DESIGN AND ANALYSIS OF ONE-PIECE 10” CARBON FIBER WHEELS FOR ZIPS RACING ZR20 FORMULA SAE RACECAR

Patrick Kruse
pwk8@uakron.edu

Henry J. Wathen
The University of Akron, hjw21@uakron.edu

Jordan J. Hyde
The University of Akron, jjh159@uakron.edu

Nicholas D. Dobben
The University of Akron, ndd30@uakron.edu

Jordan D. Blake
The University of Akron, jdb252@uakron.edu

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Senior Design Project – Final Report

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Project Group Members / Authors:

Henry Wathen (UA ID – 3158101)

Patrick Kruse (UA ID – 3124489)

Jordan Blake (UA ID – 2528581)

Jordan Hyde (UA ID – 4193364)

Nicholas Dobben (UA ID – 4183045)

Senior Design Project Coordinator: **Dr. Gopal Nadkarni**

Project Advisor: **Dr. Daniel Deckler**

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ABSTRACT

Reducing the weight of a vehicle in racing can substantially improve the vehicle dynamics and general performance capabilities. More specifically, the reduction of the unsprung corner weight can provide noticeable performance gains in handling and responsiveness, leading to a quicker, more agile car due to a lower yawing moment of inertia. Unsprung weight reduction also improves the car's ability to maintain contact between the tires and the road surface for a more consistent grip. In this project we identified the loads that act on the wheel rims according to the data collected from the sensors in the car's suspension, and we used that data to design a lighter and stronger carbon fiber wheel to handle those extreme load conditions.

Decreasing the weight of the wheel itself (changing materials from aluminum to carbon fiber) will reduce the unsprung corner weight as well as the rotating mass.

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ABBREVIATIONS

CAD -- Computer Aided Design

CAE --- Computer Aided Engineering

CF --- Carbon Fiber

CFRP --- Carbon Fiber Reinforced Plastic

DIC --- Digital Image Correlation

E -- Elastic or Young's Modulus

F --- Material Strength

FEA -- Finite Element Analysis

FRP -- Fiber Reinforced Plastic

FS -- Factor of Safety

FSAE --- Formula Society of Automotive Engineers

LC -- Load Case

PW -- Plain Weave

RF --- Reserve Factor

SAE -- Society of Automotive Engineers

TTC -- Tire Test Consortium

TRA -- Tire and Rim Association

Uni -- Unidirectional Tape

v -- Poisson's Ratio

1. INTRODUCTION

The goal of this project is to design and manufacture a 10” diameter, one-piece carbon fiber wheel to implement into the design for the Zips Racing 2020 (ZR20) FSAE race car. See Figure 1 to view last year’s ZR19 race car.

Figure 1.1 - ZR19 Race Car

The objective of this report is to provide a detailed account of the engineering design and development process of an improved, lightweight carbon fiber wheel to be used on FSAE cars. This wheel could also be utilized by other FSAE teams as well as future zips racing cars by following the process established in this project. It is common for FSAE teams to purchase commercially available aluminum or steel wheel rims as opposed to designing or manufacturing their own. This is an easy choice for time and simplicity’s sake, and because these purchased parts have been proven by others to work as they usually come from well-established wheel manufacturers. However, several teams have made efforts to successfully produce their own wheels which are lighter than the commercially available options, some of which use composite materials. Jayhawk Motorsports (JMS), the University of Kansas Formula SAE Team, is one of those teams, but it is suspected that further improvements can be made to current and previous designs. It is common with most structural components, computer aided design (CAD) and finite element analysis (FEA) software packages are used for engineering design and analysis. However, common limitations to computational resources, funding and high-end testing equipment often leads to oversimplified simulations with a lack of results which validate options. For this senior design project, a comprehensive and adjustable FEA model has been developed for this one-piece carbon fiber wheel design. This document outlines the process to create that FEA model, design and manufacture the CFRP wheel, and validate the design through physical testing.

1.1. Design Validation / Weight Reduction

When it comes to racing, it is essential to pursue maximum power-to-weight ratio. Having a high power-to-weight ratio results in better acceleration, thereby increasing the chance of having better lap times. However, all Formula SAE events are governed by rules which limit the maximum overall displacement of the engine. This restricts the maximum power output which is achieved after optimization of the engine components.

Now, to achieve a higher power-to-weight ratio, the only alternative left is to reduce the weight of the vehicle. Hence, high strength and lightweight materials, such as carbon fiber and aluminum, are commonly used to help keep the weight of the car at a minimum.

1.2. Unsprung Mass of the Vehicle

The unsprung mass of a vehicle is the mass of the vehicle which is unsupported by the vehicle's suspension. Hence, the mass of the tires, wheels, hubs, uprights and axles and such components collectively form the unsprung mass of the vehicle.

The vehicle's dynamic characteristics are heavily dependent on the unsprung mass of the vehicle. Reducing the unsprung mass results in better handling in acceleration and braking scenarios ensuring better traction and control because the suspension can react faster to the road's imperfections as it requires less effort to work against the system. Thus, it is very important to seek ways to reduce the unsprung mass of the vehicle, which is one of the validating reasons for switching the wheel material from aluminum to carbon fiber to reduce weight.

1.3. Wheel Moment of Inertia

Inertia is the tendency of an object to maintain its state of motion. Similarly, for a rotating body, the tendency of the body to keep rotating unless an external torque force is applied to it is called rotational inertia. In the case of the wheel assembly, having a lower rotational inertia would mean that lesser torque will be required in order to rotate the wheel. Similarly, lesser braking force will be required to stop the wheel from rotation.

Reduction of rotational inertia therefore helps in improving braking and acceleration efficiencies. Moreover, considering the rotational and translational motion of the wheel, the equivalent mass gained on the wheel when in motion is approximately 1.5 times the equivalent mass of the wheel when stationary. Therefore, reducing the rotating mass of the wheel, by even a small amount, is so important with respect to increasing the car's performance.

For steering the vehicle, the yawing moment of inertia of the vehicle comes into effect. The lesser the mass on the wheels, the lesser the steering effort would be and hence, there would be better steering responsiveness. Thus, the effort to turn and rotate the wheels is reduced considerably when reducing the mass of the wheel assembly.

1.4. Background / Research of Existing Carbon Fiber Wheels

UTA Racing, from the University of Texas at Arlington, was the first team ever to use a carbon fiber composite wheel. In 1993, the first carbon fiber wheel was demonstrated in FSAE.

Figure 1.2 - UTA Racing 1993 Race Car with Carbon Fiber Wheels

In 2003, an updated wheel design was implemented. The wheel design demonstrated a carbon fiber wheel rim with an aluminum rim center. The CF rim would locate the tire, while the wheel center would connect the hub to the CF rim. This setup allowed for change of the wheel center design while also achieving high wheel stiffness. It is important to have minimal wheel deflections to maintain the slip angle. See Figure 3.

Figure 1.3 - Carbon Fiber Wheel Assembly Design From 2003

This carbon fiber wheel rim design mold has been commonly used by FSAE teams until about 2016. Slight modifications with the wheel center piece allowed for better packaging and weight reduction. The wheel centers were attached to the carbon rim by using “huck” fasteners which are a combination of high performance huck bolts and structural blind fasteners. It is like riveting while being threaded.

