Santa Clara University
Scholar Commons

Mechanical Engineering Senior Theses | Engineering Senior Theses

6-2018

3D Printed Carbon Fiber Electric Mountain Bike Frame

Chris Edwards
Santa Clara University, cedwards@scu.edu

Fionn Ruder
Santa Clara University, fruder@scu.edu

Joseph Hurley
Santa Clara University, jhurley@scu.edu

Micah Thomas
Santa Clara University, mthomas@scu.edu

Mitch Spinelli
Santa Clara University, mspinelli@scu.edu

See next page for additional authors

Follow this and additional works at: https://scholarcommons.scu.edu/mech_senior

Part of the Mechanical Engineering Commons

Recommended Citation

Edwards, Chris; Ruder, Fionn; Hurley, Joseph; Thomas, Micah; Spinelli, Mitch; and Gribb, Parker, "3D Printed Carbon Fiber Electric Mountain Bike Frame" (2018). *Mechanical Engineering Senior Theses*. 83.
https://scholarcommons.scu.edu/mech_senior/83

This Thesis is brought to you for free and open access by the Engineering Senior Theses at Scholar Commons. It has been accepted for inclusion in Mechanical Engineering Senior Theses by an authorized administrator of Scholar Commons. For more information, please contact rscroggin@scu.edu.

Author
Chris Edwards, Fionn Ruder, Joseph Hurley, Micah Thomas, Mitch Spinelli, and Parker Gribb

This thesis is available at Scholar Commons: https://scholarcommons.scu.edu/mech_senior/83

3D PRINTED CARBON FIBER ELECTRIC MOUNTAIN BIKE FRAME

By

Chris Edwards, Fionn Ruder, Joseph Hurley, Micah Thomas, Mitch Spinelli, Parker Gribb

SENIOR DESIGN PROJECT REPORT

Submitted to
the Department of Mechanical Engineering

of

SANTA CLARA UNIVERSITY

in Partial Fulfillment of the Requirements
for the degree of
Bachelor of Science in Mechanical Engineering

Santa Clara, California

2018

SANTA CLARA UNIVERSITY

Department of Mechanical Engineering

I HEREBY RECOMMEND THAT THE THESIS PREPARED
UNDER MY SUPERVISION BY

Chris Edwards, Fionn Ruder, Joseph Hurley, Micah Thomas, Mitch Spinelli, Parker Gribb

ENTITLED

3D PRINTED CARBON FIBER ELECTRIC MOUNTAIN BIKE FRAME

BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF

BACHELOR OF SCIENCE
IN
MECHANICAL ENGINEERING

Robert A. Marks ______________________ 6/14/18
Dr. Robert Marks date

T. E. Shoup ______________________ 6/14/18
Dr. Terry Shoup date

Abstract

3D printing of carbon fiber composites has been a developing technology for about 5 years, and in this time, Arevo Labs has established itself as a leader in the field. Our team joined forces with Arevo, who sponsored our project as we showcased their new, innovative carbon fiber manufacturing process. To do so, we focused on the conceptual design, analysis, assembly, and material testing of an electric mountain-bike frame printed with Arevo's continuous carbon fiber printing technology. Our bike consists of the main frame and a chain stay subsystem, which connects the rear wheel to the rest of the frame and interfaces with a suspension system. Understanding how the capabilities of the printer, the properties of the materials, and the typical loading scenarios experienced by mountain bikes all worked together was paramount in analysis, simulation, and design optimization and iteration. Thus, the focus of this project is to design a mountain bike capable of withstanding typical loading patterns with a high level of safety. Further, the team aimed to optimize a bike frame which used the minimal amount of material necessary to reduce weight and cost for the user.

Acknowledgements

The Car6on Senior Design Team would like to acknowledge the following for their guidance, support, and feedback from the inception of the project to the finalized design:

Robert Marks, Ph.D.

Peter Woytowitz, Ph.D.

Timothy Hight, Ph.D.

The Arevo Engineering Team

Santa Clara University Department of Mechanical Engineering

Contents

List of Figures

List of Tables

Introduction

In September of 2017 our team reached out to Dr. Peter Woytowitz, the Director of Modeling and Algorithms at Arevo Labs, in regards to the opportunity of exploring 3D printing technology for our senior design project. He informed us that we could help the company showcase their potential to revolutionize the 3D printing industry, and in turn Arevo would sponsor our project and mentor us along the way. It was mutually agreed that a bicycle frame would be the ideal project for a couple of reasons. First, the company felt that a bike is a relate-able product for consumers and would most effectively demonstrate the wide reaching potential of 3D printing with a continuous carbon fiber filament. Further, 3D printing a bike frame opens up many design possibilities otherwise impossible using traditional manufacturing processes. Also, the high axial strength of the material is well suited to handle the typical loads felt by a bike frame, which are discussed in detail later in this report. Finally, a bike frame is a feasible product for undergraduates to design, test, and assemble in the given project time frame.

After discussing with the engineering team at Arevo and the printer technicians, however, it came to our attention that the printer has trouble printing tight radii. This coupled with the fact that the print is done on a 2D build plate and extruded up in the z-direction led our team to the decision to print a mountain bike frame with square tubes. This somewhat unorthodox design decision will ensure any bends in the frame are within the machine's limitations and the frame can be printed from start to finish without the need of support structures. The decision to make an electric mountain bike was much more simple, the CEO of Arevo suggested that this would make it interesting and unique, and we agreed.

Arevo has provided useful material strength information. This data includes material strength properties for modulus of elasticity, shear modulus, Poisson's ratio, as well as maximum stresses in the xx, yy, zz, xy, xz, yx, yz, zx, and zy directions. This data has allowed us to design and iterate based upon FEA analysis and loading simulations to ensure that our frame will not fail under circumstantial loading typical of a mountain bike. In general, carbon fiber composites do not behave like a standard isotropic material, that is, they do not behave equivalently in all directions. Instead, carbon fiber is much stronger along the axis of its fiber than orthogonal to it. This phenomena is greatly pronounced in continuous carbon fiber compared to chopped. This behavior can be an issue when designing a part, since most parts have applications which require equivalent stress flow in all directions. When designing a mountain bike frame specifically, it is important to ensure that no unexpected loading scenarios will cause failure in a direction that was not designed to hold a load. This issue of differing directional material properties can be avoided by clever manipulation of the tool path during the print. To simplify simulation and analysis, the material is being assumed to behave equivalently in all directions in the X-Y plane, which can be nearly accomplished by layering different angles of fibers on top of each other. This is called quasi-isotropic, and is most often achieved by using fibers at 0, 45, and 90 degrees. Figure 1 provides an illustration of the concept of directional stress on the planes of a material.

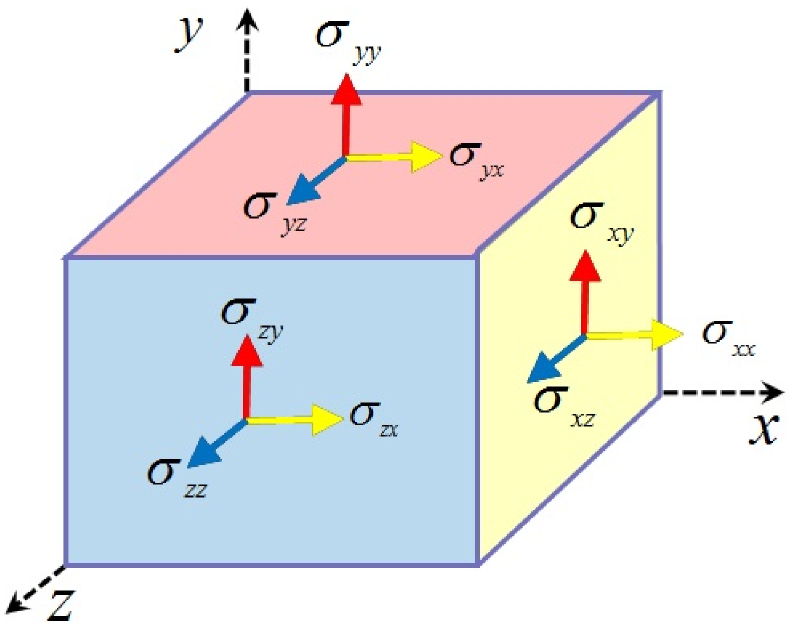


Figure 1: Illustration of Concept of Directional Stress.

The main goal of our project is to design a cost efficient 3D printed continuous carbon fiber electric mountain bike frame. Working with Arevo Labs gave our group the opportunity to showcase the capabilities of a continuous carbon fiber 3D printer while developing stress and strain analysis of the frame. Conducting finite element analysis on the frame has allowed for a streamlined design with support in typical areas of high stress for mountain bikes.

Another project goal is projecting the feasibility of 3D printing bike frames. Although the technology for continuous carbon fiber printers is new, our team recognizes the potential for this manufacturing process and developed a short term market-projection to lower cost and improve manufacturing speed. Working with Arevo and building a strong understanding of the printing process creates the possibility to develop methods to decrease the cost of materials and the time to print.

Review of Literature

The Safety of Electrically Assisted Bicycles Compared to Classic Bicycles [1].

The source is a study of crash statistics. It compares crashes from electric bicycles to human powered bicycles in terms of severity and frequency. The author argues that the crashes are similar, but more frequent on electric powered bikes. They believe more research should be done and new policies should be discussed. It seems obvious that powered bikes would be more dangerous than unpowered bikes, but we think it was worth studying the numbers more closely. The strength is that the article remained unbiased and let the numbers speak for themselves. The weakness is that the findings did not offer much insight to base decisions off of. This source is relatively recent (2014) and is written by a collection of credible university and governmental researchers in the

Netherlands. There should be no reason that the conclusions would not be abstractable to other countries. The information adds background information on the safety of the technology in our thesis.

Optimal Design and Dynamic Simulation of Mountain Bike With Rear Suspension [2].

The authors of this article developed a mathematical model for a coupled system of a rider and full-suspension mountain-bike. They analyzed the model with varying rear suspension parameters to determine optimal characteristics for ride comfort and efficiency. They argue that they found a specific trend in their results which show an optimal configuration for their rear suspension system. This is a good argument because it is clear from their results and they proceeded to test their conclusions. The strength of this source lies in their experimental procedures used to ensure realistic data. The weakness is that the model itself cannot be verified or easily recreated by an average reader. The source is trustworthy due to the five author's varied and extensive credentials in mechanical research. The data is also presented in an easy to consume manor, and the assumptions and results are backed up with experimental work. This article contributes to the topic of design of a full suspension bicycle of any construction.

Impact Damage on Fibre-Reinforced Polymer Matric Composites [3].

This article discusses the effects of various impacts on carbon fiber composite materials. They collected data and analyzed parameters of the impact such as shape, speed, weight, environment, ... Nothing is specifically argued, however, the findings and data is useful to others who might perform further studies or work with similar composites because it saves time. The main strength in their experiments is in the depth of study into varying types of impacts and their results. The weakness is that the experiments are not completely controlled and would be challenging to consistently repeat. This is a very trustworthy source, due to the authors' extensive background research and the number of further studies that have successfully used their data as a reference. It contributes to the overall field of composite materials by presenting useful information for anyone who desires to work with carbon composites.

Analyzing The Influences of Bicycle Suspension Systems on Pedaling Forces and Human Body Vibration [4].

This source analyzes the effect of suspension systems on bicycles on the overall performance and comfort of the human body. The focus is on the effect of rear suspension because front suspension is seen as necessary for off road bikes. They argue that the suspension systems alter the muscles that are doing the most work while biking and that human body vibration is reduced. Therefore, specific workouts could be tailored to improve off-road performance. The article is strong with its use of multibody models and software, and the various testing circumstances. The weakness for my purposes is that it is tailored towards someone with knowledge about the human body. The authors are researchers from various universities and are experts in this field. The article contributes more to the sport of off-road biking and how different suspension systems affect the biker than it does to the actual design of the bike.

3D Printing for COntinuous Fiber Reinforced thermoplastic Composites: Mechanism and Performance [5].

This article discusses the 3D-printing process and techniques used by the researchers to print continuous fiber reinforced thermoplastic composites (CFRTPCs). It also shows preliminary material testing data from their process. The authors argue that this process has potential to integrate itself into the market where a cheaper manufacturing process is desired. The article makes a good argument based off their findings and current costs of continuous fiber part manufacturing. The authors make a strong case while remaining unbiased and showing both the pros and cons of their research results. The weakness is that the printing technology is only discussed as a high level concept. The research is supported and verified by multiple state level labs and universities in China. They add to the scholarly conversation by comparing their results to standard, but expensive, processes for the same materials, and also to more standard materials with a similar process.

Choosing the Optimum Material for Making a Bicycle Frame [6].

This article uses FEM results to compare three different materials for bike frames. It is argued that due to a selection criteria based on strength, weight, and cost, titanium is the optimum frame material choice. This conclusion is poor because their selection criteria is very basic and subjective. The strength of the article is in its simplicity of breaking down the pros and cons of different material choices. The weakness is in the simplicity of the FEM model and the unsubstantiated claim of the best material. The background of the authors is not obvious and while the source seems trustworthy, the research seems to be at a Masters level at most. They add to the conversation by comparing less common material choices including carbon fiber and titanium instead of steel.

