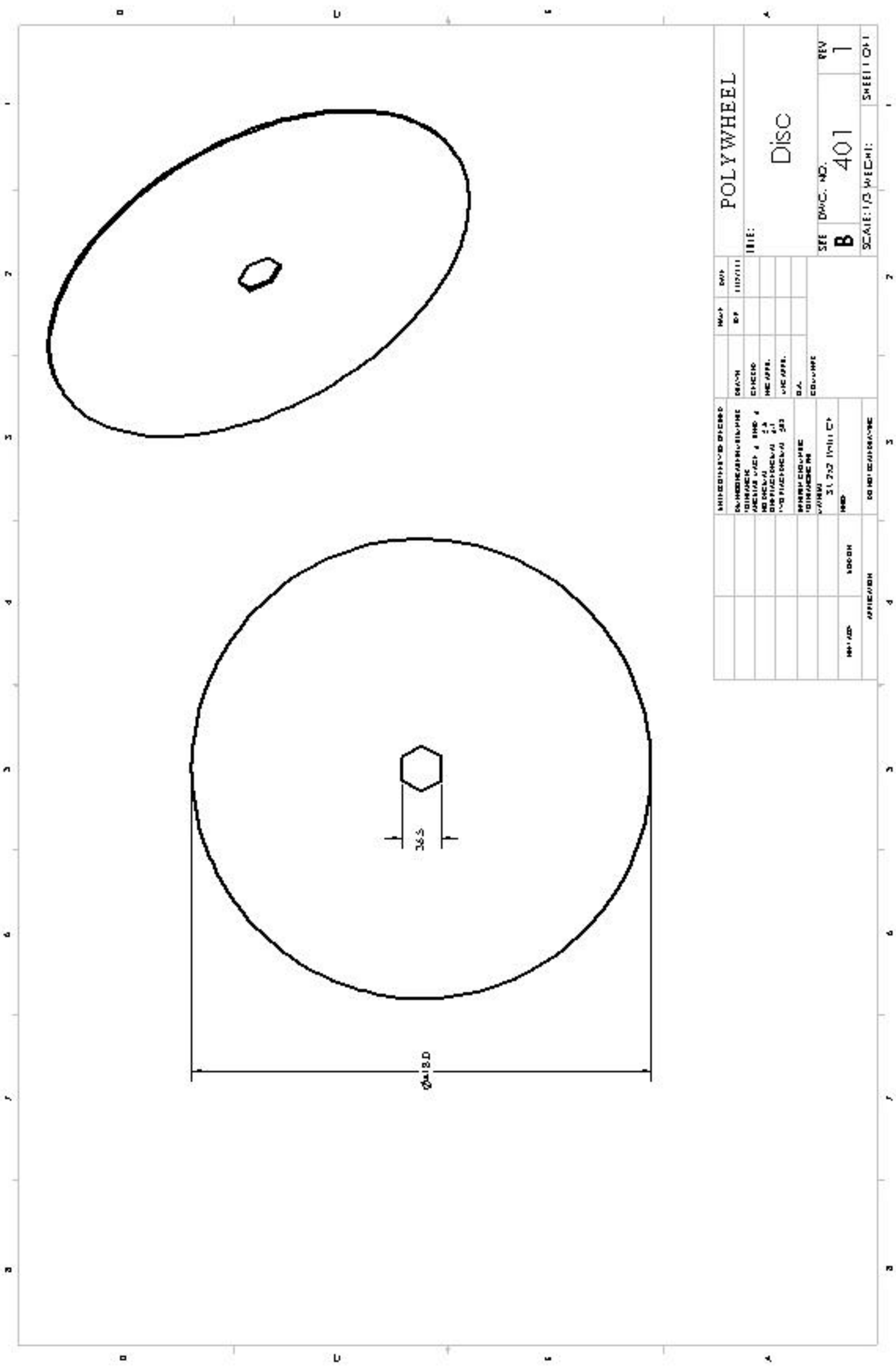
SCALE: 2:5 | WEIGHT: | SHEET 1 OF 1

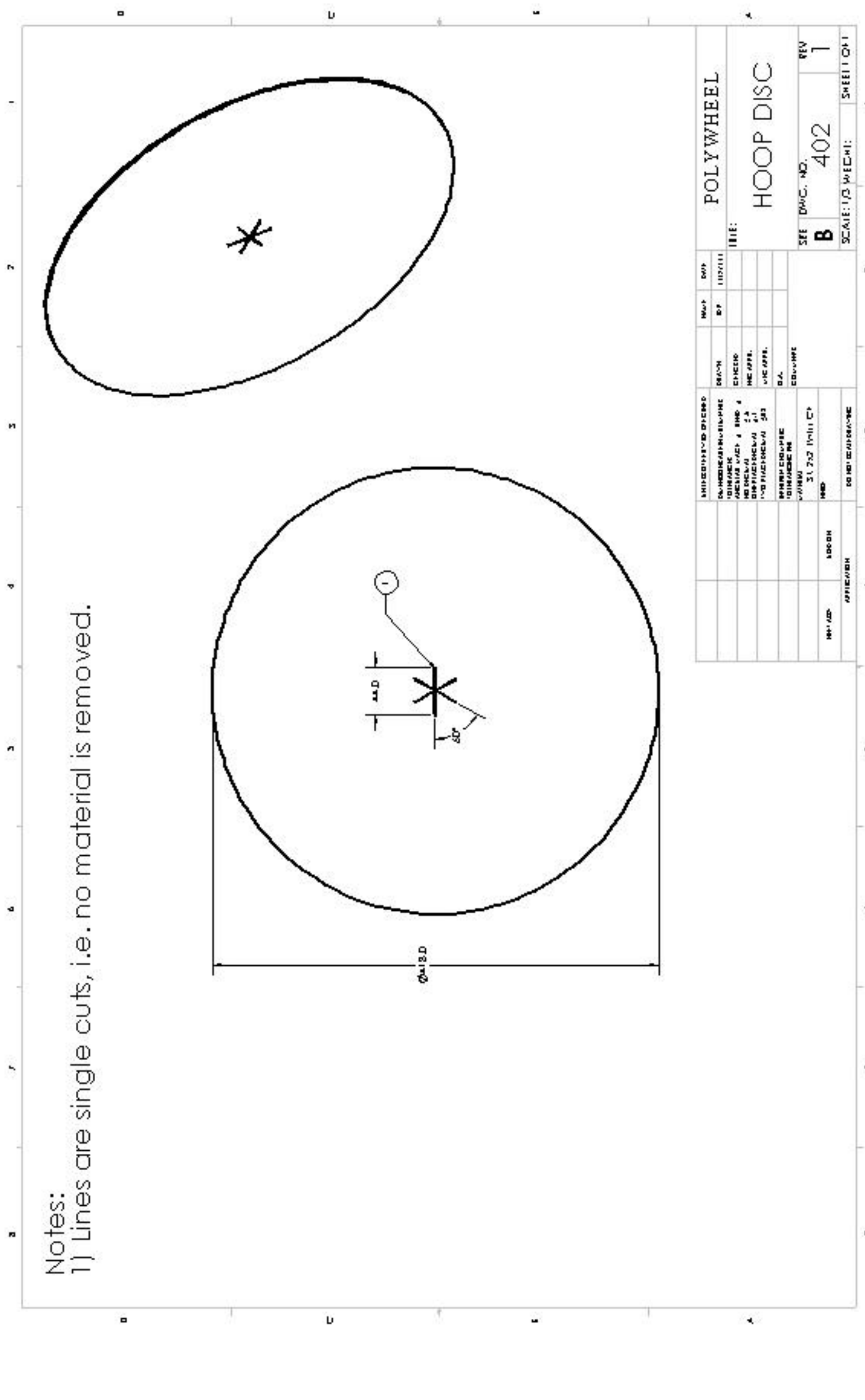

POLYWHEEL
TITLE:
Rim and Disc
SIZE B
DWG. NO. 301
REV 3
SCALE: 1:4
WEIGHT:
SHEET 1 OF 1
DRAWN JDP 4/22/11
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
UNLESS OTHERWISE SPECIFIED:
MATERIAL CARBON FIBER
FINISH AS CURED
DO NOT SCALE DRAWING
300
NEXT ASSY
FINAL ASSEMBLY
USED ON
APPLICATION
SECTION A-A
SCALE 3 : 2
R9.0
18.0
15.0
2x R2
37.0
A
Ø423.3
(OUTER DIA.)
418.3
(SEAT DIA.)