Two members of the 2016 Zips Racing Combustion Team, Christopher DiSante, and Anna Davies designed a similar carbon fiber wheel rim with an aluminum wheel rim center. See Figure 4. The new CFRP wheel design aims to replace this assembly with a full, one-piece carbon fiber wheel.

Figure 1.4 - Zips Racing 2015 Carbon Fiber Wheel Rim Assembly

Another design we have researched is TU Graz Racing Team from Graz University of Technology in Austria. At the 2015 Formula SAE competition in Michigan, TU Graz Racing team demonstrated a 3 spoke hollow wheel design which they have successfully been using for years. They use trapped rubber molding to get hollow spokes for weight reduction and stiffness.

Figure 1.5 - TU Graz Racing Team's 2015 Carbon Fiber Racing Wheel

1.5. Objectives / Development Process

The objective of this senior design project is to replace the ZR19 10" aluminum wheel assembly with a full one-piece carbon fiber wheel. The primary targets of this design are as follows:

1. Achieve a minimum 30-40% weight reduction in the wheel assembly
2. Achieve a stronger wheel stiffness and strength compared to the previous aluminum wheel assembly
3. Design a modular wheel mold with an adjustable wheel width.

Our design development process is broken down into several different stages. These stages are used to break down the project into manageable milestones. In addition, these steps were also used in synchronizing the development of the wheel rim with the rest of the FSAE race car.

This interaction with the rest of the team was critical because of the high degree of system integration that happens with the vehicle dynamics. The different design phases are as follows:

1. Carbon fiber prepreg material selection
2. Establish worst-case load cases
3. Hand calculations to determine carbon fiber layup design
4. Material testing to validate design - (tensile and flexural tests)
5. Setup and validate design with FEA model and Fibersim
6. Select specific design concept and finalize design / dimensions

7. Fabricate molds and centerlock hub
8. Layup carbon fiber and cure in autoclave
9. Post processing
10. Validate design with physical testing

2. THEORETICAL FRAMEWORK

2.1. Design Requirements

Before starting our design, we needed to complete hand calculations to determine the requirements for the minimum load forces that the wheel rim will have to withstand with an added factor of safety. There are four main types of loads that will be acting on the wheel rim:

- Torque on the shaft axis, caused mainly by braking situations (prevailing over the torque caused on the acceleration situation).
- Radial Forces. These are vertical forces exerted in the radial direction towards the center of the wheel. They can be caused for different situations, like the vehicle weight itself, the driver ingress in the vehicle, and the bumps or irregularities of the road.
- Lateral / Cornering Forces. These are forces produced by the vehicle during cornering, inducing normal and lateral load components on the rim.
- Pressure. Inflation pressure from the tire produces a static load on the rim, producing a uniform inward pressure on the rim surface. This load may be uniform or non-uniform.

2.2. Loading Conditions on Wheel Rim

To ensure that our wheel rim will not fail, four critical load cases were determined to represent the most extreme conditions the rim would experience during operational use on the racecar. We excluded situations like striking a curb or hitting a pothole because the surfaces that the FSAE vehicle runs on are very well known. A detailed description for each loading condition used in analysis is described below.

2.2.1. Cornering Load

Cornering is the most performance critical of the loading cases as well as the most extensively examined condition. Not only are the forces on the wheel rim the largest in this case, but the deflection because of cornering forces has a significant effect on the tire performance, and in turn the overall cornering ability of the car.

2.2.2. Accelerating / Braking

The loading case of accelerating and braking is the same. The design goal in this case is to minimize the forward and reverse rotation of the wheel under accelerating and braking loads, or what is known as toe change. In automotive engineering, “toe” is the symmetric angle that each wheel makes with the longitudinal axis of the vehicle. Negative toe, or toe out, is the front

of the wheel pointing away from the centerline of the vehicle. Positive toe, or toe in, is the front of the wheel pointing towards the centerline of the vehicle.

2.2.3. Pressurization of the Wheel

This case simulates the tire being over inflated to seat the tire bead of the rim. Since the wheel is deflated prior to use, there are no performance concerns during this load case. The only requirements of this case are to ensure that the wheel rim bead does not fail during the process of mounting and dismounting the tires onto the wheel rim. The maximum pressure was determined by the maximum pressure the tire data rated for during the beading process, which for our custom Goodyear tire is 12 psi.

2.2.4. Cornering While Accelerating / Braking

This is the most critical of the load cases examined since the rim in this case will experience the most force. Braking and accelerating at a full g-load during a turn could cause the car to lose control, so performance in this case is neglected and a purely failure prevention approach was taken. In addition, since large deflections are expected in this case, caliper clearance was also considered in the design, with a minimum of 0.25” clearance between the wheel and caliper after deflection which was deemed to be acceptable.

2.3. Composite System Design / Selection

There has been an increasing emphasis on the use of composites because composite materials are designed to be stiff, light, and durable. Although metals have excellent strength and toughness combinations, they are quite dense, and many corrode. Attention has been turned to ceramics and polymers, which are lighter and more corrosion resistant, but lack toughness.

2.4. Composite Material Selection

A composite is a combination of generally two materials which exhibit desired properties such as compressive strength of the matrix and tensile strength of the fibers. Usually, they consist of ceramic or polymer fibers embedded in a matrix, usually a thermosetting resin such as an epoxy or polyester but can also be thermoplastics or ceramics or even metals. The three main types of fiber used are glass, carbon, and aramid (aromatic polyamides, such as Kevlar).

The choices of composition and of the materials used for the matrix and fiber depend on the required properties of the application.

2.5. Carbon Fiber Selection

Fibers are the dominant constituents in a fiber-reinforced composite material. Simple micromechanical analysis leads to the conclusion that fibers dominate only the fiber-direction modulus of a unidirectionally reinforced lamina. Lamina properties in that direction have the potential to contribute the most to the strength and stiffness of a laminate. Thus, the fibers play a dominant role in a properly designed laminate. Such a laminate must have fibers oriented in the various directions necessary to resist all possible loads.

Fiber selection is usually based primarily on the required strength or stiffness. That selection process is relatively straightforward, but other selection factors require more

consideration. In all applications, a fiber-matrix bond is essential, so a fiber surface treatment or coating often must be used.

2.6. Fabric Selection

Carbon fiber products start as a woven fabric of carbon tows. Tows are bundles of tiny carbon filaments, which are counted in thousands: 1K, 3K, 6K, 12K, etc. The most popular thread count is 3K.

The carbon fiber we will be using is a prepreg system from a sponsor company who sponsored our project, Adhesive Prepregs for Composite Manufacturers, LLC (APCM), a company in Connecticut that we found through Composite Envisions. It is a 3K, 2x2 twill weave, prepreg fabric. We selected this material based on our design parameters because it is easy to work with, it has a high heat resistance, and has a long shelf life. APCM also agreed to sponsor us and supply the fabric and appropriate pre-impregnated resin system for the cheapest price. In addition, they also were helpful answering our questions and they provided us with recommendations about the resin they would like us to use and technical documentation that describes their product.