Nondestructive Evaluation of Carbon Fiber Bicycle Frames Using Infrared Thermography [7].

This article explores the use of infrared thermography as a viable non-destructive evaluation method for carbon fiber composite bike frames. The authors argue that due to the nature of impact energy propagation through the composite, thermal imaging should provide rapid, cost-effective, and useful information. This is a strong argument because it is well reasoned and proven to be effective after some post-processing techniques. The article is quite strong, as it provides thorough background, analysis of their equipment settings and choices, and instructions on how to perform similar evaluations. The weakness is that they did not really contextualize the numbers in their results to discuss whether the frame was still safe to ride. The article seems very professional and trustworthy, and the authors come from a variety of backgrounds related to infrared imaging and testing and material science. They add to the conversation of this topic by providing clearly useable results using a very quick and relatively cheap testing method.

Optimization of Electrical and Electrical Equipment [8].

This article discusses current eBike electric motors, and proposes a comparable design. The authors show how their take on the design and implementation of a electronic module including a microcontroller for an eBike. They ultimately built and tested their motor which performed up to the current market standard. The strength of the article is that the process of design along with all the electronic logic and math is shown in depth. The weakness is that nothing was really innovated. The article seems trustworthy as the authors seem to be graduate students, which is sufficient in this case. Not much is added to the overall conversation on brushless DC motors for electric vehicles; however, this article would be useful for anyone wishing to gain deeper understanding of the topic or desiring to build a similar motor.

Effortless Hybrid Bicycle with PMDC Motor and Solar Assembly [9].
This article gives a high-level description of an hybrid electric bicycle. The authors argue that e-Bikes pose a legitimate solution to the climate issues related to traditional cars. They believe that there is much room for improvement in the electric bike field. The arguments aren't very novel, and the article does not go to much trouble trying to prove them, but they are still valid. The strength of this article is in the detailed descriptions of each subsystem within an electric bike. The weakness is that these descriptions take up almost the entire article, and while useful, do not do much to back up any claim made by the authors. The overall trustworthiness of the article is not very important because nothing is really being claimed or achieved; it seems the authors are likely a group of masters students in mechanical or electrical engineering as none of them have the title of PHD or Dr. There is not much added to the conversation of electric bicycles as an alternative method of transport, however, the information on how they work is useful.

A Typical Approach to Design and Analysis of Foldable Bicycles [10].
This article documents the product development process for a folding bicycle. It is argued that there is a need for an improved folding bicycle design given our fast-paced and mobile lifestyle, and that current models have yet to capture the need for the simplest, lightest system possible. The article backs up their claim with thorough market research and selects their design based on realistically weighted criteria. Overall, it is quite a strong article which goes in depth about all the design process decisions and gives the pros and cons of the fabricated bicycle. The main weakness seems to be a lack of funding or time to really make an impressive prototype of their final design. The article is trustworthy because all of their decision are backed up by research and unbiased selection criteria. The article is a collaboration between a professor, an engineer in industry, and three students. They add to the conversation of bicycles by posing the idea that there is a lot of room for an improved foldable bike design, and they tell the reader which areas are being missed by the competition.

Design of Human-Powered Vehicles [11].
Highlights the design of vehicles with wheels that are powered by human muscle alone. Limited to land use, this book describes in detail why the designs of certain vehicles are beneficial. Contents include manufacturing, modeling, components, performance and much more.

Application of 3D Computed Mictrotomography for Investigating the Microstructural Defects of Carbon Fiber Reinforced Composite Made by 3D-Printing [12].
Defects are most harmful when improper printing procedure occurs and additive processes are not observed. These mistakes can significantly can cause low density and delamination which impairs the strength and reliability of the carbon fiber product.

A Method for Quantifying Impact Loads from Stone Impact in Mountain Biking [13].
Carbon fiber has weakness in transverse loading. A mountain bike has potential to fail when transversally impacted. Due to this we need to know how to assess stone impact as well as where common impact occurs.

3D-Printing of Meso-Structurally Ordered Carbon Fiber/Polymer Composites with Uprecedented Orthotropic Physical Properties [14].
Reference of 3D printed carbon fiber composites and their physical properties.

Choosing the Optimum Material for Making a Bicycle Frame [15].
This article analyzes the pros and cons of manufacturing aluminum, titanium, and carbon fiber frames based on criterion from a client. Carbon fiber received the second best score behind the titanium bike albeit titanium being the most expensive.

Systems-Level Chapter

Customer Needs

Intuition tells a person that when designing anything that will be used by humans, it should be safe as to ensure the product does not put the user in harm. This is especially true in the case of an electric mountain bike, which is designed for intense terrain and to assist those who may be physically unable to ride without the help of a motor. Not only should a product be safe enough to handle the conditions it is marketed for, but it also should not be overly supported as to raise the price for the customer. Thus the main customer needs of our product are low cost and safety. To figure out how best to achieve this goal our team met with bicycle shop owners and avid bicyclists to get their input.

After conducting several interviews with potential customers and bike shop owners it was found that the biggest issue with current carbon fiber bike frames is the cost. Carbon fiber bicycle frames manufactured using weaves are costly, (Trek's cheapest full suspension, carbon fiber frames are $3,000) however their tubes are incredibly thin, are lightweight (often around half of a pound), and are extremely durable. Thus the idea of using carbon fiber for bike frames should be investigated more, with the goal of reducing the price for the customer. After continuing to interview possible customers our group found that reducing materials to lessen the cost is not always the best solution. While the initial cost of the bicycle may be cheaper, it is more likely to fail and therefore will need to go into the shop more frequently and face more repairs, which can get pricey. Our goal then is to conduct mechanical testing of the material combined with finite element analysis and model optimization to find the ideal amount of material to keep the cost of the frame as low as possible, yet with the proper geometry to ensure proper stress flow, rigidity, and safety.

Another common issue with carbon fiber bike frames is that when the frame fails, it generally experiences a catastrophic failure. This means that there are no cracks or otherwise visual or audible warnings before the frame fails. The reason for such failure in carbon fiber is that it is a brittle material, so as opposed to metal there is almost no deformation before it fractures. This is also a benefit when designing a bike frame, however, since brittle materials have a high resistance to dynamic loading and fracture due to fatigue, provided that the maximum stress experienced by the frame stays within the area of infinite life for the material. Carbon fiber is also relatively weak to any loads that are not along the axial direction of the fibers. To account for this, we will use a quasi isotropic approach which lays the fibers at different angles, which increases the strength in all directions and will help the durability of the frame when it experiences unexpected impacts and loads. We will also be using continuous carbon fiber rather than chopped carbon fiber which will increase the durability of the frame in the direction of the print. By researching the typical stresses experienced by a mountain bike frame, our team will be able to design a frame with a complex geometry capable of creating a stress flow along the axial direction of the print, maximizing strength.

Thus, to address the main needs of the potential customers of our product, our team must have an immense understanding of the typical loads experienced by a mountain bike as well as the material properties of continuously printed carbon fiber. Knowing such properties will ensure our team can design a mountain bike frame that is lightweight, strong, safe, and inexpensive.

System Sketch and User Scenarios

Usage scenarios are straightforward; individuals engaged in the sport of mountain biking will use the bicycle system to traverse both on and off-road terrain. The electric motor mounted on the frame is designed to offer assistance to those who enjoy the sport but may be physically unable to traverse difficult terrain. The battery which powers the motor can be charged using regenerative braking, or simply plugging it into a power outlet. The handlebars will feature the typical hand brakes to slow the bike, a gear shifter for when the motor is off, a power button and electronic gear shifter to turn on the motor and control it, and finally an electronic readout which displays speed, distance traveled, and remaining battery life. The double suspension system allows for an incredibly smooth ride by dampening impulses and vibrations, allowing for a user with physical impairments to enjoy the product. Lastly, the carbon fiber frame is intended to be sold to bike manufacturers where they will use this to produce functioning bikes that are lighter and more durable than existing mountain bikes. A first full system sketch is presented below in Figure 2 while material comparisons are presented below in Figure 3.

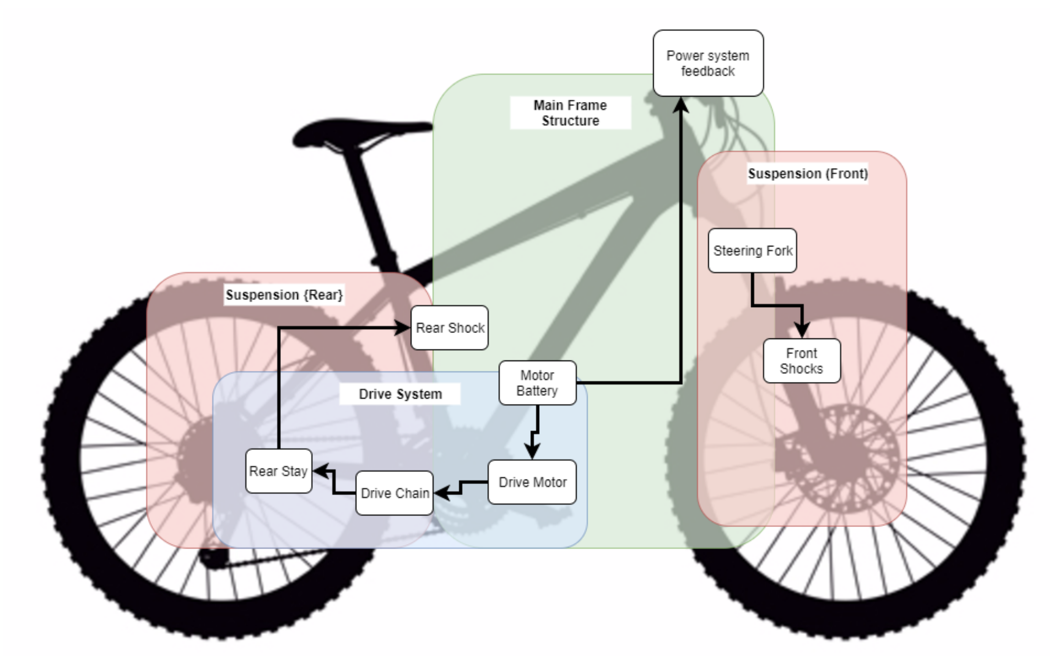


Figure 2: System Level Sketch.

Functional Analysis

Functional Decomposition

The function of our 3D carbon fiber bicycle frame does not differ from any other standard bicycle frame, in that it is to provide a safe, convenient and/or entertaining mode of transportation. However, there are advantages over traditional frame materials and manufacturing techniques which are hoped to be captured. The first of these is to maintain a lightweight carbon fiber bike frame, while also being more durable than current carbon fiber bike frames using the innovative manufacturing technique of printing with continuous carbon fiber. While doing this, we also hope to reduce the cost of the frame to be a competitive frame supplier and for the benefit of the consumer. The frame will need to be able to incorporate all the additional parts needed, such as: handlebars, motor, battery, wheels, pedals, gears, seat, etc. The frame will also need to be able to support the loads from a rider and withstand unexpected impacts experienced while mountain biking in rough terrain. Since carbon fiber is a brittle material, it is important that the frame can handle any unexpected impacts because of it's unexpected failure mode.

The largest difference in this product from a traditional bike is the integrated motor system. As previously mentioned, this system allows for riders of all ages, sizes, and skill sets to enjoy the sport of mountain biking. When working correctly, the bike functions to assist the rider uphill, or simply when pedaling on level ground.

Inputs and Outputs

The first anticipated input to the bike frame will be the weight of the rider, with the corresponding output being the stress experienced by the frame. However we will have to account for the multiple locations where the rider will focus their weight. The anticipated static rider weight locations are: first; all the weight focused on the seat and handlebars, second; all the weight focused on the pedals and handlebars, and third; a combination of the two. Of course, the associated output for each scenario will be different.

In the first case the top tube, seat tube, and head tubes will experience the brunt of the stress. The second case will effectively transfer all rider weight from the pedals into the motor and ultimately will be felt by the interface between the motor and the frame. The last case will combine the loading scenarios and thus produce an expected output of stress flow throughout all members of the continuous frame. This output will manifest itself in material deflection in the frame and failure if designed improperly.

The second anticipated input to the bike frame is impact forces that are experienced while mountain biking caused mainly by rocks and other debris kicked up from the wheels. There are many possible outputs that may arise from such forces. First is the obvious small surface deformations which could potentially create stress-concentrations and even fracture nucleation sites. The carbon fiber strands will be continuous strands and aligned in a quasi-isotropic pattern to increase the strength of the frame and be able to resist these impacts. Another possible output from impact forces is vibration within the frame. However, these are negligible compared to other possible modes of vibrations of a bicycle, as discussed later in the paper. By running tests, we can determine where the frame will be most likely to fail due to these impacts, and can therefore add extra material and supports to these areas.

The last anticipated input to the bike frame is dynamic and cyclic loading patterns caused by pedaling, uneven surfaces, and other unexpected forces applied by the rider. The output response of these loading scenarios is fatigue in the material. Our team is confident that our frame will be able to withstand the cyclic loading and corresponding material fatigue without any signs of failure with a high level of safety, as discussed using mechanical test data later in the paper.