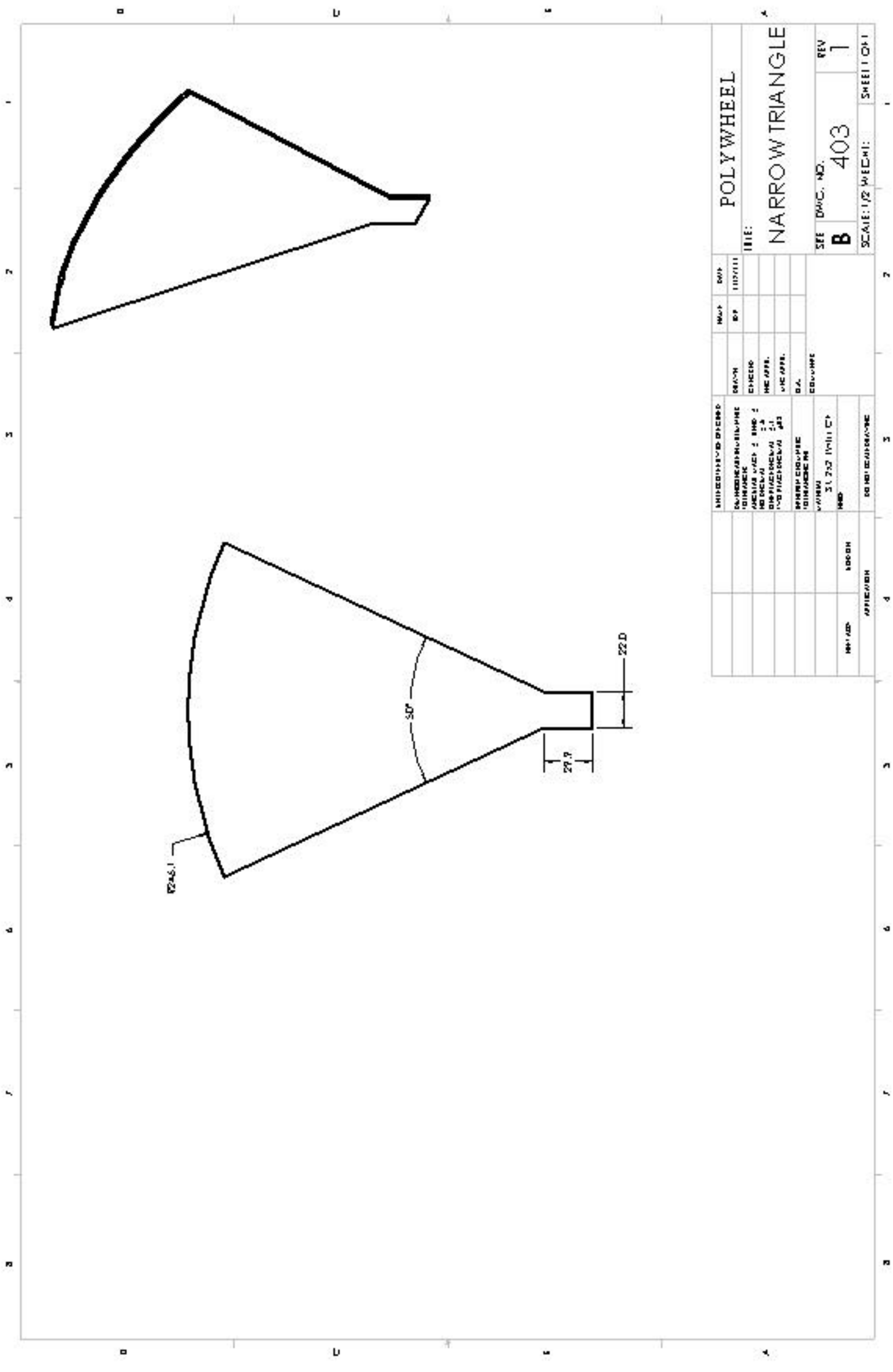

POLYWHEEL
TITLE:
Disc
SIZE B
DWG. NO. 302
REV 3
SCALE: 1:4
WEIGHT:
SHEET 1 OF 1
DRAWN JDP 4/22/11
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
MATERIAL CARBON FIBER
FINISH AS CURED
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
FINAL ASSEMBLY
300
37
Ø418