[redacted]

[redacted]

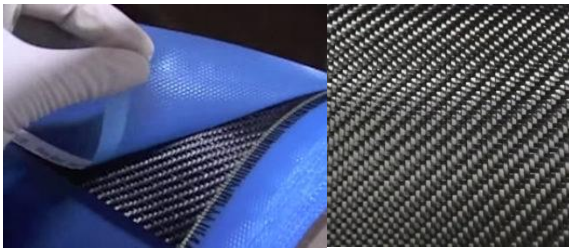


Figure 2.1 [redacted]

Based on the 2x2 weave design and tow size of 3K filaments per fiber, this fabric offers substantial strength and stiffness when compared to other fabrics. 3K carbon fiber material is also very easy to manipulate and is commonly used in applications such as aerospace, marine, automotive, and sporting goods.

A **"tow"** is an untwisted bundle of continuous filaments of carbon fibers. Tows are designated by the number of fibers they contain. So, if the carbon fiber material says 12K, that means there are 12,000 filaments per "tow" and in our case, our tow size is 3K meaning there are 3000 filaments per tow. Each carbon filament in the tow is a continuous cylinder with a diameter of about 5-8 micrometers and consist almost exclusively of carbon.

There are several different weave patterns of carbon fiber. **"Twill weave"** serves as a bridge between a plain weave and the satin weave patterns. Twill has good pliability and can

form into complex contours, and it is better at maintaining its fabric stability than a harness satin weave, but not as good as plain weave.

The **"2x2 pattern"** looks like a 1x1 plain pattern, but the diagonals are synchronized, and the braids are over-over-under-under. As the 2x2 name implies, each tow will pass over 2 tows then under two tows. 2x2 twill is one of the most widely used and most recognizable carbon fiber weave in the automotive industry. It is elastic and it is good to use on complex shapes (like our wheel rims) because the weave is looser.

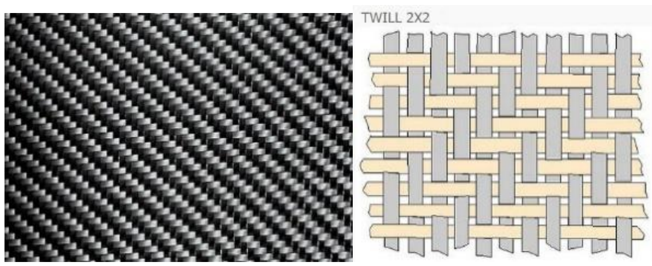


Figure 2.2 - 2x2 Twill Weave Pattern

[redacted]

2.7. Physical Properties

[redacted]

2.8. Mechanical Properties

MECHANICAL PROPERTIES

[redacted]

2.9. Matrix / Epoxy Selection

[redacted]

[redacted]

[redacted]

[redacted]

2.10. Fiber Direction / Orientation - Effect on Properties

Upon looking at a section of carbon fiber, one will see that the fibers go in different, specific directions. Comparing different styles of carbon fiber, one might notice that the fiber direction, or orientation, is not always uniform. Fiber orientation influences the properties of carbon fiber and some specific properties are often ideal for specific applications.

Fibers can be oriented in any direction between 0° and 180°, although fiber orientation beyond 90° is usually referred to as a negative angle value. For example, a 135° fiber angle would be equal to a -45° angle.

The way fibers are oriented in a carbon fiber layup significantly influences its resulting properties. It is therefore very important for us to consider these properties during the design process of our carbon fiber wheel orientation / layup design. Most carbon fiber available on the market today utilizes a combination of two or more of the following orientations of carbon fiber layers:

0° orientation -

This orientation provides axial strength and stiffness ideal for beams and columns that must resist axial loads. When fibers are oriented in the same direction of the load, they are the strongest and stiffest. For example, in most carbon fiber tubing, the fibers are oriented in the zero-degree angle direction which would be along the length of the tube to contribute to the bending stiffness and strength of the tube.

If a part were to only be loaded in one direction, it would be ideal to have all the fibers oriented in that direction. Tubing are good examples of a part that would contain only 0° fibers. Since most parts are not loaded in only one direction however, it is necessary to add other angles to maximize strength. A tube that only experiences bending and no twisting would still likely benefit from some additional fiber angles. Adding 90° layers would help the tube maintain its shape better so that it does not buckle prematurely.

90° orientation -

This orientation provides transverse strength and stiffness ideal for creating a consolidating layer that keeps everything together and provides strength in pressure vessels. Ninety-degree fiber angles are used when bending in both directions is required. As stated earlier, 90° fiber layers are often added to tubes oriented in the circumference of the tube to help make the tube more resilient to buckling or crushing when loaded.

High concentrations of 90° or “hoop” layers can also be commonly found in pressure

vessels. Since the force is trying to enlarge the tube in a pressure vessel, 90° layers would resist the force best. When 90° layers are used in conjunction with 0° layers in a carbon fiber plate, this would be referred to as "bidirectional." Using bidirectional woven carbon fiber cloth is an easy way to quickly build parts with fiber in both the 0° and 90° directions.

± 45° orientation -

This orientation provides shear and torsional strength and stiffness that is ideal for torsion shafts and shear webs such as I-beam webs. 45° angles are often used in conjunction with zero and ninety-degree plies to create a quasi-isotropic layup. When used on a tube, 45° layers contribute to twisting stiffness and strength. Woven carbon fiber is often referred to as having a 0/90-degree fiber angle since there are fibers in both directions, but in a single piece.

45° layers serve different purposes depending on the application. A positive 45° layer is almost always paired adjacently to a negative 45° layer. This is to keep the laminate balanced and from forcefully twisting when loaded. When 45° layers are used in a plate that already contains an equal mix of 0° and 90° layers the plate becomes quasi-isotropic. Whereas a bidirectional plate has equal properties in two directions, a quasi-isotropic plate has quasi-equal properties in any direction. In a tube, 45° layers add torsional strength and stiffness. That is because when a tube is twisted, the force acting on the laminate is at 45°. Some laminates will use angles other than 45° as a compromise between bending, crushing and torsion performance. Since 0° layers are not possible on filament tubes, it is common to see 10° or 15° layers used instead.

2.11. Analytical Methods for Composites

When designing carbon fiber composite parts, one cannot simply compare the properties of carbon fiber vs. steel, aluminum, or plastic, since these materials are in general homogeneous (properties are the same at all points in the part) and have isotropic properties throughout (properties are the same along all axes).

By comparison, in a carbon fiber part, the strength resides along the axis of the fibers, and thus fiber properties and orientation greatly impact the resulting mechanical properties. Carbon fiber parts are in general neither homogeneous nor isotropic.