Similar Products on the Market

There are many different ways to design bike frames on the market. The first thing to ask oneself is what type of bike one is interested in. Currently, there are many different types of bikes, the main types being mountain bikes, road bikes, and cruisers. The frames of these three bikes vary greatly due to the expected loading scenarios of each. For example, road bikes are designed for high speeds on roadways, and therefore have a thinner and lighter frame. Compare this to mountain bikes, which have a thicker frame and are designed to be durable and able to withstand impacts and higher dynamic loading patterns. There are also different materials that these frames can be made of, each with their own advantages and disadvantages. The most common material that is used to make bike frames is metal, such as steel or aluminum. The reason that these are the most common materials is that they are the cheapest material, are durable, and are easy to work with for manufacturing and post processing. However, the disadvantage to metals is that they are heavier than other bike frame materials. The other popular bike frame material on the market is alloys which have a high strength to weight ratio and have a low density. The issue with metal alloys is that they are not as easy to work with and are more vulnerable than the other materials to fatigue. Our team has decided to work with carbon fiber since it has an incredibly high strength to weight ratio with some exciting new innovative manufacturing processes. Figure 1 provides a comparison of different frame materials, their key features, and associated frame cost.

Table 1: Comparison of commonly used frame materials.

Frame Material	Key Features	Average Cost ($)
Steel:	High strength Inexpensive High density Easy to work durable	200-650
Carbon Fiber:	Expensive Low density Corrosion resistant Highest strength-to-weight ratio Non-metallic Easiest to work Not durable	600-2000
Aluminum:	Low strength Low density Inexpensive Good strength-to-weight ratio Vulnerable to fatigue Less easy to work Short lifespan	300-700
Titanium	Expensive High strength-to-weight ratio High density Excellent corrosion resistance Difficult to work	1000-3000

Within carbon fiber frames, there are different techniques used to design and manufacture the frames. The most common way that carbon fiber frames are made is through bladder molding. Bladder molding is a method in which the carbon fiber is wrapped around an inflatable bladder and then placed in a mold cavity. From here, pressure and heat is applied to shape the parts to the mold cavity. The benefit to this method is that many different designs can be created with minimal costs once the mold cavity is created. The problem with this method, however, is that if the pressure is not applied evenly throughout the mold cavity then there will be weaknesses in the frame which increases the chance of failure. This also means that the strength can vary from frame to frame based on the pressure applied. Figure 3 illustrates this technique.

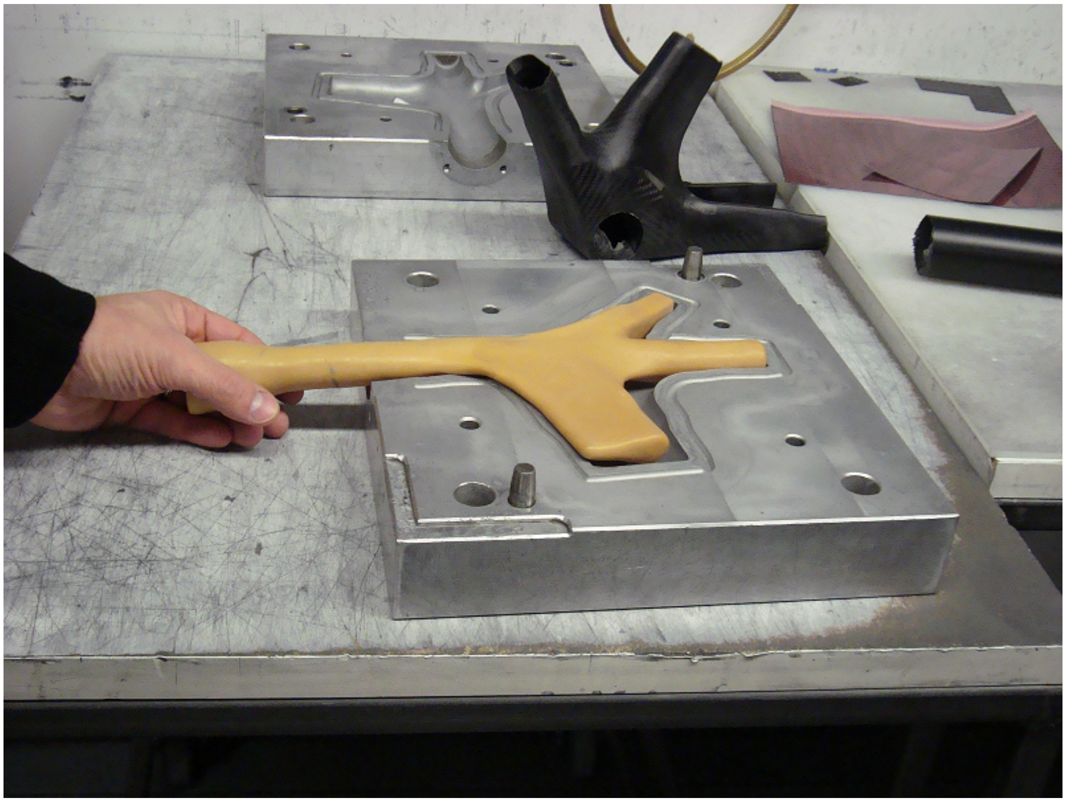


Figure 3: Example of Bladder Molding Technique.

Another method in which carbon fiber frames are made is through roll-wrapping. This method takes a steel mandrel in the shape of the desired final product. Carbon fiber is then wrapped around the mandrel, pressurized, and heated until it hardens. The advantage to this method is that it allows the most custom designs, as any shape can be made. The drawback to this method is that it is a very time consuming process and cannot be used for mass production. This method is more suited for custom molds, than for bike frame production.

As far as 3D-printing with carbon fiber, the most common method utilizes chopped carbon fiber. This means that the carbon fibers are chopped into small strands and are randomly oriented throughout a plastic foundation. This printing method produces durable isotropic products with great geometric complexity, however there is high potential to greatly increase the durability and strength by introducing continuous carbon fibers. Since bike tube frames are fairly long we can use continuous strands as this will provide more strength than chopped fibers in the axial direction of the print.

CAD Design Phase

At the beginning of the design process, our team understood we had much to learn about both bike frames and the unique continuous carbon fiber printing process. To this end, we sought to design our frame mimicking the steps of additive manufacturing process while maintaining a high degree of model adaptability.

Spline Based Model and Printing Process

The continuous carbon fiber 3D printing process works very similar to "traditional" thermoplastic extruder 3D printing technologies. Model geometry is sliced into individual build layers, and each build layer represents a planar surface the toolhead will follow, extruding material along predetermined toolpaths to build the layer. The figures below illustrate this design sequence. First, a projection of the frame profile is laid down on the build plate to provide both one of the flat faces of the frame, and a base support for the next stage of vertical building. This stage is shown in Figure 4. Because the printer cannot currently extrude a filament in the 'z' direction, vertical geometry is created in successive layers. A snapshot of this process is shown in Figure 5. .

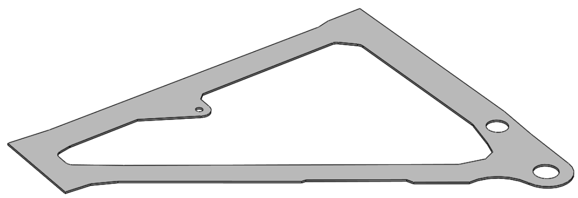


Figure 4: Initial printed layer

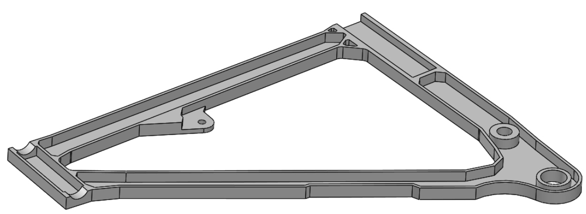


Figure 5: Secondary printed features, with vertical walls partially printed

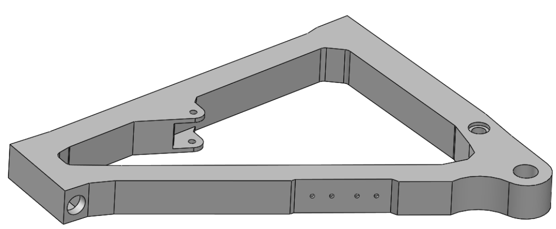


Figure 6: Final build layer, completed geometry

All of our models were designed along this process. We reasoned by designing the frame in the same way it would eventually be built, we could anticipate and avoid issues early on. However, we were conscious of the inevitable need for design changes. To this end, we were careful to design our frame to allow for a maximum level of adaptability. We achieved this goal by using a spline and line segment based design. The outlines of the initial build layer in Figure 4 were created from an extruded profile sketch with numerous draggable control vertices. These segments were offset inwards by our wall thickness of 4 mm, before being extruded to form the walls visible in Figure 5. An example profile sketch is shown below in Figure 7. Dragging a control vertex or adding a relevant dimension to this sketch resulted in the changes propagating throughout the entire model, allowing for a very flexible, adaptable approach for multiple designs.

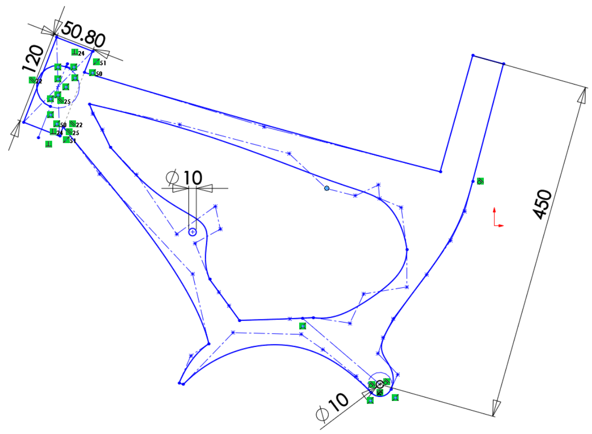


Figure 7: Example profile sketch with spline control vertices

First Frame Design

Our initial design required extensive modification, on account of our initial inexperience with frame design and the printer's capabilities. Additionally, this design was created before we had made our external hardware selection, and eventually underwent substantial renovation to accommodate future hardware choices. With this design, we wanted to leverage the 3D printer's ability to print smooth continuous arcs, so we aimed to incorporate organic curves that would be difficult to produce with traditional welded-tube frame designs. While theoretically printable, this design suffered from predictable stress concentrations in regions of sharp angles and rapid profile changes, highlighted below in Figure 8.

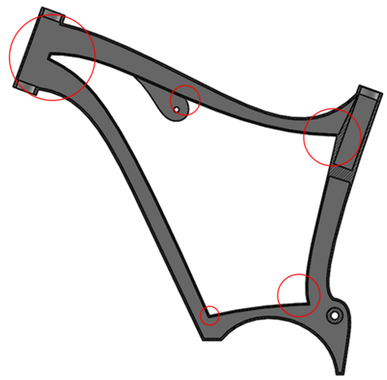


Figure 8: Cross section view of initial design, with stress concentration areas highlighted by red circles

At this point, we had elected to use a mid-drive motor secured to the bottom bracket of the frame for power, however we were unsure exactly which model. This first design was created around the assumption we would use a motor that secures to the bottom bracket with an extra fastening bracket, completely encircling the motor with carbon fiber. The rear suspension shock would connect to the frame via the symmetric flanges dropping down from the top tube, and provide dampening to the back wheel through pivoting rear stays.

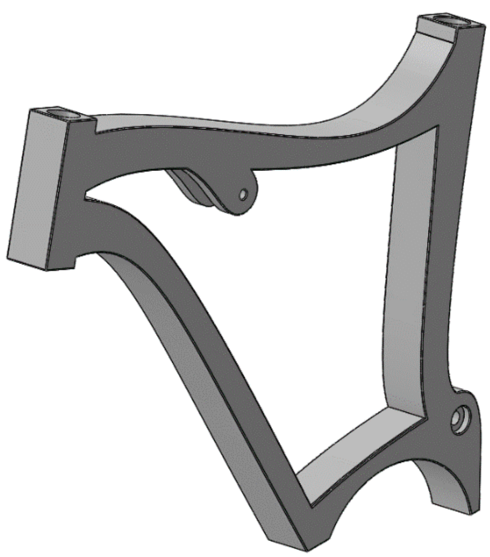


Figure 9: First frame design, pre-hardware integration

Despite the problems associated with this frame, it provided a good exploration of component placement that informed all of our later frame designs.

Second Design, post external hardware choice

Our second design greatly improved upon the first. At this point in the design process, we had isolated our choices for a motor and power supply, and were able to create a much more fully-realized design, with a full model shown below in Figure 10.