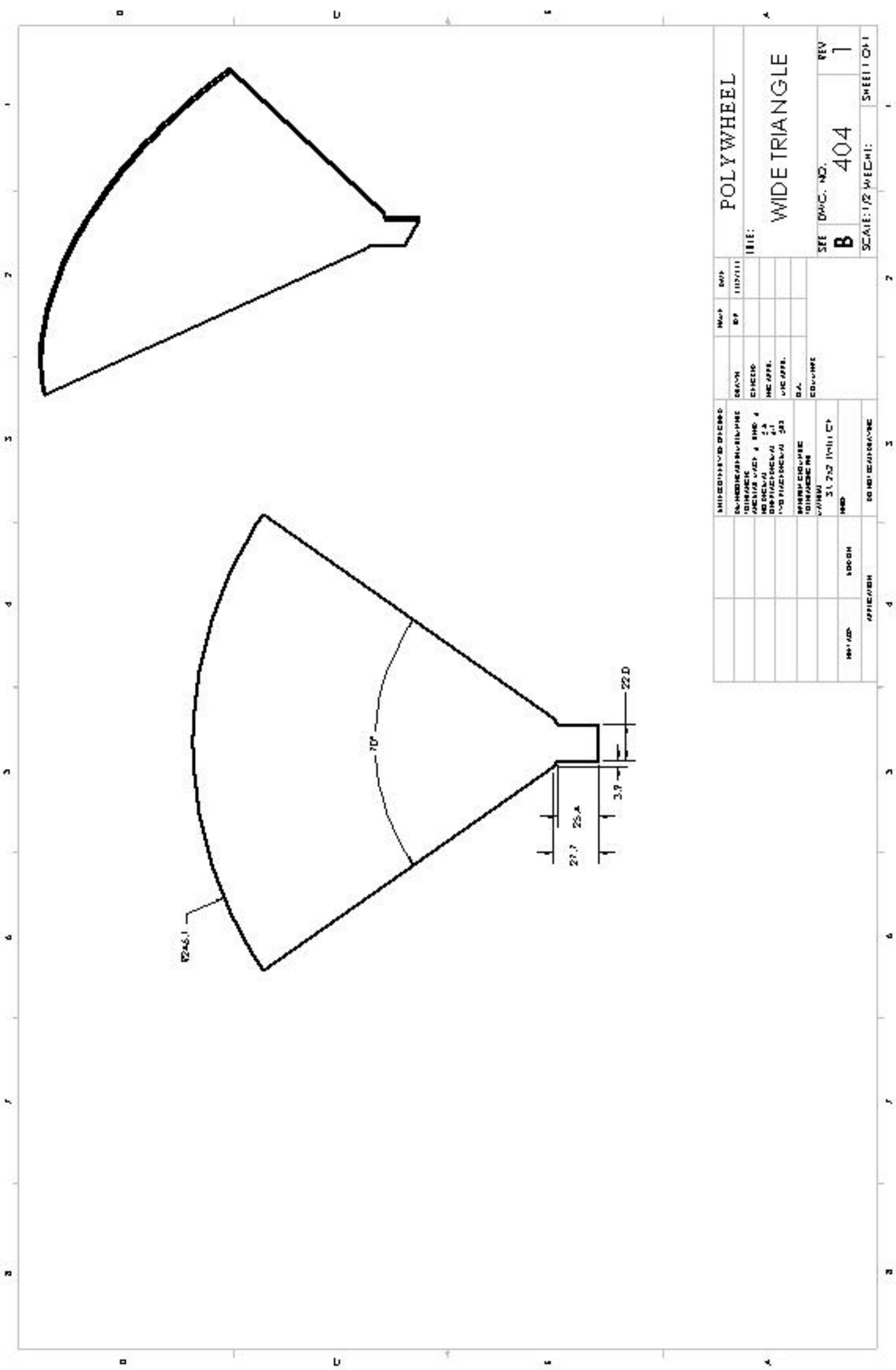

POLYWHEEL
TITLE:
HUB
SIZE
B
DWG. NO.
303
REV
3
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
ANGULAR: MACH ± BEND ±
NO DECIMAL ±.5
ONE PLACE DECIMAL ±.1
TWO PLACE DECIMAL ±.03
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
6061 T-651 AL
FINISH
MACHINED
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
JDP
4/22/11
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
300
FINAL ASSEMBLY
NEXT ASSY
USED ON
APPLICATION
76.0
29.4
9.9
6.3
Ø34
M14.0x1.0
R10.5
R2.5
x10 EVENLY SPACED
11.4
37.0
M14x1.0 TAPPED THRU
A
A
Ø29.26
45°
Ø24.8
11.14
59.0
SECTION A-A