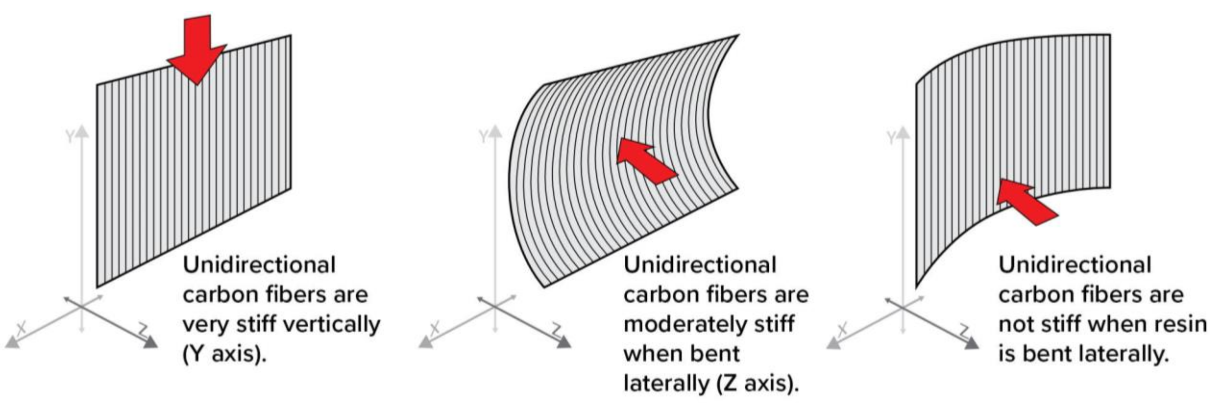


Figure 2.3 – Carbon Fiber Axis Direction Strengths

2.11.1. Ultimate Strength

In many composites' applications, loads are predominantly uniaxial and therefore the layup design would be oriented in the same direction of the load. In such cases, the ultimate strength would be dominated by those primary load bearing tows in the textile.

2.11.2. Ultimate Tensile Strength

Ultimate tensile strength is the maximum stress that a material can withstand while being stretched or pulled before breaking. Several different layup designs were tested for this mechanical property in the mechanical engineering lab on an Instron tensile testing machine (see Physical Testing Section).

2.11.3. Compressive Strength

Compressive strength is the capacity of the material to withstand compressive loads that reduce the size of the structure. The compressive strength of the material resists being pushed together, whereas tensile strength resists tension. For aligned loads, compressive failure is either by delamination or Euler buckling of delaminated plies.

2.11.4. Shear Strength

Shear strength is the strength of the material against yielding or structural failure when the component fails in shear. A shear load is a force that produces a sliding failure on the material along a plane parallel to the direction of the force applied.

3. HAND CALCULATIONS

3.1. Load Force Calculations

In order to calculate the forces on the race car wheel rims for each case scenario of loads, an Excel spreadsheet calculator was developed taking data from the sensors on the vehicle suspension system in order to determine the forces that the wheel rim would experience in each the following load cases:

ZR20 Upright FEA Loads (N)

[redacted]

Figure 3.1 [redacted]

3.2. Torsional Load Calculation

[redacted]

[redacted]

Equation 3.1 – [redacted]

[redacted]

[redacted]

[redacted]

Equation 3.2 – [redacted]

Parameters:

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

3.3. Bending Load Calculation

[redacted]

[redacted]

Equation 3.3 – [redacted]

[redacted]

[redacted]

[redacted]

[redacted]

3.4. Radial Load Calculations

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

3.5. Tire Pressure Load - Pressure Vessel Hoop Stress Calculation

[redacted]

[redacted]

[redacted]

[redacted]

Equation 3.4 – [redacted]

[redacted]

3.6. Lateral Loading Calculation

[redacted]

Equation 3.5 – [redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

3.7. Layup Design and Ply Layer Orientation / Configuration

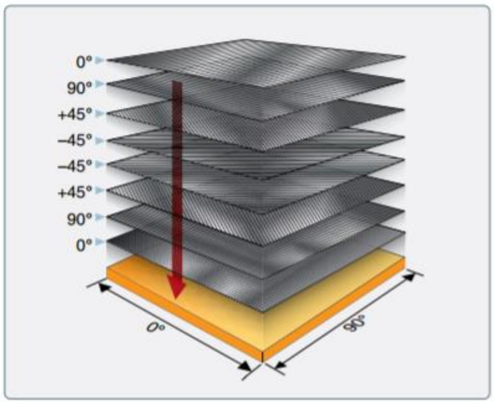
[redacted]

[redacted]

[redacted]

3.8. Quasi-Isotropic Laminate Design

When working with carbon fiber, it is important to understand how the fiber orientation factors into the strength and stiffness of the CFRP laminate. There are different approaches to laminate design for composites where the laminates are angularly oriented differently to yield different structural properties. The properties are isotropic, quasi-isotropic, and anisotropic.



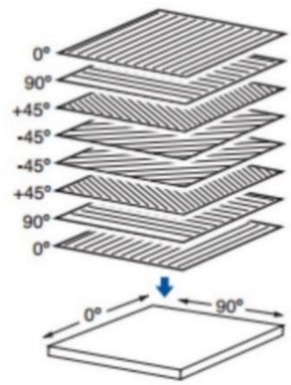


Figure 3.2 - Unidirectional Carbon Layup - Quasi-Isotropic Ply Orientation

The "mid-plane" is the centerline of the lay-up. See Figure 3-7. Quasi-isotropic means having isotropic properties in-plane. "Isotropic" means having the same properties in all directions. A quasi-isotropic part has either randomly oriented fibers in all directions, or has fibers oriented such that equal strength is developed all around the plane of the part.

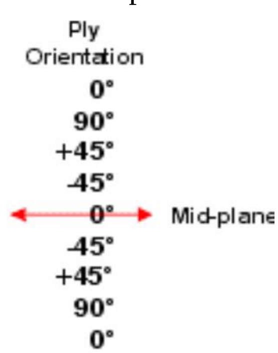


Figure 3.3 - Balanced and Symmetrical Laminate

3.9. Required Number of Layers

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

3.10. Weight Reduction Calculation

[redacted]

[redacted]

Figure 3.4 – [redacted]

[redacted]

[redacted]

[redacted]

Figure 3.5 – [redacted]

[redacted]

4. FEA ANALYSIS

Ansys ACP is used to simulate the structure of the CFRP Wheel. FEA simulation tools are important to save money on materials and testing time by troubleshooting failure points early in the design phase. Due to the complexity of CFRP, modeling it to match the wheel's exact layup schedule is difficult. The eventual plan is to use the templates created by Fibersim to import the laminates and their orientations to match exactly.

Ansys Toolbox is used to efficiently run new iterations on the simulation. Multiple load cases, orientations of fibers, layer counts, and material choices can all be changed and ran without even having to open the model back up after the initial set up.

Some boundaries that made this FEA difficult was the complexity and size of the model requires a large element count. ANSYS student offers limited computing on element counts of 32,000. To truly get a better understand of static results from this FEA a full license is required to increase the element size.

4.1. FEA Model Setup

[redacted]

[redacted]

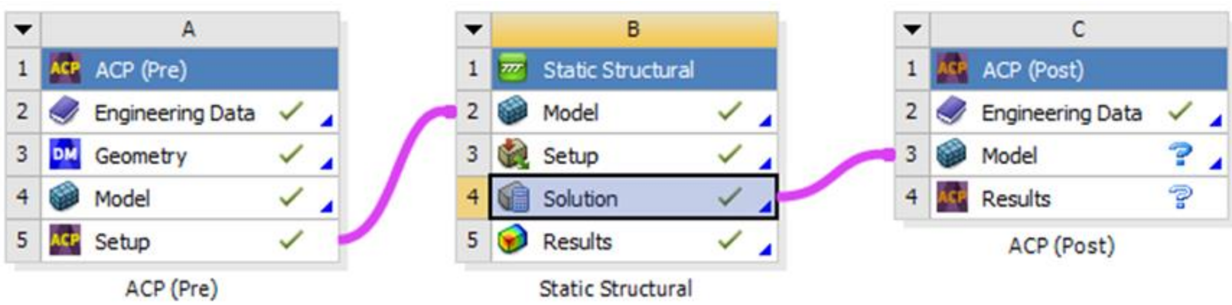


Figure 4.1 -Ansys Toolbox

ANSYS Toolbox is used to optimize the iterative process for running multiple simulations or making quick changes. Parameters such as layup schedule, fiber orientation, loads, fixtures, and material data can all be changed without even opening the model. This allows for rapid editing based on changing to determine the best loads.