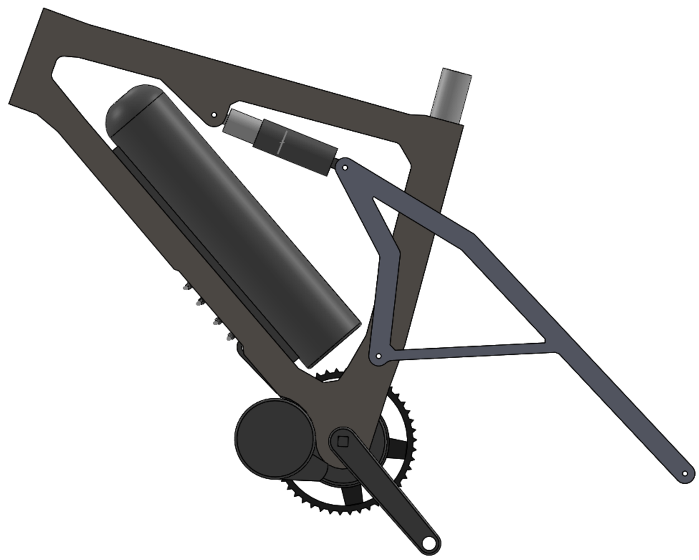


Figure 10: Second major design iteration, with motor and battery integration

We opted for a more traditional frame profile, reminiscent of the welded-tube paradigm, but still wanted to promote a continuity between all geometric features. In all regions of stress concentration with the previous model, we smoothed out sharp changes in geometry with a combination of fillets and chamfers on the interior and exterior of the frame. We also drew away from the curved tube profiles of our first design; we discovered virtually all tube-mountable battery solutions required a linear mounting surface. In order to mount our chosen hardware, we had to straighten the down tube to accommodate the bottle style battery. These changes are easily visible with the profile cross section shown in Figure 11.

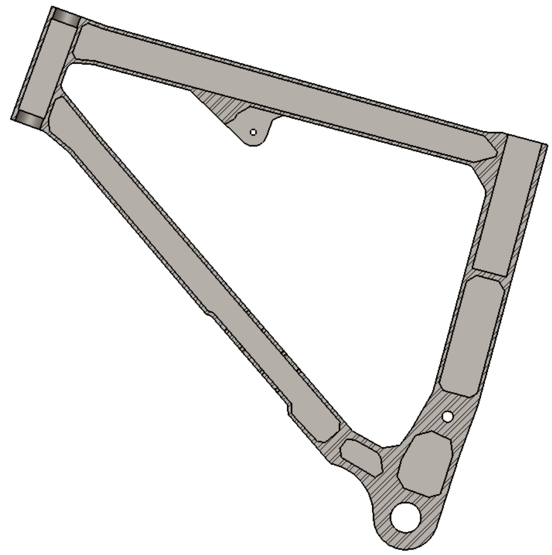


Figure 11: Cross section of second major design iteration

The bottom bracket of this design was much more developed than the first design, on account of knowing the exact geometry of our drive motor. We opted for a slide-in style BBS02 500W 48V mid drive motor, shown below in Figure 12.

Figure 12: Motor drive system purchased from Bafang

The BBS02 motor system doesn't require an additional mounting bracket. This motor is designed to upgrade existing traditional bike frames to an electric drive. The pedal cranks are detachable and the motor interfaces with the frame by sliding through the pedal hub. The motor is then secured with a Y shaped washer on the opposing side. The motor is housed in the forward cylinder, and is designed to lay flush with the bottom bracket geometry as shown in Figure 13.

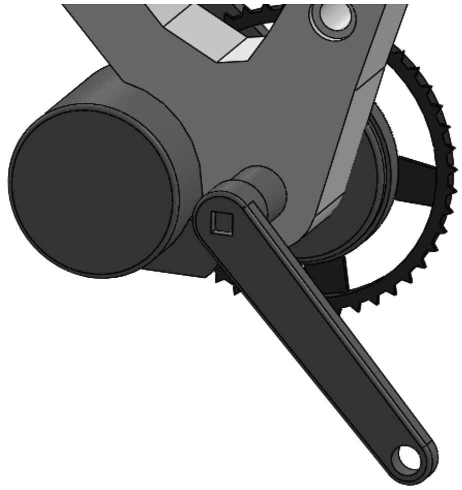


Figure 13: Motor-frame interface design

In anticipation of load concentrations at the interfaces between frame and hardware, extra printing material was allocated to reinforce the frame interior at the interface points. Though Figure 11 depicts these regions as solid, in actuality they were designed to be printed as a 20 - 30 percent infill ratio. With 3D printers, infill percentages are almost always used instead of solid volumes, because the latter method drastically increases printing time and material usage. For our purposes, printing solid carbon fiber regions would lead to print times on the order of weeks instead of days. Despite carbon fiber's strength to weight ratio, solid regions greatly increase frame weight for marginal improvements in strength. To augment the savings of the infill strategy, the frame was designed with voids strategically placed to further reduce material usage without sacrificing strength.

Final Design

Upon comparison of a previous design with the developing printer's capabilities, we learned the process was currently unable to print curves with less than a 20 mm radius, for a minimum printable hole diameter of 40 mm. This new knowledge required a number of changes to the frame profile geometry; any sharp angles were unable to be printed in a continuous path, and would require the toolhead to approach the same region from a different angle. This limitation would increase the printing time per layer. The best design was one where each layer could be printed in a continuous manner. With this in mind, we created our final design shown in Figures 14 and 15.

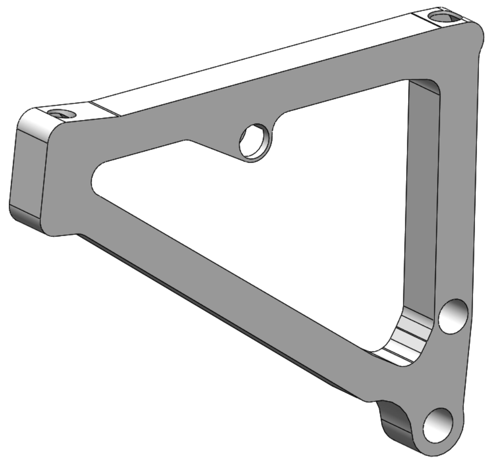


Figure 14: Isometric view of final frame design

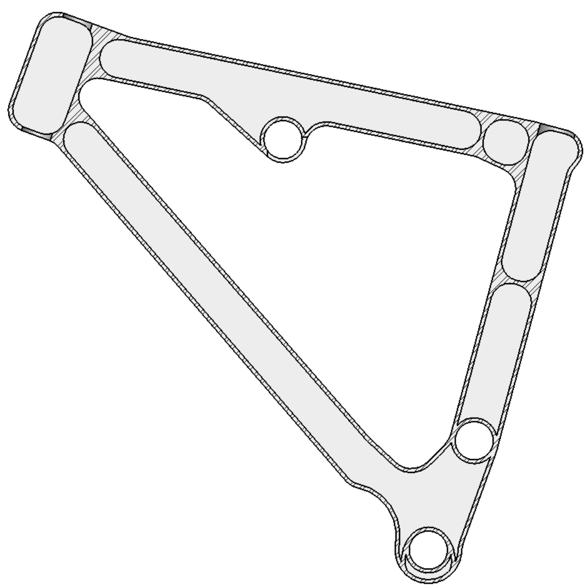


Figure 15: Cross sectional view of final frame design

Every corner of the frame needed additional curvature, and all holes were enlarged to satisfy the minimum radius requirement. These new curvatures resulted in slight protrusions on the head and seat tubes visible in Figure 15. Additionally, the radius limitation forced the removal of all the small chamfers and fillets of the previous design for a set of 20 mm radius fillets between all tube junctions. This limitation also required the design and manufacture of a set of aluminum sleeves and spacers to step down the 40 mm diameter holes to the dimensions of our second model. Ultimately, this change yielded a design that incorporated both the aesthetic curvature of our initial design while maintaining the hardware placement developed in the second design. Otherwise, all other major dimensions and hole placements remained unchanged from the previous model.

System-Level Issues

The key system-level issues in a bike frame are those which cause the entire bicycle to no longer function safely and as intended. Therefore, these key issues are centered around failure and fracture of the frames subsystems. The first issue that would cause function failure would be in the design phase. The stresses caused by the inputs discussed above in the functional analysis are, by nature, unpredictable, so the subsystems must be designed for worst case scenarios. All the tubes and structures which make up the bike must be analyzed and tested intelligently to be confident that the design will not be an issue. The next issue would come from the manufacturing of the frame. This is the more likely phase in which unforeseen problems might arise. 3D printing provides a lot of control and customization of the part, but this can come at a cost. Much faith must be put into the robotic system which performs the printing. Any mistakes will create defects, which might be so small as to go unnoticed but large enough to cause failure over time and repeated use. Lastly, issues can arise during storage of the frame. This phase is in the hands of the consumer so it is important to relay any known problems with storing carbon-fiber or bicycles. However, this does not affect the design of the frame in any way.

There are many slight changes in the geometry of a frame which will create a different riding experience, aesthetic, and strength characteristic. It does not make sense to really dive into these slight changes until later in the design process when finite element methods will be used to analyze and iterate different designs. Instead, the focus is on bigger picture design options and their trade offs. The main options have to do with the suspension system, the front part of the bike (including the seat stay, bottom bracket, and down, top, and head tubes), and the rear part (including the rear and chain stays).

The options for suspension are simply whether to design the frame for no suspension, front suspension only, or full suspension. The main trade-offs here are that more suspension leads to a more comfortable ride with less shock to the frame and drive system, but also costs more money and is more challenging to design and analyze.

The main, high-level, front options have to do with its general shape. Three options were considered: a very simple triangular shape with points at the head tube, bottom bracket, and seat; a frame with a cantilevered seat which comes up and out from a more obtuse triangular shape; and a frame with a seat tube that is raised vertically above the top tube, allowing for a supporting truss member between them.

Three options were also considered for the rear system: a simple triangle that would have one side attached directly to the the front system, a horizontal V-shape with the two ends of the v attached separately to the front system, and only a chainstay which would attached the rear wheel to the seat tube in a straight line. For a visual representation of the front and rear options, see the sketches in Appendix B.

The trade-offs for the front and rear systems are very similar. More complex designs leave more room for innovation and customization and can create a product which really “stands out” for Arevo’s marketing purposes. But this complexity comes at the cost of more challenging design, analysis, and testing phases. There is also a major trade off between strength and weight which will need to be balanced. Weight is also directly related to cost by the volume of material needed. Finally, printability, amount of machining needed after printing, and assembly must all be considered.

After determining criteria and weighting them due to their importance to the project (see the selection matrices in Appendix A for detailed concept scoring), it was determined that a full suspension system should be sought after. It doesn't make sense to choose the winning front or rear system without taking into account the overall context of the design, so for the full suspension solution, the supported seat tube was chosen, while for the hard-tail solution, the cantilevered seat was chosen.

System-Level Design

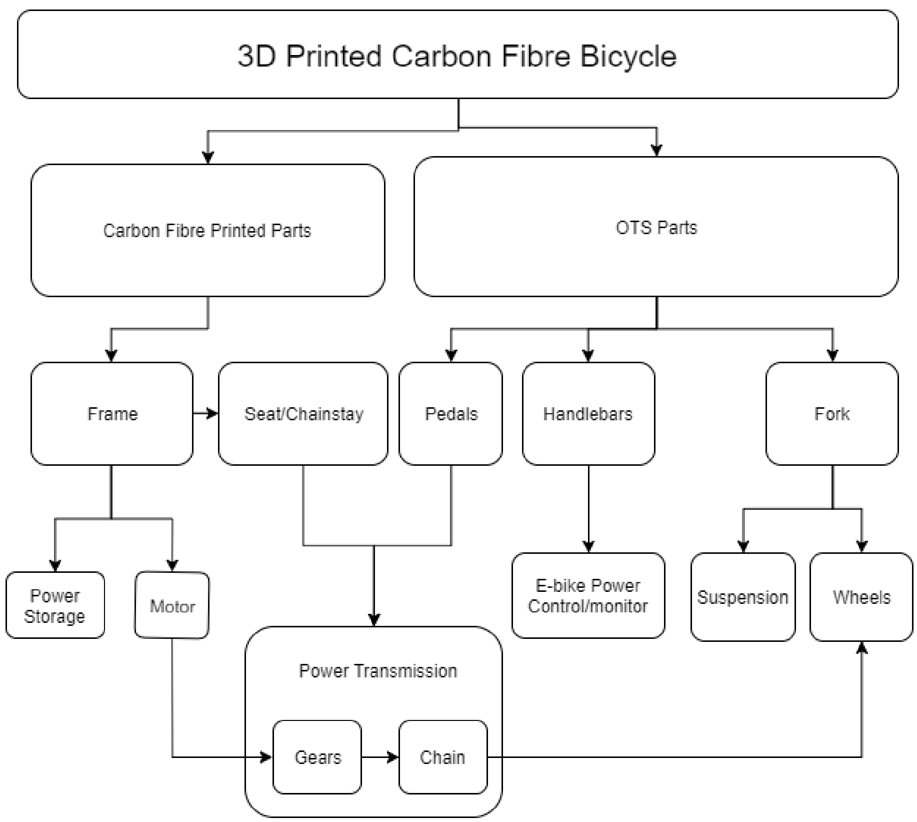


Figure 16: Chart showing breakdown and connections of subsystems.

The bicycle will consist of both custom designed continuous carbon fiber printed parts and off-the-shelf components. The main bicycle frame will be designed to be manufactured via Arevo's printing process, and serve as the support housing the bike's electric propulsion and energy storage subsystems. These subsystems will be linked together and monitored by a display on the bike's handlebars. This monitor will provide feedback to current speeds, power reserve levels, and possibly other system and environmental variables such as GPS headings, route times, and rider vs electric power assist energy expenditures. Off the shelf handlebars will house this system to be easily visible to the rider.