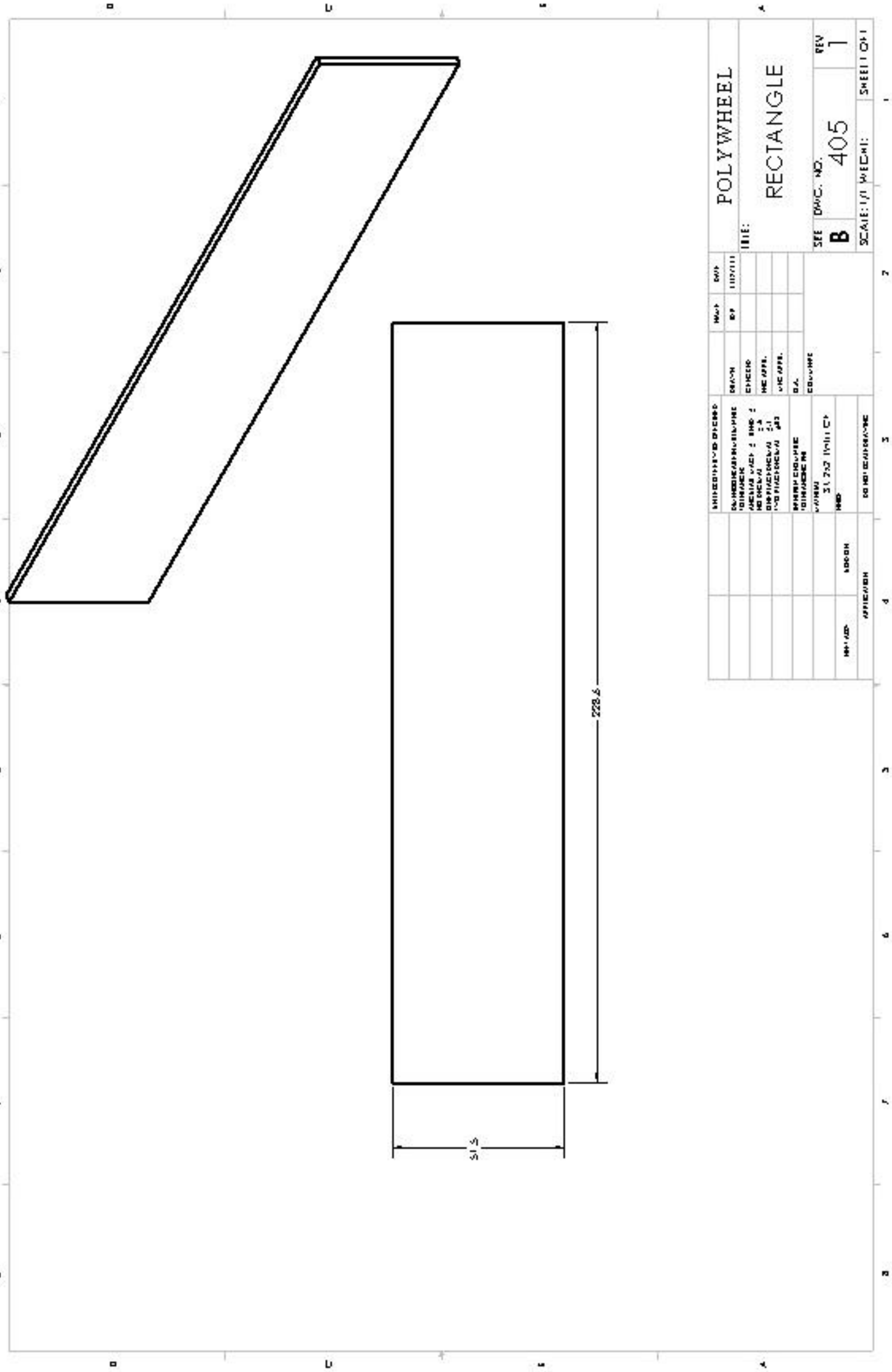

NOTES:
1) BOND DISC TO RIM WITH EPOXY AROUND OUTER FACE AND HUB
2) HEX PORTION OF HUB TO BE EXPOXIED TO PREVENT GALVANIC ERROSION WITH CARBON
1
2
3
3 Hub 303 1
2 Final Disc 302 1
1 Final Rim 301 1
ITEM NO. DESCRIPTION PART NUMBER QTY.
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
ANGULAR: MACH ± BEND ±
NO DECIMAL ±.5
ONE PLACE DECIMAL ±.1
TWO PLACE DECIMAL ±.03
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
NAME DATE
DRAWN JDP 4/28/11
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
POLYWHEEL
TITLE:
FINAL ASSEMBLY
SIZE B
DWG. NO. 300
REV 1
SCALE: 1:3
WEIGHT:
SHEET 1 OF 1


POLYWHEEL
Disc
DWG. NO.
401


Notes:
1) Lines are single cuts, i.e. no material is removed.
POLYWHEEL
HOOP DISC
DWG. NO.
B
402
REV
1


POLYWHEEL
NARROWTRIANGLE
DWG. NO.
403
B
REV
1
SCALE: 1/2
R246.1
50°
22.0
29.9


POLYWHEEL
WIDE TRIANGLE
DWG. NO.
404
REV
1
SIZE
B
SCALE: 1/2
70°
R246.1
22.0
3.9
25.4
27.7


POLYWHEEL
RECTANGLE
SIZE B
DWG. NO. 405
REV 1
228.6
51.5

Appendix C – Baseline Testing Results

All the results in this section come from a ME 410 term project conducted by Jack Pearson and Chad Carpenter. The wheel tested was a standard 27”, 36 spoke rear road bike wheel. An overview of the testing methods can be found in Section 6.