[redacted]

Figure 4.2 [redacted]

[redacted]

4.2. ANSYS Results

[redacted]

Figure 4.3 – [redacted]

[redacted].

5. FIBERSIM

To create the CFRP wheels, simulation needs to be run over the parts to determine the manufacturability. In CAD, 3D surfaces can be flattened down into 2D surfaces that can then be used to cut out plies of carbon fiber which will be placed on the mold during the manufacturing phase. We can estimate this 2D pattern using Siemens Fibersim. This program was created to analyze composite engineering and manufacturing. Through CAE, carbon fiber material can be virtually "laid up" using surfaces. This allows for the engineer to check stretch and compression throughout a CFRP layup. This tool can also help optimize overlaps between different layers of the wheel and determine which orientation the carbon fiber needs to be laid up to reduce the number of cuts.

To explain the Fibersim process, we will use one surface of the bottom wheel mold to go into detail. This process was completed for each surface ply when designing the wheel.

5.1 Results

First the surface is imported from the mold model in SolidWorks to Siemens NX CAD program. Once the surface model is in NX, Fibersim can be started. The Fibersim interface can be seen below.

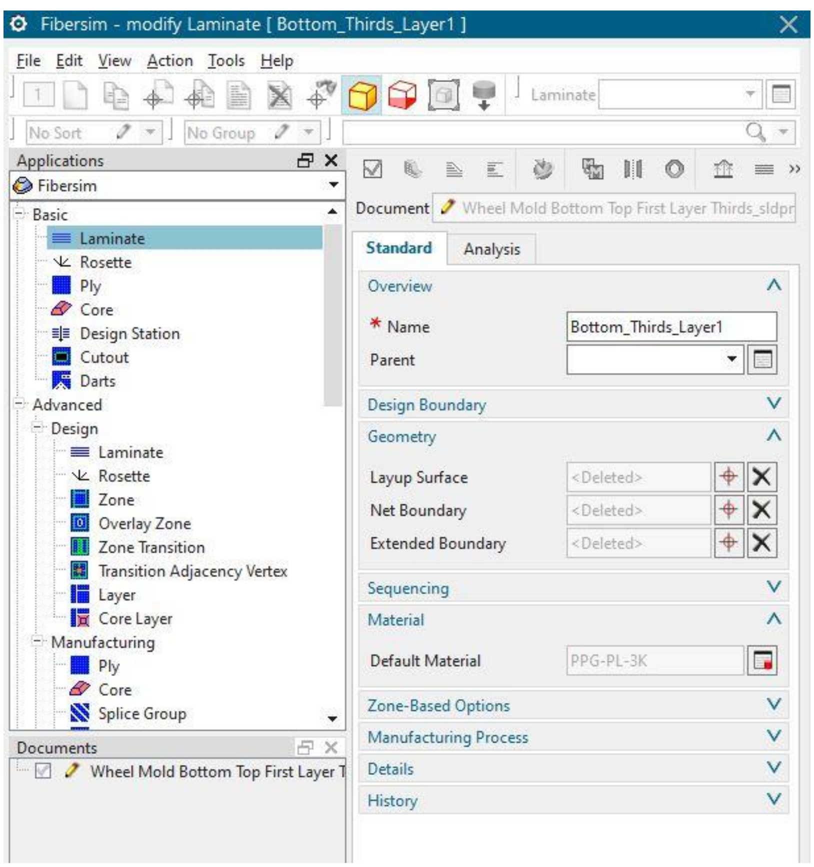


Figure 5.1 – Fibersim Interface

[redacted]

[redacted]

[redacted]

Figure 5.2 [redacted]

[redacted]

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Figure 5.3 – [redacted]

[redacted]

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Figure 5.4 – [redacted]

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Figure 5.5 – [redacted]

[redacted]

[redacted]

Figure 5.6 – [redacted]

[redacted]

Figure 5.7 – [redacted]

6. WHEEL MOLD AND CENTERLOCK HUB DESIGN

6.1. Wheel Rim Geometry Design

The CFRP wheel saw many design revisions all trying to converge to a simple, reliable, and lightweight wheel for our race car. Solidworks 2020 was used to model the components. Here are some renders of the wheel for reference:

Figure 6.1 - CFRP Wheel Design Revision 9

We documented our design iterations and revisions in an Excel spreadsheet called "Wheel Design Matrix" (See Figure 4.9)

In the end, we finalized a 3 spoke wheel design using the Tire and Rim Association (TRA) guidelines for dimensions and standards. This geometry allows for simple manufacturing, stiffness, and a beautiful appearance.

[redacted]

Figure 6.2 - [redacted]

6.1.1. Rim Profile Dimensions

[redacted]

[redacted]

Figure 6.3 - [redacted]

6.1.2. Centerlock Hub

Figure 6.4 – CFRP Wheel, Centerlock Hub, and Nut

[redacted]

6.2. Mold Design

To create a carbon fiber wheel, a mold must be manufactured to lay the carbon fiber plies onto. After consideration of varied materials to machine the mold with, we found that it would make the most sense to use [redacted] that we had on hand in the University of Akron Design Center.

Previous stock which was used for the previous wheel rim with aluminum center would be machined down to create the new molds. Using this stock which was already on hand would save time and money for our project. Once the wheel rim was designed in Solidworks, the molds could be designed. An overview of the Solidworks mold assembly is shown below.

[redacted]

Figure 6.5 - [redacted]

6.2.1. Solidworks Model

[redacted]

[redacted]

Figure 6.6 - [redacted]

[redacted]

Figure 6.7 - [redacted]

[redacted]

[redacted]

Figure 6.8 - [redacted]

[redacted]

[redacted]

[redacted]

Figure 6.10 – [redacted]

[redacted]

[redacted]

Figure 6.11 – [redacted]

7. MANUFACTURING

7.1. Molds and Tooling

To fabricate CFRP parts with a desired finish, strength, and profile, the use of curing the prepreg CFRP in an autoclave is required. As stated earlier, we designed and machined the

molds to the correct geometry and profile of our wheel. [redacted]

7.1.1. Mold Machining

[redacted]

[redacted]

Figure 7.1 – [redacted]

[redacted]

Figure 7.2 – [redacted]

[redacted]

[redacted]

Figure 7.3 – [redacted] Figure 7.4 – [redacted]

[redacted]

[redacted]

[redacted]

[redacted]

Figure 7.5 – [redacted]

7.2. Carbon Fiber Cutting

Once all the carbon fiber plies have been made into flat patterns using the Fibersim software, each individual ply can be cut out. This process can be done by printing out each template and cutting them with a knife blade by hand. This process is inefficient and inaccurate. A company by the name of Autometrix which is headquartered in Grass Valley, CA and has an office in Akron, OH. Autometrix specializes in integrated cutting solutions for businesses. Their applications range from canvas and leather to composites and carbon fiber. After working with

them we were able to use their demo cutting table in Akron, OH. For the cutting of our prepreg carbon fiber, their Argon machine was used. A description of this machine is shown in figure 5.6.