Off the shelf parts will include remaining structural components of the bike. This will include a form of front and possibly rear suspension. Pedals will interface with the electric assist subsystem. Ideally, regenerative braking will convert gravitational potential energy and excess momentum to useful reserve power for the bike motor and monitoring systems. Frequent elevation change and brake usage is expected during normal bike usage, warranting implementation of such a system. Activation of the electric power assist subsystem will likely be executed through pedal-assist; most riders will want to maintain the experience of pedaling while mountain biking as opposed to a hand or thumb throttle toggling.

Team and project management

Constraints

Over the course of this project there were several constraints and challenges that we had to overcome. After designing our first frame design, we met with Dr. Peter Woytowitz at Arevo Labs and began to discuss the capabilities of the printer. We learned that our initial idea of creating a frame with sharply curved edges was not a feasible concept due to the stiffness of continuous fibers filaments. Using continuous carbon fibers meant that there were limitations to the minimum curvature radius that we could print. To overcome this constraint, we had to modify our design, so the minimum frame and hole diameter was within the printer's capabilities. We also had to reduce the amount of material we were using in order to minimize weight while also reducing print time.

The next issue that we faced was the time that we as a team and Arevo Labs had to print the bike frame and rear stays. In order to cut down on the print time we agreed to print a skeleton frame, which meant the frame would be printed without the walls, as can be seen in Figure 31. We also agreed that the rear stays did not need to be 3-D printed, as the key aspect of this project was the continuous carbon fiber frame. To design these rear stays we instead laser cut 4 pieces of acrylic to the shape of our rear stays then cut out foam to the same design. We then bonded acrylic to either side of the foam in order to help the rear stays hold their shape. With the skeleton frame and rear stays formed we then had to wrap these components in carbon fiber for both aesthetic purposes and to provide more strength. This then presented us with our next challenge of learning how to wrap carbon fiber.

One of the biggest challenges that we as a group faced was learning how to wrap using carbon fiber. We began by cutting out strips of carbon fiber then dunked this in a resin and hardener mixture, however we quickly learned that this shrunk the carbon fiber cloth and made it very difficult to work with, as the cloth would become mushy. This led to a first layer of wrap that included numerous holes, bubbles and rough edges. This meant that we had to sand these abnormalities off to prepare to apply a second layer. With the second layer we decided upon a new strategy of applying the carbon fiber cloth then applying the resin and hardener mixture to the cloth that had already been laid and wrapped on the bike. We found this to be the best strategy and continued this for a total of 4 wrapped layers. However, after our struggles on the first layer there were still bubbles throughout the frame as well as several rough edges even after we completed our sanding process. To fill in these voids and cover the rough edges we then applied an Apoxie Sculpt to the frame and rear stays for aesthetic purposes as well as to prevent riders from cutting themselves and getting splinters on these rough edges.

The next challenge that we faced was figuring out how to drill our holes into the rear stays since they had to be perfectly aligned in order to attach these components into the frame and attach the rear tire. To do this, we attempted to clamp the 2 rear stays together perfectly in line. Clamping presented a problem due to the fact that the rear stays did not have any flat surfaces making it difficult to clamp these parts in perfect alignment. After doing this, we then had to determine a way in which to clamp the 2 rear stays to the mill in order to drill the holes. After struggling for a short while, we eventually determined a way to clamp the rear stays to the mill and finally drill out our holes.

Another issue that we had to overcome was determining how to assemble the bike. As mentioned above, our skeleton frame was printed with a greater hole diameter than we had intended, which meant that we then had machine parts. These parts would be inserted into these holes and then provide a smaller hole diameter that we could then insert rods through to hold all the components in place. Upon finishing these machined parts, we were able to insert them in place and begin assembling the frame.

After beginning assembly, we realized that when designing our frame, the dimensions were designed so the parts would fit directly out of the printer. This did not take into account the extra material from carbon wrapping the frame after the printing process. This meant that in order to install all the components, we had to remove sections of the wrap where all the electrical and other bike components would be installed. If we were to repeat this project again we would take into account the extra material that is accumulated from wrapping or ideally the entire frame would be printed and we would not have to add extra carbon wrap to the frame.

Budget

As discussed before our group partnered with Arevo Labs to design and 3-D print our bike. Arevo Labs offered to cover all of our expenses for the design and manufacturing of our bike. All of our components were ordered individually other than the printed frame itself. The material needed and the printer itself were provided to us by Arevo Labs. We were not given specifics for the costs of these materials or the printing time since the company was funding the entire design. For more details on our expenditure see Appendix C.

Timeline

We began this project in September by discussing the goals of this project with Dr. Peter Woytowitz. Most of September through December was spent doing research about different bike frames and the advantages of using continuous carbon fiber printing methods. We also began to come up with initial frame designs both through sketches and SOLIDWORKS models. We were able to then bring our top 2 designs to Pete and learn more about the capabilities of the printer and what designs would be feasible. Coming back in January we were able to lock down our final design and chose to go on with the full suspension frame. From January through mid-March, much of our time was spent working on the SOLIDWORKS design and modifications for our frame, as well as running stress strain analysis. This also included meeting with Arevo Labs design team on several occasions and finishing our final design to be printed. Coming back in April, we were able to finally print the frame and begin sanding and wrapping the frame as well as the rear stays. While this was being done we were also able to machine our metal parts in the SCU Mechanical Engineering Machine Shop that were then inserted into the frame in order to assemble the bike. Once these components were all completed in late April we were finally able to begin assembling the bike. For a full detailed timeline see Appendix D.

Design Process

This project began by speaking with Dr. Peter Woytowitz, from Arevo Labs, who gave us the idea to design and 3D print a continuous carbon fiber electric bike frame. We began by doing research on the different types of bicycle frames and carbon fiber printing to familiarize ourselves with the project. The first step in our design process was to create sketches of different frames and then narrow this down to the 2 best solutions. Once we decided upon our 2 designs, we began creating CAD models for them, using SOLIDWORKS. We were then able to meet with Arevo Labs and learned about the capabilities of the printer. We learned that our initial single piece hard-tail frame was not possible due to the size of the printing platform and the current bridging capabilities. From here we had to go back and make corrections to our CAD models, which included making the hard-tail frame 3 pieces rather than a single piece. While this was being done, we also began deciding upon a kit for all the other bicycle parts that would be needed. This was necessary since the frame would have to be designed to account for these parts, mainly accounting for the mid-mounted motor. Once these CAD models were updated we were able to run initial stress-strain tests in SOLIDWORKS to determine where the frame had the greatest chance to fail.

From here, we then decided that rather than proceed with 2 designs it would be best if we committed to one idea and continued with that design. After reviewing our 2 designs we decided to move forward with the full suspension frame. Working with only the one frame, we were able to begin having more discussions with Pete about whether our design was printer friendly. This allowed us to go through several modifications of our design and run more stress strain analysis in SOLIDWORKS as well as in ABAQUS to determine where extra material would need to be added to provide more support. After running these simulations and going through several frame modifications we were finally ready to send our model to Arevo Labs to be printed. After sending this model, the design team at Arevo made final modifications in order to prepare the frame for printing. Upon discussions with the Arevo design team, we decided that we would only be printing the skeleton frame in order to reduce print time. This meant that we needed a creative new way to manufacture our 2 rear stays. This led us to 2 different ideas: one being to create a foam mold with acrylic on either side to hold the shape, and the second being to water jet metal into the shape of our rear stays. We decided to go forward with the former of the 2 ideas and then to wrap this foam and acrylic mold in carbon fiber to provide strength and for aesthetic purposes to have the same appearance as the frame.

Coming back from Spring Break we were done with the design stage and were finally able to begin the manufacturing process. The skeleton frame was printed on a polycarbonate plate which meant that we had to use a jigsaw, a router and a chisel to remove the frame from the build plate. We then brought our rear stay designs along with a sheet of acrylic to be laser cut to the shape of our design. We then used these parts to cut out the foam into a similar shape and could then bond the foam and acrylic together to prepare them to be wrapped. From here we were able to begin wrapping the frame and rear stays in carbon fiber. The first layer was done and was then left to sit for 24 hours to allow the resin and hardener mixture to harden. We were then able to sand down any rough edges and wrap the carbon fiber in a second layer. This process was repeated again and then a fourth layer was applied to all holes and imperfections. After this layer hardened and was sanded, an epoxy Sculpt was applied to all rough edges and voids. While this was being done, we were also able to begin machining all the parts that were necessary in order to assemble the bike. This was done in the SCU Mechanical Engineering Machine Shop. With all of our parts machined we were finally prepared to begin assembling the bike. We began by bonding all the machined parts to the frame and then connected the shock and rear stays using a rod and pinning these parts in place, along with installing the motor. With all of these parts in place we were then able to bring our bike into a bike shop along with the front fork that we had previously ordered to be fitted for tires and handlebars. We were given these parts and attached them to our bike before installing the seat to have an assembled bike.

Risks and Mitigations

The risks involved in designing our e-bike were very minimal. The only areas that posed potential risks for injury were the 3-D printing process, carbon fiber wrapping the frame, and the assembly of the bike. The 3-D printer has an innumerable amount of risks involved due mainly to the high temperatures and harmful chemicals that are being printed. However, we will be printing at Arevo Labs and will not be anywhere near this technology while it is printing, so as to remain out of harm's way. The next potential issue came from using a resin and hardener mixture that produced fumes described to us as being "very nasty". To prevent from breathing in these fumes we used respirator masks as well as rubber gloves. As far as assembly, we used manual and powered hand tools in the Santa Clara University Mechanical Engineering Machine Shop as well as at the Arevo Machine Shop to attach all the parts. In doing this, we followed the Machine Shop guidelines and always had supervision when working with power tools. We have also prepared a Safety Review, as can be found in Appendix H, which covers these risks in more detail.

Team Management

We began our team management by assigning roles to each individual member. Everyone had multiple roles, with the most important roles being our team leader and note taker. The team leader's role was to make sure that we met at least once a week and made sure that we remained on schedule. His responsibility was also to be the main form of communication about meeting times with our advisors. The note taker's role was to record all important topics covered at our group meetings and the meetings with our advisors. He also holds onto all important documents that were given to the group. All other roles were meant to keep us on track both with our class assignments and design goals.

We ran into an issue in late October when we had our designs but did not know all the capabilities of the printer and were therefore unable to move forward in our design process. This led our group to not meet for 2 weeks and fall behind where we expected to be. Once we realized that we were falling behind we had a group meeting in which we reorganized ourselves and determined what everyone would need to do to get us back on track to complete our goals. The other issue was that since we have a large group, with 6 team members, it was difficult to find times that we could all meet. Initially we felt that we all had to be together to have a group meeting, however after falling behind we decided to break into sub-groups and meet at different times. After these meetings we would then communicate to the rest of the team the progress that we had made. This was a more productive method and helped us to catch up and meet our goals.

Coming back in January we continued this approach delegating several members to dedicate their time towards the frame design while others focused more on ordering all of our necessary parts and obtaining material for testing the carbon fiber material. This strategy worked well for our group and we had our design finished and ready to print on time and had our materials ready for testing. Coming back in April we again dedicated half our group to work at Arevo Labs to wrap the frame and rear stays in carbon fiber and apply the epoxy Sculpt. The other half of the group worked in the SCU shop to design and machine our metal components that would be inserted into the frame. This method worked well as we were able to complete all of these parts in a timely manner. From here, we worked as a full group to assemble the bike and make all minor adjustments necessary for this assembly. We then assigned individual roles for everyone to focus on for our final presentation and began practicing individually and then together.

Subsystem Chapters

The final design of the bike frame was divided into two distinct subsystems which can be called the main-frame and sub-frame. These two subsystems are also referred to as the front-frame and rear-stays respectively due to the parts of the bike which they make up. Figure 17 below shows the the main and sub frames and their comprising subsystems.

The purpose of the main-frame is to house the electronics, power generation, front wheel, and steering system, and to support the rider. It is comprised of the head-tube (A), top-tube (B), down-tube (C), seat-tube (D), and bottom-bracket shell (E). Included in the main-frame is space designated to the attaching of the electronics (namely the battery and motor) along with a drop-down of material (F) off of the top-tube for attaching the rear suspension. There is also a hole (G) near the bottom-bracket which allows for a direct pinned connection of the sub-frame.

The purpose of the sub-frame is to split the bike into two parts connected at a pivot point on bottom and a spring-damper suspension mechanism on top, such that shocks to the wheels during riding can be absorbed. It has a “gull-wing” shape which serves the purpose of the seat-stays (H) and chain-stays (I), and includes rear drop-outs (J) in order to attach the rear wheel. Similarly to the main-frame, the sub-frame has an upper (K) and lower (L) hole which allow for the pinned connection to the suspension system and main-frame respectively.