C.1 Static Testing

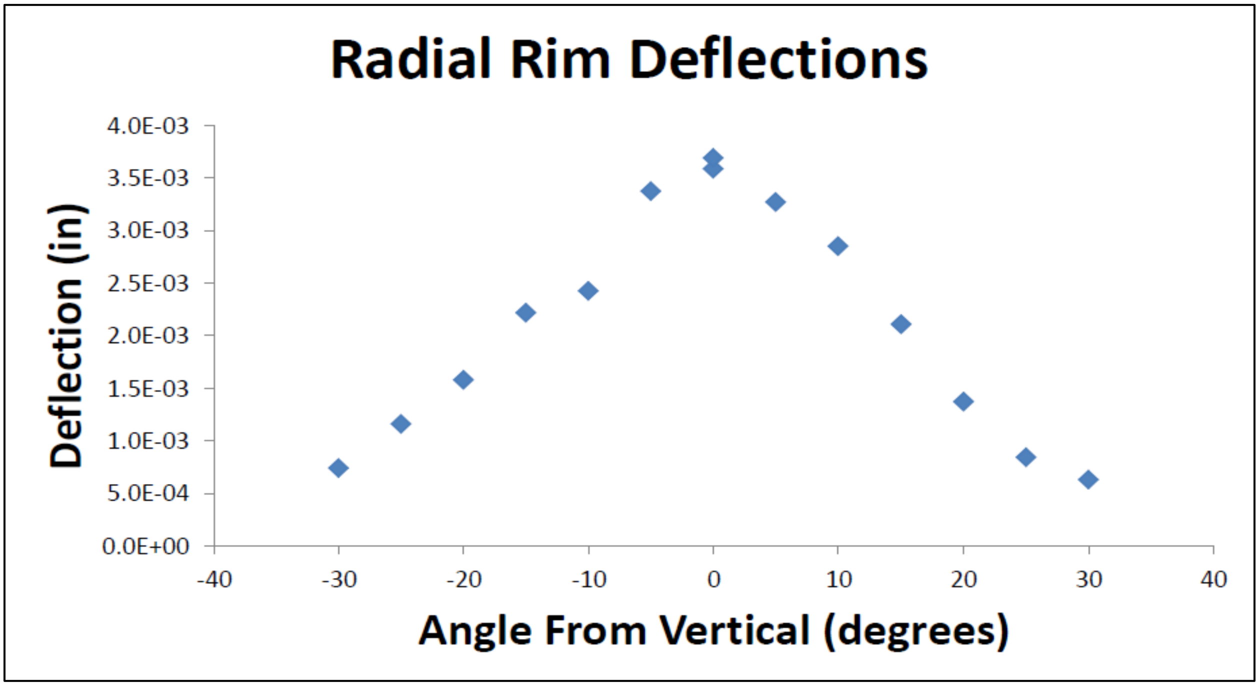


Figure 33. Static radial deflection of 27" spoked wheel

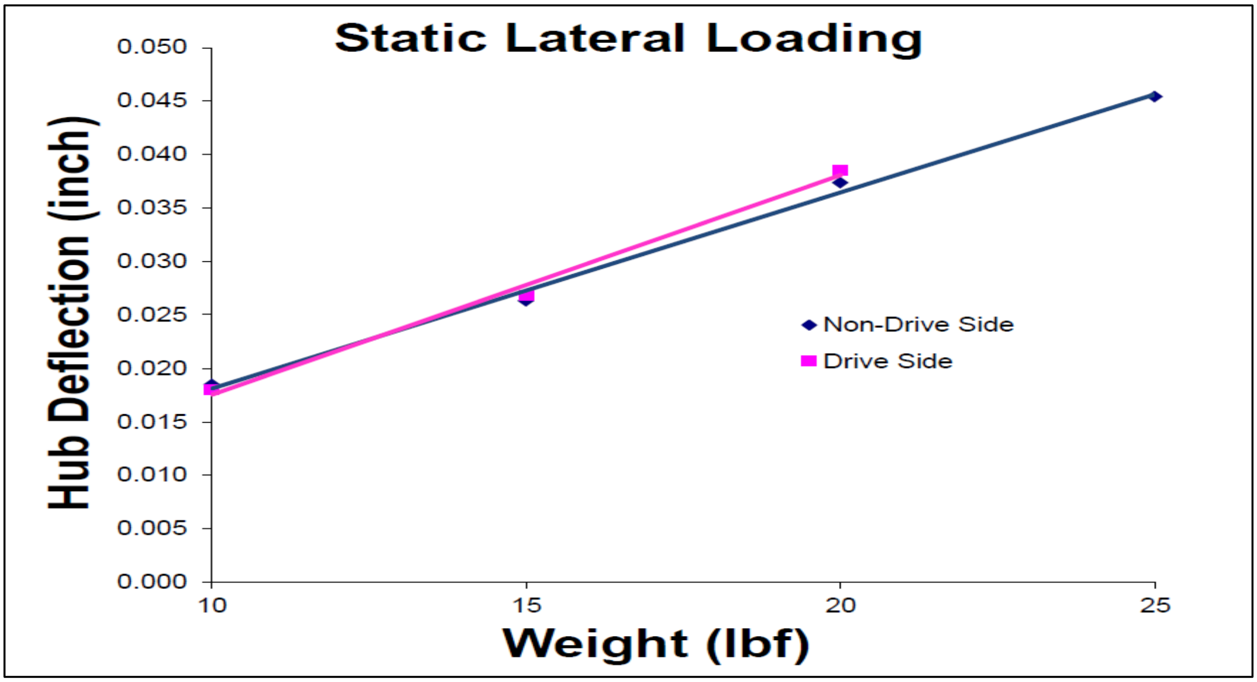


Figure 34. Static lateral deflection of a 27" spoked wheel

C.2 Dynamic Testing

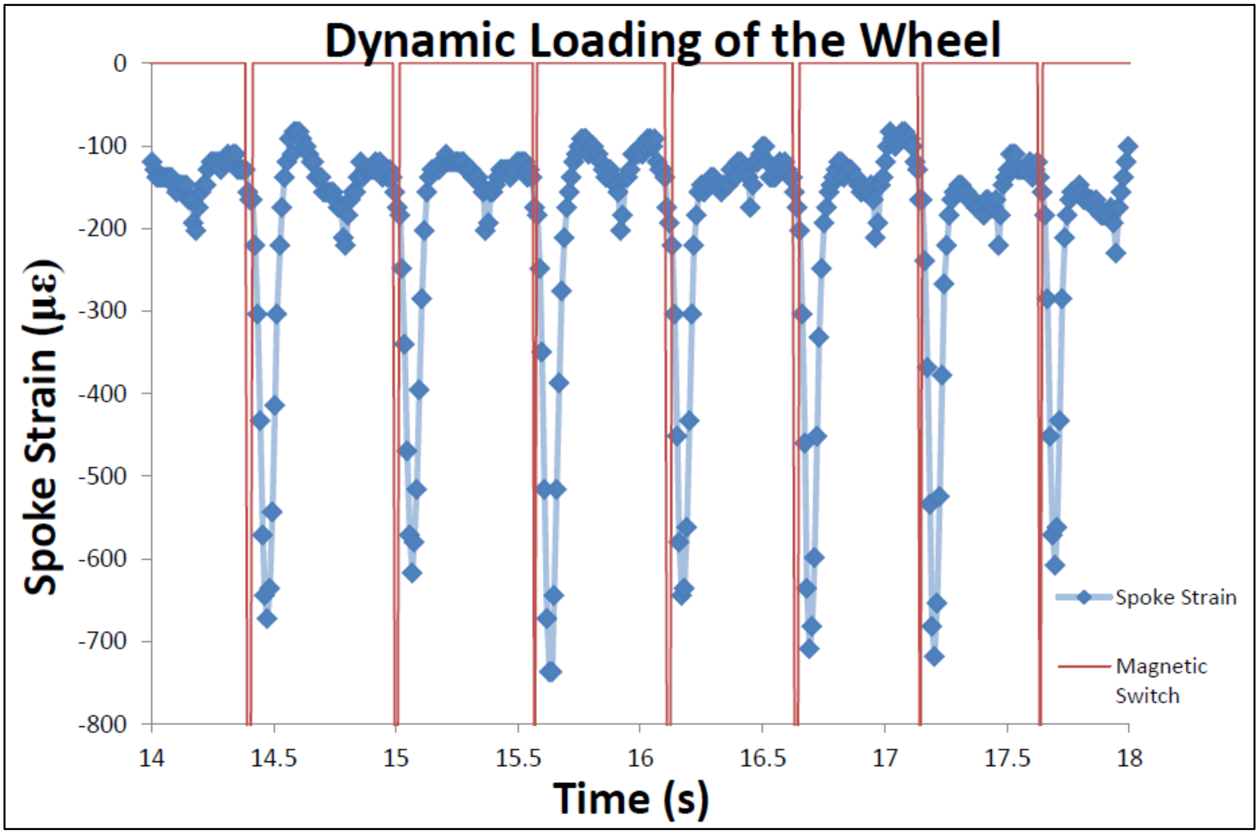


Figure 35. Dynamic spoke strain on a 27" spoked wheel

Figure 35 above lists the maximum strain to be approximately 700 micro-strain. This corresponds to a rim deflection of approximately 0.008".

Appendix D - List of Vendors

Vendor	Contact Info.	
Panaracer	411@panaracer.com	(510) 538-9099
McCarthy Steel	N/A	(805) 543-1760
McMaster-Carr	atl.sales@mcmaster.com	(404) 346-7000
Soller Composites	information@sollercomposites.com	(603) 671-7016