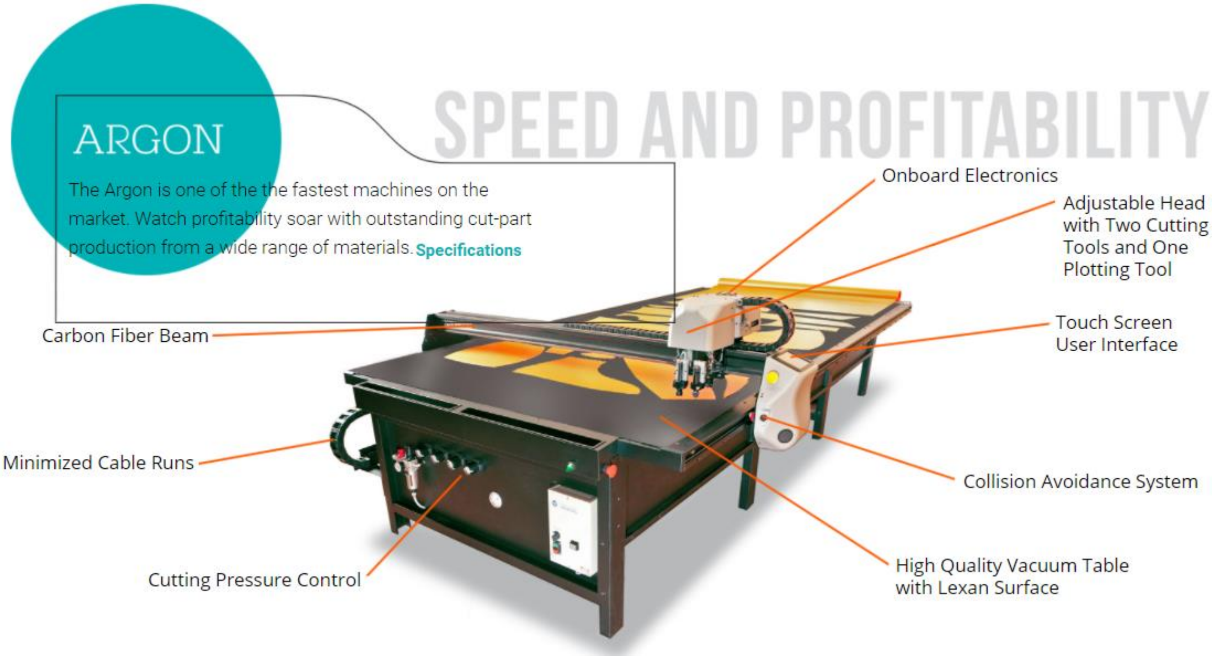

Figure 7.6 – Autometrix Argon Cutting Table

[redacted]

[redacted]

Figure 7.7 – [redacted]

[redacted]

Figure 7.8 – [redacted]

[redacted]

[redacted]

[redacted]

Figure 7.9 – [redacted]

[redacted]

[redacted]

Figure 7.10 – [redacted]

[redacted]

Figure 7.11 – [redacted]

[redacted]

[redacted]

[redacted]

Figure 7.12 – [redacted]

7.3. Core of Wheel

[redacted]

[redacted]

[redacted]

Figure 7.13 – [redacted]

[redacted]

[redacted]

Figure 7.14 – [redacted]

[redacted]

7.4. Manufacturing Process

7.4.1. Layup Assembly

[redacted]

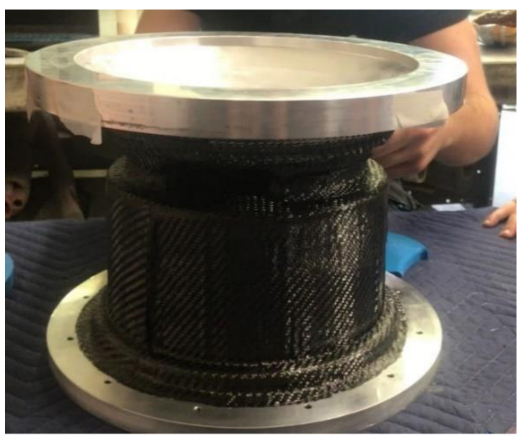

Figure 7.15 – Finalized Layup on Mold

7.4.2. Autoclave

[redacted]

Figure 7.16 – Algie Composite Autoclave in Springfield, Ohio

[redacted]

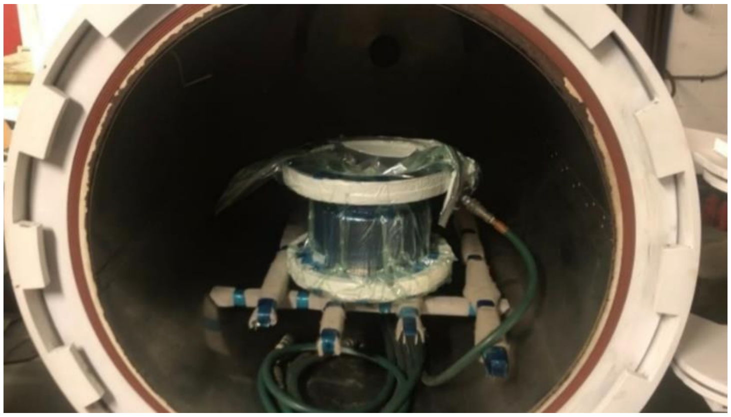

Figure 7.17 – Mold Vacuum Bagged in Autoclave

7.4.3. Final Processing

[redacted]

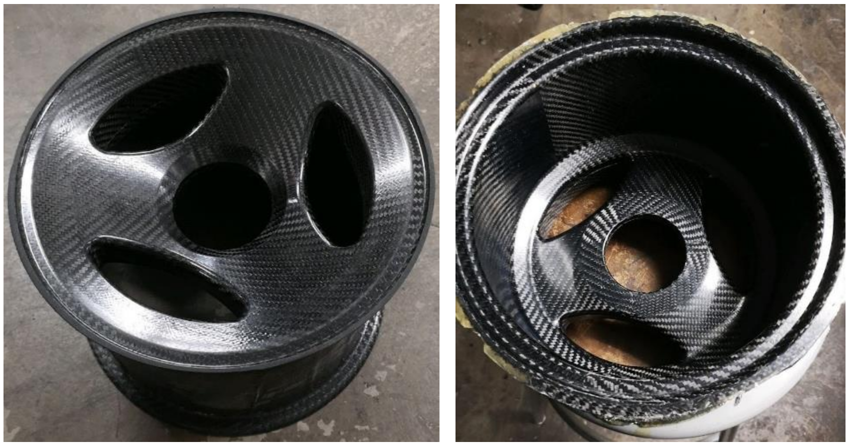

Figure 7.18 – Final CFRP Wheel

After the wheel has been trimmed down to size, the valve stem is added by drilling a hole and inserting the valve stem from the inside. This is shown in the following figure.