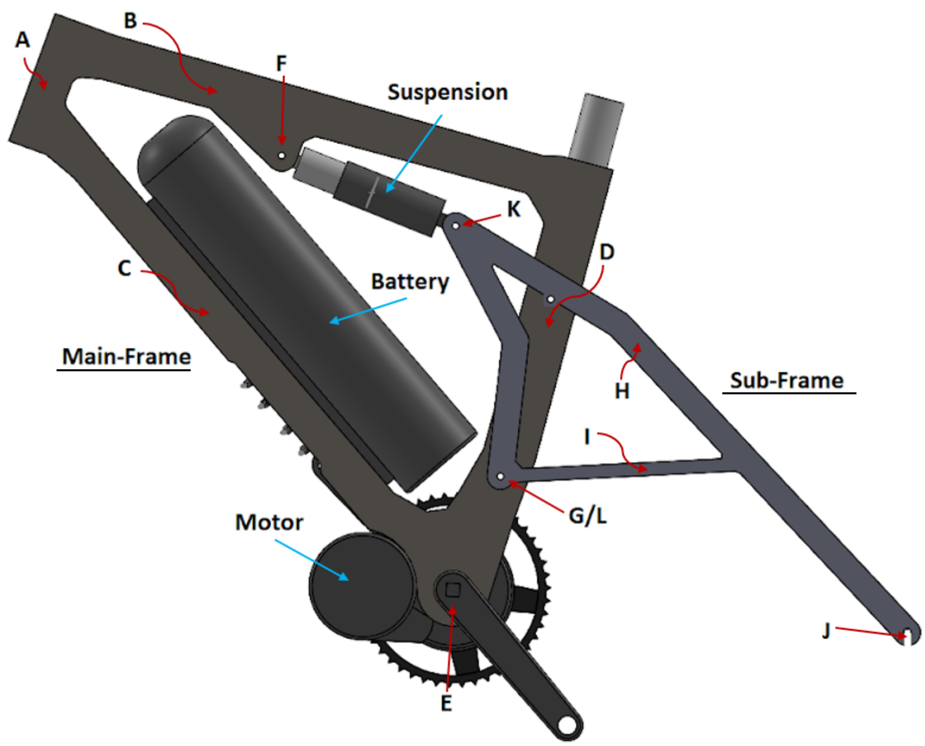


Figure 17: CAD model of the final frame design with labels for each subsystem.

This section is dedicated to breaking down both the main and sub frames into their individual components. For each component the final design/selection, rational for the choice over the alternatives considered including supporting analysis if applicable, and test/verification data will be provided. However, before continuing the decision to design a full suspension electric mountain bike with two distinct frame sections is justified.

Top level system justification

As has been discussed in the earlier sections of this thesis, the choice to design and build a 3D-printed full-suspension electric mountain-bike happened in steps. In each step different constraints or trade-offs were considered which led to a choice resulting in the chosen end product. These steps are laid out below:

1. **Decision to work with AREVO, INC for the Project:** The first step of the decision process was partnering with Dr. Woytowitz at AREVO. This translated directly to choosing to design and 3D-print a product out of carbon fiber.

2. **Choosing a bike frame as the project:** After learning of the continuous fiber capabilities of the printer, a bike frame was determined to be a good application of the technology.

3. **Mountain bike:** The size constraints of the printer lead to the choice of a mountain bike design as opposed to a road bike. This was due to the printer's demonstrated excellence at printing square tubes coupled with the inability to print the stiff fiber in a tight aerodynamic radius.

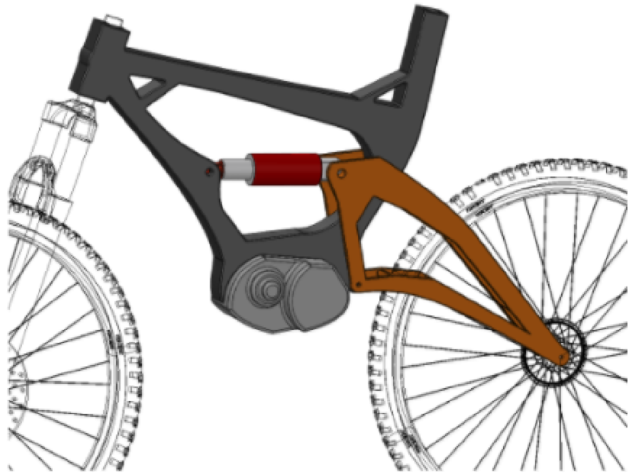
4. **Electronic assistance:** The inherently bulky size of the frame along with market and cultural trends lead to the choice of integrating electronic power assistance into the frame design.

5. **Full suspension:** After choosing a mountain bike frame as the product, the decision between a full-suspension and a hard-tail design had to be made. Full suspension was chosen to dampen shocks and vibrations on the heavy electronics, improve the comfort of the rider over rough terrain, and provide a more exciting design challenge. This necessitated the choice to split up the frame into two distinct systems.

6. **How to break up the frame for printing:** Finally, with the product chosen, it was necessary to figure out the ideal way to print the frame. Given printing constraints such as the build-plate size and the challenge/waste of integrating support structure in order to print out of plane, the decision was made to design the bike out of completely planar square tubes. This meant that the rear sub-frame had to be broken up into two identical pieces which surrounded the main-frame and shock before connecting to each other.

The decisions described above were all made during the conceptual design phase of the project. This means that they were based solely off of brainstorming, intuition, and weighted selection criteria (see the decision criteria and matrix for the suspension system in Appendix A. Figure 18 shows two of the preliminary CAD models used to decide between a full-suspension or hard-tail frame design.

(a) Hard-tail model with cantilevered seat-tube.



(b) Full-suspension model with supported seat-tube.

Figure 18: Two early conceptual CAD designs, comparing a hard-tail frame with a full-suspension frame.

Now, the following subsections will break down the frame into its lower level components. The final thing to note is that, while certain design for the actual frame can be described in words and weighed with criteria, the overall geometry of the frame was finalized using subtle changes with iterative designs. Many of these decisions were based more off of the printing technology than concrete analysis and are described in the previous CAD design phase section. In the following sections of the Subsystem Chapters, only the final design will be justified with finite element method analyses.

Main Frame (one piece)

As discussed above, the main(or front)-frame subsystem consists of not only the frame itself, but also the other subsystems which it houses.

The Actual Frame

The main describable decision for the actual frame component of the main-frame was the way to integrate the seat-tube with the rest of the frame. There were three main options considered, a "cantilevered" tube (as seen in Figure 19a), a seat tube which is raised above the the top tube (see Figure 19b), and a standard seat-tube which starts immediately at the end of the top-tube (see the final design in Figure 17).

(a) Example of cantilevered seat tube. (b) Example of raised and supported seat tube.

Figure 19: Real examples of two of the different conceptual design options for the seat tube on the main-frame (images printed without permission from media.4rgos.it and icanbikes.com).

Each option has some pros and cons listed in Table 2 below:

Table 2: List of the pros and cons of conceptual seat tube designs

Cantilevered seat-tube:

- **Pros:**
  1. Additional mass-spring-damper system increases rider comfort.
  2. Extended tube allows the rear shock to connect directly the the back of the main-frame.
- **Cons:**
  1. The extended tube must support the entire weight of the rider which creates a strength concern.
  2. The sharp geometry change creates a stress concentration.

Raised seat-tube:

- **Pros:**
  1. The raised tube allows the top tube to connect closer down towards the bottom bracket, creating a sleeker profile.
- **Cons:**
  1. The amount of space within the triangle of the main-frame is reduced.
  2. The raised tube acts as a column in compression reducing its strength.

Standard seat-tube:

- **Pros:**
  1. The space inside the main-frame is maximized.
  2. There is no additional stress concentration or unsupported members added to the geometry.
- **Cons:**
  1. The design lacks in creativity.
  2. The rear-frame pieces are required to go around the seat tube.

The final design chosen for the main-frame did not include either a cantilevered nor a raised seat tube. The standard option was chosen because the maximum amount of space possible within the frame was needed to fit the battery and creating more stress on the frame than needed seemed like a risk due to the novelty of the manufacturing technique (see the criteria and scoring matrix for this decision in Figures 34b and 36 respectively for more information).

Electronics

The choice of electric drive system, although not designed by the team, is important because it will inform the design of the frame. It was chosen to use a complete mid-drive system in which the drive motor completely replaces the traditional pedal hub. The drive motor interfaces directly with the frame and existing pedals, and is powered by an external battery pack and intelligent controller mounted on the handlebars.

Like many design decisions, the reason for choosing a mid-drive motor has to do with the anticipation of rough conditions for a mountain bike. The motor makes up a significant percentage of the finished bike frame (especially with the composite material), thus keeping it near the center of the frame helps keep the bicycle balanced. The other option considered for motor placement was in the rear wheels hub. The additional space in the wheel typically allows rear motors to be more powerful. However, the rear subsystem, including wheel, absorbs much of the shock of the bike and it would have been problematic to subdue the motor to those forces.

The motor torque will be transferred to the rear wheel via the drive chain to provide powered forward motion. Choosing the specific motor allowed the design of the bottom portion of the main-frame to be finalized.

The battery was chosen in conjunction with the motor. It is a 48 Volt 12AH Bafang bottle style. This battery was chosen for its simple mounting mechanism, its convenient shape which fit well with the frame concept, and its high energy storage. A mountain bike is expected to perform numerous and steep climbs on a single trip, so it is important that the battery have sufficient charge to keep up with the demands of the high-powered motor. It was mounted this onto the down-tube as seen in Figure 17.

Rear Frame (two pieces)

The rear sub-frame of the designed bicycle is much simpler than the main-frame component. However, its own challenges arose from the overall printing process. As described in part 6 of the Top-level System Justification list, the sub-frame had to be broken up into 2 separate but identical pieces in order to keep all of the parts printable with planar square-tubing.

The Actual Frame

Three basic conceptual design options were considered for the sub-frame component. These were termed: the “V” (shown in Figure 20a), “chain stay only” (shown in 20b) and “triangle” which is the most basic option and standard for most hardtail models; it is just like the V except that the two arms are connected to each other with a vertical member (see Figure 19b).

(a) Example of V type rear system.

(b) Example of chain stay only rear system.

Figure 20: Real examples of two of the different conceptual design options for the rear sub-frame (images printed without permission from trek.scene7.com and cdn.road.cc).

The pros and cons of the three options are listed below:

Table 3: List of the pros and cons of conceptual rear sub-frame designs

V-shape:

- **Pros:**
  1. Good balance between lightweight and strong
- **Cons:**
  1. Does not excel in one area

Chain stay only:

- **Pros:**
  1. Very lightweight
  2. Unique frame design
  3. Additional shock absorption for hardtail frame
- **Cons:**
  1. The single member must bear the entire load of the rear wheel
  2. Unable to include rear shock

Standard triangle shape:

- **Pros:**
  1. Provides the most strength and stiffness
- **Cons:**
  1. Lacking any innovation
  2. The heaviest option

As with the main frame design, these initial conceptual options were discussed and scored using specific weighted criteria (see Figures 34c and 37 in Appendix A). However, they were used only as guidelines for future designs. The chain-stay only scored the highest, but was quickly discarded due to the decision to include rear suspension.

A few different designs were modeled and analyzed before settling on a final design. One example of an intermediate geometry is shown in figure 19b, which is a modified version of the standard triangle. The final design chosen combined aspects of the triangle for strength with the chain-stay only concept for a unique aesthetic and to reduce material. This design was coined the "gull-wing" and is shown in Figure 17.

Initially, it was thought that the gull-wing would benefit from internal structural members to increase its strength. However, a brief finite element analysis (FEA) of the sub-system, with and without the members, led to the decision to remove them and further reduce print time and weight. Figure 21 below shows the two simulations.

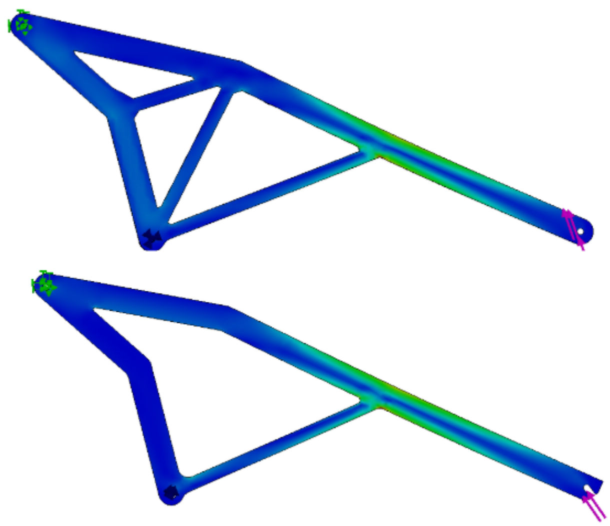


Figure 21: Basic finite element comparison of the gull wing sub-frame design with vs without supporting truss members.

At the time of running these simulations, loading scenarios had not been decided to run the simulations. Therefore, there are not accompanying numbers with the FEA. What is important is that increase in stress the bottom design (after removing internal beams) was negligible. The stress flow and magnitude is shown to be identical by the coloring of the models.

Suspension and Frame Connections

In order to complete the design of the frame, we first needed to ensure a proper method of connecting all frame components to the suspension system. These choices occurred concurrently with the main and sub frame designs so that they would all work together.

First, the decision between a hard-tail option versus full suspension system had to be made. While the fixed system has the potential to be objectively stronger, a lack of energy dissipation in the rear will lead to unavoidable stress concentrations at tube joints. Still, a thoughtful design could direct as much stress as possible towards the fork of the bike, as the entire system would rely heavily on the front suspension for energy dissipation. This presented an argument for the inclusion of a higher-performance, more expensive fork component than was necessary with a rear suspension design. However, ultimately the cost of production for the hard-tail design is expected to be comparatively less as the rear suspension design necessitates extra bearing components, a central shock, more complex design, and increased expected maintenance costs.