Appendix E – Analysis

$A_{\text{unidirectional carbon fiber}} = 0.005(w)$

$E = 17$ Msi

$\sigma_u = 200$ Ksi

$A_{\text{spoke}} = \frac{\pi}{4}(.0641'')^2 = 0.003227$

$E = 30$ Msi (steel)

# of spokes: 16

$\sigma_u = 119$ Ksi

Equivalent stiffness

$$\frac{A_c E_c}{L} = \frac{A_s E_s}{L}$$

$$\frac{(.005)w\,(17\text{ Msi})}{L} = \frac{0.003227\,(30\text{ Msi})}{L}$$

For equivalent lengths (L), $w = 1.14''$ (width of unidirectional)

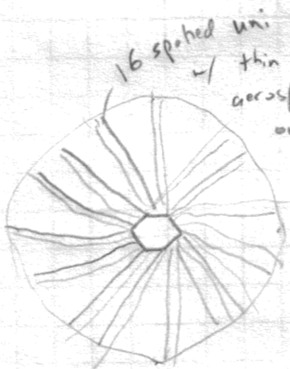
the length of the uni may travel around the rim profile giving an increased length, but will this result in lower stiffness?

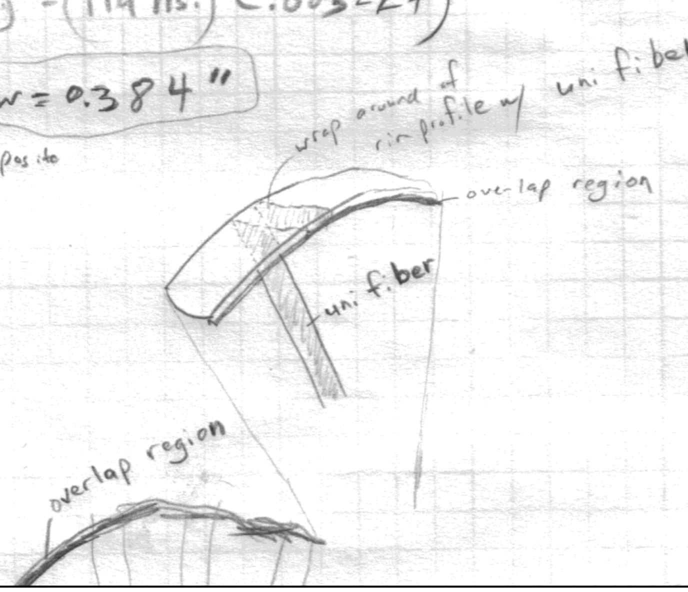
Equivalent Strength

$$\sigma_c A_c = \sigma_s A_s$$

$$(200\text{ ksi})(.005)(w) = (119\text{ ksi})(.003227)$$

$$w = 0.384''$$





Appendix F - Product Specifications

Hex Stock Aluminum

Material	Multipurpose Aluminum (Alloy 6061)
Shape	Hexagonal Bars
Finish/Coating	Unpolished (Mill)
Tolerance	Standard
Length	12"
Length Tolerance	±1"
Hex Size	1-1/2"
Hex Size Tolerance	±.003"
Straightness Tolerance	Not Rated
Test Report	Without Test Report
Temper	T651
Hardness	95 Brinell
Yield Strength	35,000 psi
Temperature Range	-320° to +300° F
Specifications Met	American Society for Testing and Materials (ASTM)
ASTM Specification	ASTM B211
WARNING	Hardness and yield strength are not guaranteed and are intended only as a basis for comparison.