Figure 7.19 – CFRP Wheel with Valve Stem

8. PHYSICAL TESTING

8.1. Material Testing

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

Figure 8.1 - Instron Machine: Tensile and Flexural Testing

8.1.1. Test Series 1

[redacted]

[redacted]

[redacted]

[redacted]

Figure 8.2 - [redacted]

[redacted]

[redacted]

8.1.2. Test Series 2

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

Figure 8.3 - [redacted]

[redacted]

8.2. Tire Change Testing (Test Planned but incomplete)

[redacted]

[redacted]

[redacted]

Figure 8.4 - [redacted]

[redacted]

8.3. Radial Fatigue Testing (Test Planned but incomplete)

[redacted]

[redacted]

[redacted]

[redacted]

Figure 8.5 - [redacted]

8.4. Cornering Fatigue Testing (Test Planned but incomplete)

[redacted]

Figure 8.6 - [redacted]

[redacted]

8.5. **Centerlock** Wheel Test Adapters

[redacted]

[redacted]

Figure 8.7 – [redacted]

[redacted]

[redacted]

9. COST AND SCHEDULE

9.1. Estimated Project Budget (Mostly Materials)

[redacted]

[redacted]

9.2 Estimated Cost of Labor

[redacted]

10. CONCLUSIONS

We have determined that carbon fiber wheels can outperform aluminum wheels and therefore decided to test and manufacture carbon fiber wheels. While during the publication of this report our wheels remain incomplete, design and testing have been used to validate further production for use by Zips Racing team soon. While many components ended up being cost driven, we are confident in our method and process that these wheels will be sufficient for years to come saving the University money and advancing Zips Racing towards the cutting edge of wheel design.

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APPENDIX A

MatLAB Code for Hand Calculations

[redacted]

[redacted]

[redacted]

[redacted]

APPENDIX B: PHYSICAL TESTING

B.1: Tensile Template, Test Series 1

[redacted]

[redacted]

B.2: Tensile Template, Test Series 2

[redacted]

[redacted]

B.3: Tensile Specimen, Test Series 2

[redacted]

[redacted]

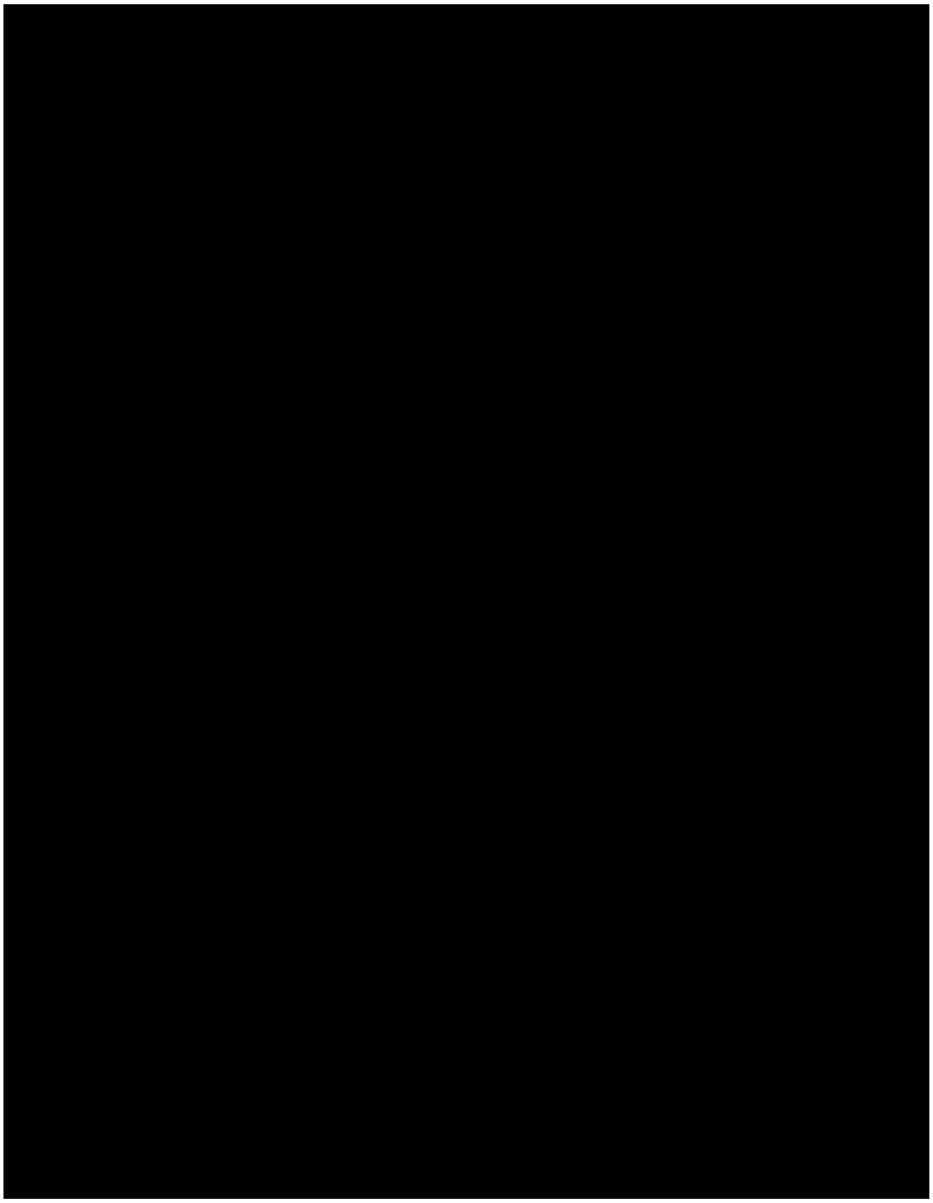
B.4: Flexural Template, Test Series 2

[redacted]

[redacted]