However, the rear suspension design represents a much more comfortable mode of performance for the ride. Bumps encountered by the rear wheel will be attenuated before arriving at the seat stay and transferred to the rider. Though more costly up front, if properly maintained the rear suspension design is expected to last longer than the hard-tail design by replacing points of potential stress concentration with bearing connectors.

There is also a trade-off between the two options when it comes to power transmission efficiency of the bike. With full suspension, as the rear stay moves relative to the main frame, the distance between the rear wheels axis of rotation and pedal axis varies slightly. Tension on the drive chain connecting these axis will be cyclically lost and gained, leading to “pedal bob”. This is most notable when the rider is standing up off the seat to use their body weight to assist in turning the pedal, generally when traveling up an incline. A hard-tail bike is stiffer overall and eliminates this issue. Ideally, the influence of pedal bob on the overall riding experience can be mitigated via the pedal-assist feature of the e-bike system.

With all of the differences in mind, the previously mentioned choice was made to move forward with a full-suspension frame. This choice is further explained by the decision criteria and matrix shown in Figures 34a and 35 respectively. After choosing to build a full-suspension frame, it was quickly decided to use a single-point pivot system for the rear suspension. Although this choice resulted in a slightly bumpier ride compared to the potential of a more complex, multi-bar linkage system, it presented the most feasible printable design given the project constraints.

Single Point Rear Suspension Design

Below in Figure 22, a cross section view of an early frame design shows the rear suspension mechanism. and the single point pivot is clearly visible. In this design, energy transferred to the frame from external impacts will be dissipated through a horizontally oriented shock cylinder. We want the stresses entering the frame from the rear wheel attachment point to be directed along the members of the rear stay rather than perpendicularly across them.

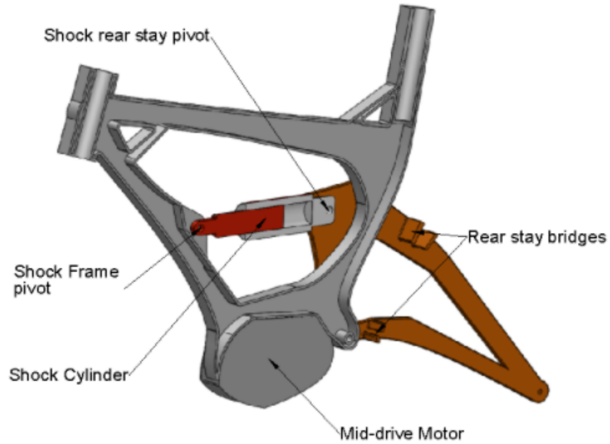


Figure 22: Rear suspension design.

Comparing Figure 22 with the final design shown in Figure 17, it is obvious why the location of the pivot system had to be changed. The chosen battery requires all of the space on the down-tube, so the suspension linkage had to be relocated to a drop-down tab on the top-tube. This move along with the redesign of the rear system also lead to the lower pivot point being moved upwards on the main-frame.

In total, there are three points of connection between the main and sub frame. One direct pivot connection towards the bottom of the frame, and one connection on either end of the rear shock. All of these are freely rotating pinned connections. The materials chosen were high-strength steel pins encased in ball-bearings.

FEA Analysis of final frame design

The final frame design was driven by multiple constraints. These can be boiled down into three categories:

- **Printing**: The ability of the final design to be printed on AREVO's continuous printer given the aforementioned limitations. This also includes minimizing the required print time.
- **Assembly**: The ability and ease of combining all the individual components into a completed bike frame. This includes designing ample space for the electronics.
- **Strength**: Making sure that the finished frame would last and be safe to ride, while minimizing the necessary amount of material.

The first two categories were successfully adhered to by working closely with experts at AREVO, INC and using good dimensioning and tolerance practices. On the other hand, meeting the strength requirements was completed through the use of finite element software. Many small decisions were justified through the use of FEA (such as removing the trusses in the gull wing rear frame), but the focus of analyzing the frame was to verify the final design which met the other requirements.

Static Loading Simulation and Analysis

In order to run the simulations, some preliminary information had to be provided to the software, and certain assumptions were necessary.

The assumptions were:

1. The composite material will have the previously discussed quasi-isotropic properties.
2. The stress on the frame as a rigid body (by constraining the rear shock and pivot point) will be greater than the real stress including the shock absorption.
3. The relevant loads and resultant stress occurring during riding can be simulated with combination of point loads as shown in Figure 23.

Assumption 1 was justified due to the way in which the frame was printed in conjunction with the wrapping process used to finish the frame. Assumption 2 should hold true based on intuition. The 3rd assumption is not easily justified; the loading scenarios considered (discussed further below) were sufficient for any reasonable downward force or impact on the frame. However, torsional loading due to high-power pedaling, sudden cornering, or any irregular impacts were omitted from FEA. This was mainly due to constraints on time and FEA expertise during the project. Further analysis in this area would be suggested if the the project was continued or reproduced.

The loading scenarios considered and shown in Figure 23 below.

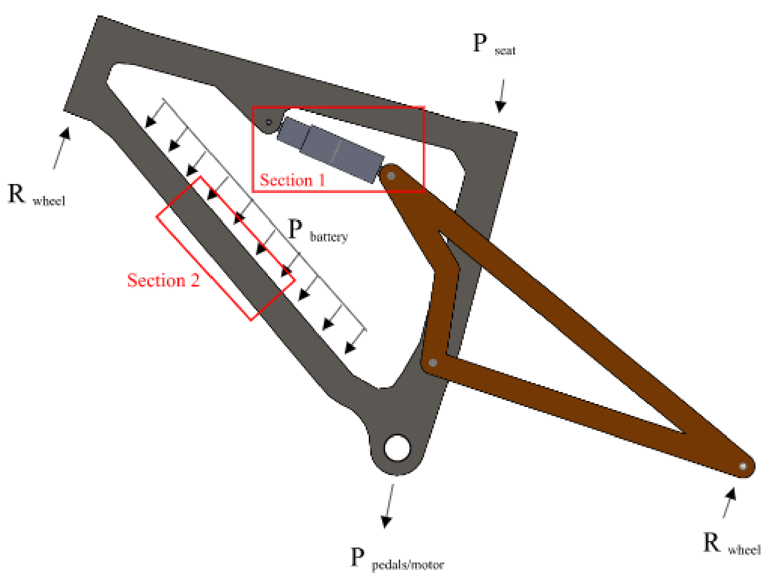


Figure 23: The loading scenarios used to analyze the bike frame with finite elements. Point forces were applied in some combination to the contact locations of the seat and pedals, with reactions at the wheels. A distributed battery load was included.

The box around "Section 1" in the figure draws attention to the fact that the shock was immobilized. The length of the linkage was set in the middle of the stroke length of the purchased shock.

The material of the shock was also made to be extremely stiff and strong such that it would directly transfer any stress to its neighboring components.

The rest of the bike frame was simulated with the following material properties given in Table 4.

Table 4: The quasi-isotropic material properties used to run simulations.

Property:	Elastic Modulus	Poisson's Ratio	Shear Modulus	Ultimate Tensile Strength
Value:	29.1 GPa	0.319	2.35 GPa	800 MPa

All simulations were run using a simulated rider weight of 300 lbs. Three different categories of tests were performed: the entire weight on the seat ("seat-loading"), the entire weight on the pedals ("pedal-loading"), and the weight distributed equally between the two.

Within each category, a static test was run as well as a simulated drop test. The drop test was simply performed by increasing the magnitude of the rider weight such that it mimicked a scenario in which the rider fell from a height of 2 feet. This assumed that the rider will not be dropping a further distance, which should be the case because the electric bike is not meant for aggressive riding with jumps.

The following equations show how the increased weight load was determined.

$$Energy = mgh = \frac{1}{2}mv^2, \quad (1)$$

where m is mass, g is the gravitational acceleration, h is the height before falling, and v is the velocity at impact.

$$F_{max} = 2mgh/s, \quad (2)$$

where F_{max} is the highest force felt during impact, and s is the deformation distance throughout the impact.

with $mgh = (300lbs)(2ft)$, and a deformation distance assumed to be at least 1/2 ft (due to the compression of the front and rear suspension along with the tires), the maximum force is just under 2500 lbs. Thus, this was the load used for the drop test simulations.

Clearly, the drop tests generated the most stress on the frame, so they were used as the overall metric for meeting the strength requirements.

The following two figures show the results of the FEA for the seat and pedal loading scenarios with the 2500 lb load. The simulations with the distributed load is omitted from this report because the resultant stress was lower than the two edge cases shown. Figure 24 shows the seat-loading scenario.

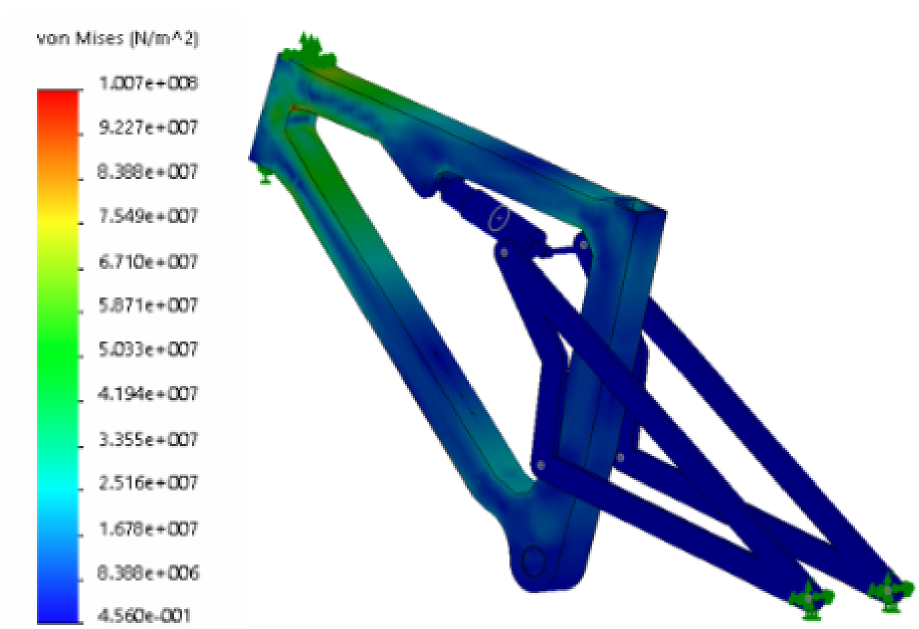


Figure 24: Finite element simulation of a 2500 lb load applied exclusively the seat of the bike frame with a von Mises stress contour plot on the model. The maximum vM stress is 235 MPa.

It is seen that the stress is concentrated at the front of the frame with a peak of 101 MPa, well below the ultimate tensile strength (UTS) of 800 MPa.

In the following, Figure 25, the pedal-loading scenario is shown.

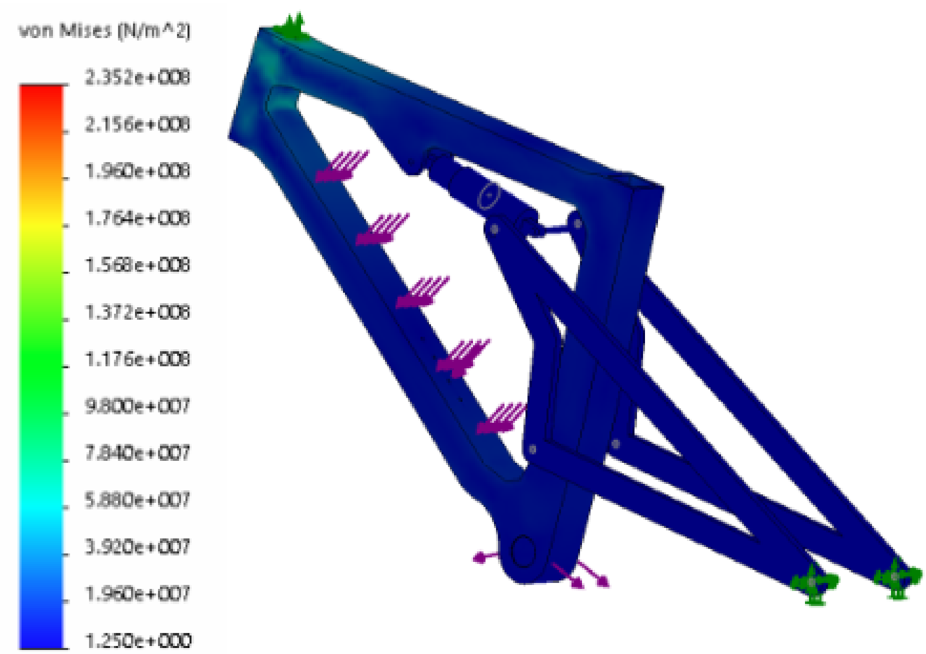


Figure 25: Finite element simulation of a 2500 lb load applied exclusively the pedals of the bike frame with a von Mises stress contour plot on the model. The maximum vM stress is 101 MPa.