B.5: Resin Tensile Mold

B.6: Template CNC Cutting Method



B.7: Test Series 1 Results

Modulus of Elasticity and Ultimate Strength from Matlab Code

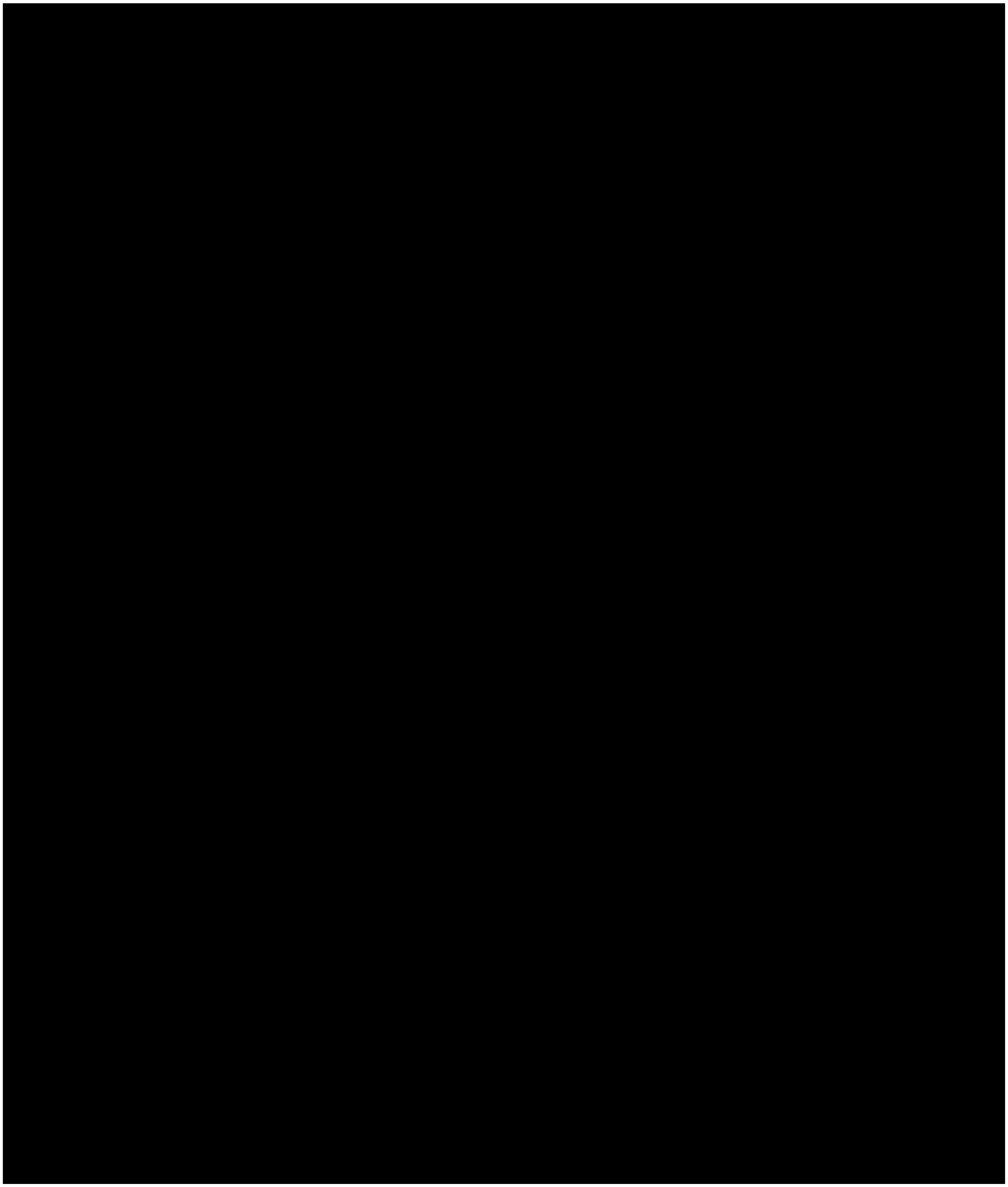
Example of Test Series 1 Results from Matlab Code

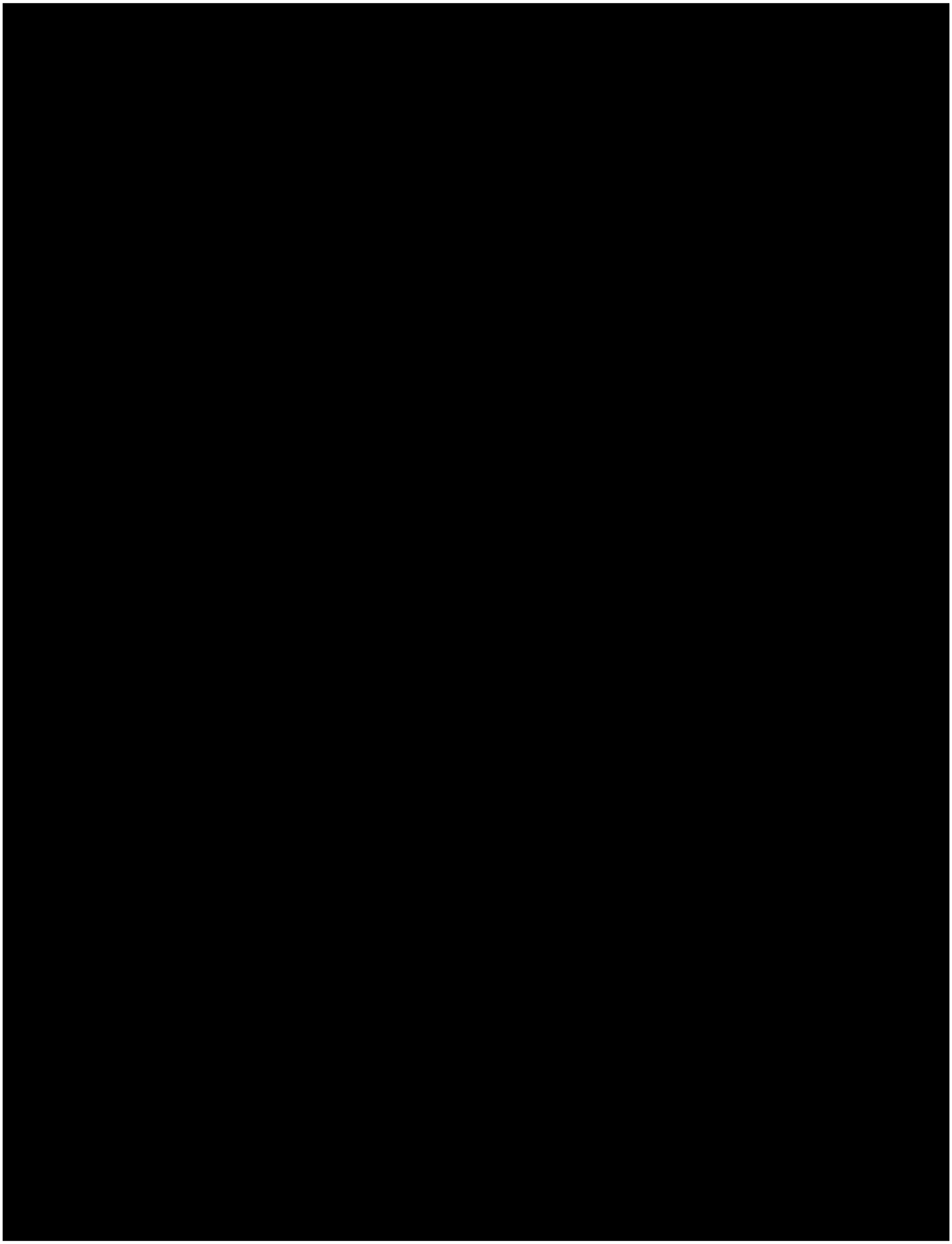
[redacted]

[redacted]

B.8: Tensile and Flexural Test Matlab Code

[redacted]





B.9: Testing Machine Adapters

[redacted]

[redacted]

[redacted]

[redacted]

B.10: Test Adapter Analyses

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

APPENDIX C: WHEEL MOLD DRAWINGS

C.1: [redacted]

[redacted]

C.2: [redacted]

[redacted]

C.3: [redacted]

[redacted]

C.4: [redacted]

[redacted]

C.5: [redacted]

[redacted]

C.6: [redacted]

[redacted]

C.7: [redacted]

[redacted]

C.8: [redacted]

[redacted]