This figure shows that the stress is similarly concentrated at the head-tube on the front of the frame. In this case, the concentration is even more drastic than the seat-loaded frame. This makes sense conceptually, because when the seat is loaded, the top-tube acts as a somewhat of a cantilever beam which carries bending stress; this flow is seen in Figure 25. The more contained stress in the pedal loaded frame resulted in a higher peak stress of 235 MPa. This is still well below the UTS and provides a factor of safety of 3.4.

However, as will be discussed shortly in the next section on fatigue testing of the composite material, the real goal of the frame is to have a peak stress of less than 400 MPa to avoid failure from cyclic loading. This means that the frame currently has a factor of safety of 1.7, an acceptable number. This factor of safety is especially conservative because the cyclic loading from the 2500 lbs used for the drop test is highly unlikely. Instead the bike will likely be cycled with a load 8 times less.

Vibration Mode Analysis

The final analysis of the frame was finding the lowest frequency mode of vibration which could cause resonance, and potential failure due to continuous high-amplitude deformation. Research showed that the dominating factor of the frequency of vibration for a bicycle is the rotating wheels [6]. Many other factors can cause vibrations such as – wind, rough road surfaces, rider movement, etc. These scenarios can easily increase the amplitude of the vibrations if the phase matches up with the wheels, however they do not drive an increase in frequency.

Thus, a simple calculation showed that while riding at 50 mph (a generous overestimation), the frequency of wheel rotation is 10 Hz. This calculation is shown in Figure 26 below.

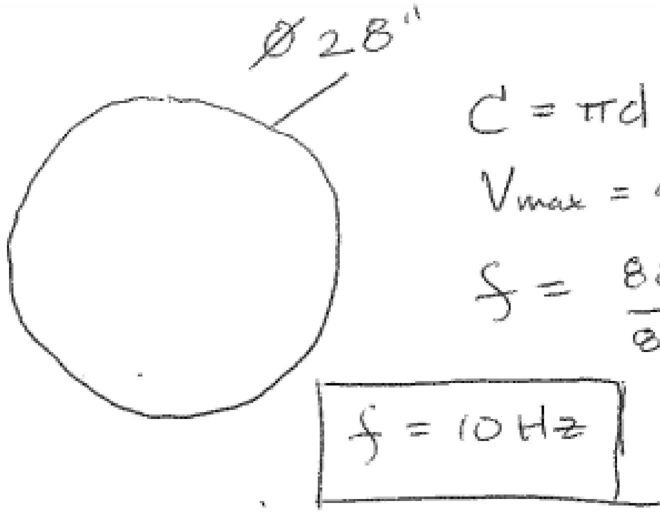


Figure 26: Hand calculation to find the frequency of a rotating 28" bicycle wheel while riding at 50 mph. This frequency is the main concern when considering bike frame vibration modes.

This number was compared with a finite element simulation for finding the bike frame's vibration modes. This is shown in Figure 27 below.

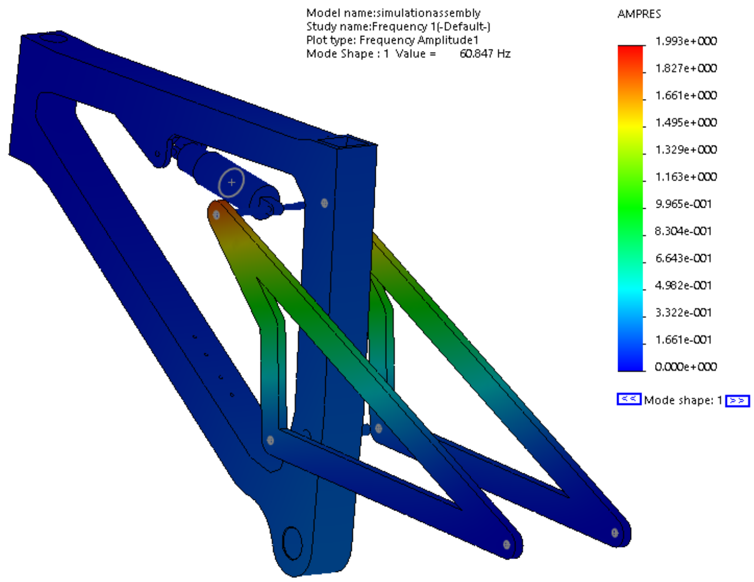


Figure 27: Finite element simulation of the bike frame, used to find the first mode of vibration. The mode is at 61 Hz.

This simulation found the first mode of vibration for the frame to be at 60 Hz, well above the 10 Hz frequency of the rotating wheels. Therefore, there exists a lot of room for unexpected increases in frequency while riding before there is any danger of causing resonance. This was deemed to be acceptable.

System Integration, Tests, and Results

The first set of testing that we did was through SolidWorks. Our team ran multiple simulations to account for possible loading scenarios that a rider would face. This included seat loading, pedal loading, a combination of the two, vibration analysis, and others. We decided to choose a rider weight of 300lbs to add an extra level of safety in our design. After inputting the material data into the software, we found that the maximum stress that our bike faced with pedal loading was 235.2 MPa (von Mises) the inside lower curve where the top tube and front tube meet. This was to be expected. As we knew, the material has superb strength in the axial direction. Areas that we knew would be introduced to the most stress would be curved sections. This value was well below the yield strength of the material.

We then conducted physical tests with the help of our advisor, Robert Marks, Ph.D. The Arevo team had already ran their own tests and determined many of their material's properties. One area of testing that the company had not been able to complete, that we had the means for, was fatigue testing. This would give insight for our team, as well as Arevo, into the resilience and stiffness of their material.

The first test was supposed to run at a loading cycle of 1Hz for 200,000 cycles. The intended loading conditions were to cycle from 100 to 250 MPa. Initial concerns about this loading condition lie in the fact that the peak condition was still only 1% of the available load cell capacity. When running the experiment there was thermal overload on the hydraulic fluid pump. This caused the test to end after $\sim$65,000 cycles. The data we received after this amount of time was still useful. Figure 28 below shows the force (N) and stiffness (N/mm) versus the number of cycles. The fit line reveals a very minuscule slope. In theory, this tells us that the material can withstand numerous loading cycles without losing much of its stiffness. While we are not entirely sure of the accuracy of the data received in this experiment, the results are reassuring.

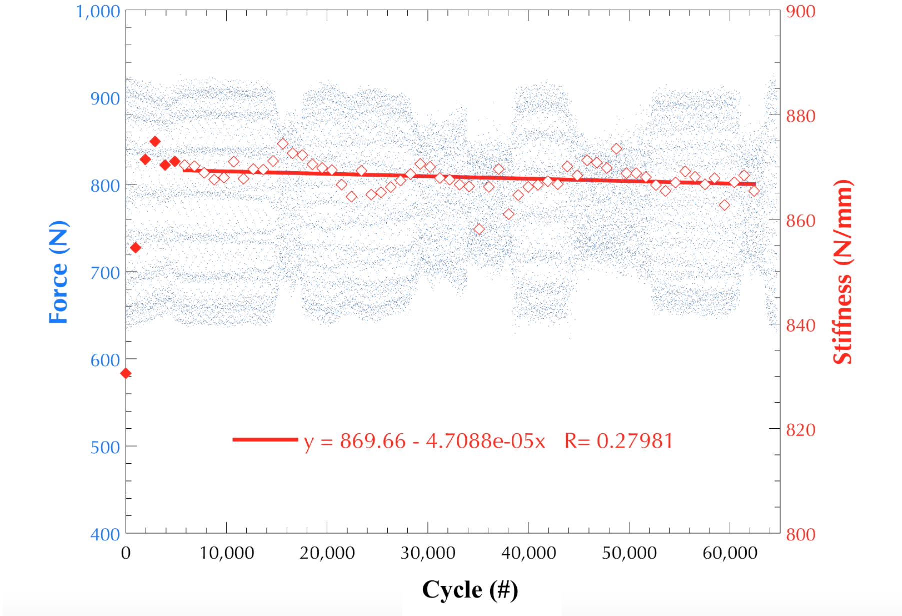


Figure 28: Specimen #1, Force and Stiffness vs. Number of Cycles.

The second experiment was designed to test the strength of the material more so than the first. It was decided that the same frequency should be used and roughly the same number of cycles. Figure 29 below shows a similar trend line when compared to experiment 1. The slope of the fit line is smaller than in the first experiment by an order of magnitude.

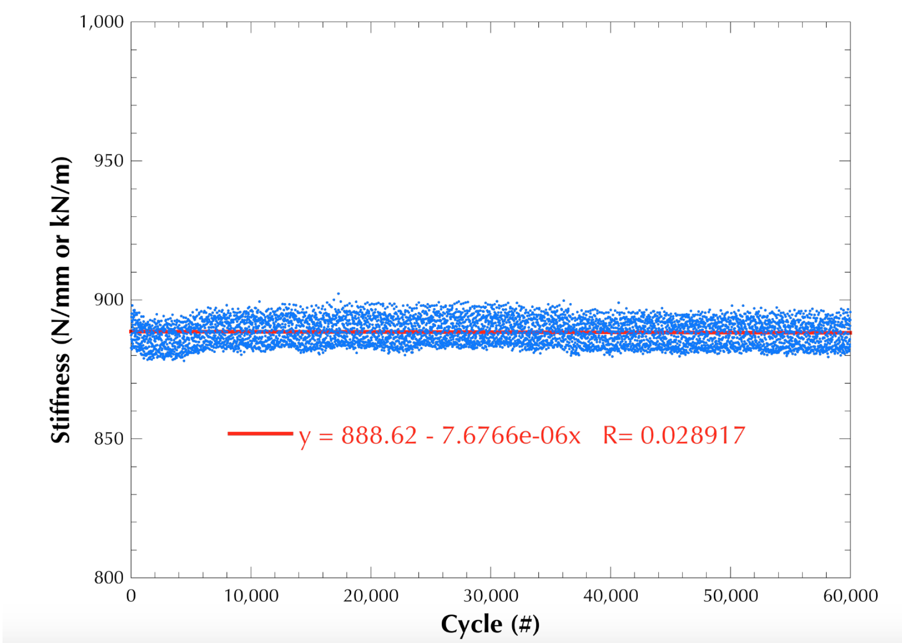


Figure 29: Specimen #2, Stiffness vs. Number of Cycles.

This data suggests that stresses upwards of 400 MPa are not large enough to induce lasting damage in the test specimens. This data should be explored further but given the fact that 400 MPa is around half of the yield strength of the material, and two times as much as our maximum load with a 300 pound rider, the results are promising. Specimen 2 did not fail after 60,000 cycles. When running for a further amount of time, Dr. Marks was tuning the PID controls of the machine and the specimen broke. No data was received that could conclusively reveal the load at which the specimen failed.

Knowing that a significant amount of cycles would be required to have a specimen fail at peak loads of 400 MPa, specimen 3 was cycled again at 1 Hz, but from 100 to 600 MPa. The data for this experiment is shown in Figure 30 below.

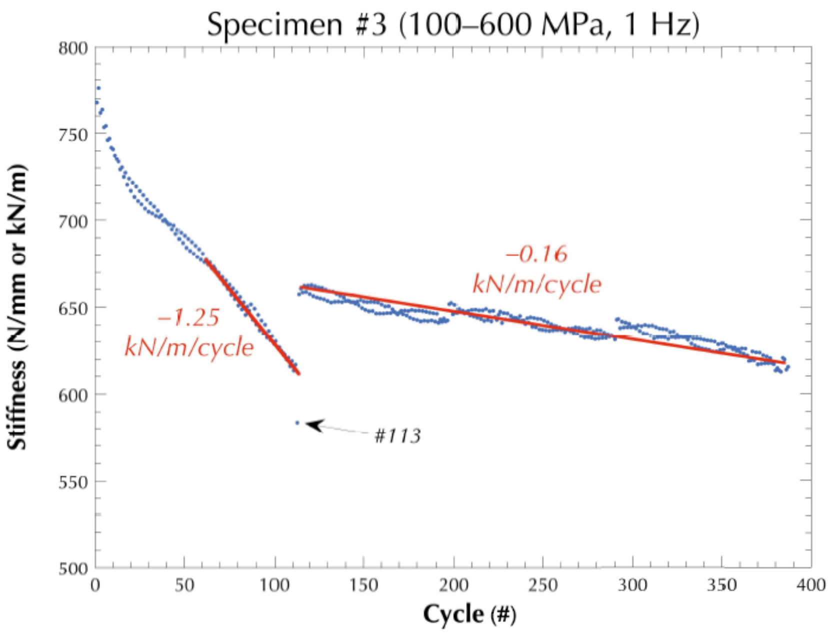


Figure 30: Specimen #3, Stiffness vs. Number of Cycles.

This specimen failed after 388 cycles. This data coincides with a 20% decline in stiffness when compared to the initial value. The data received from this experiment reveal that a peak loading condition is too large of a stress to remain underneath the materials endurance limit. Some factors to note are that the experiment was stopped at cycle 113 in order to adjust the contact rollers which had been displacing during testing. During this pause period, the specimen was quasi-statically loaded close to 500 MPa before resuming testing.If there is a time dependent factor in the stress-strain behavior of Arevo's material, this extended period of loading could be a contributing factor to the failure of specimen 3.

Further investigation should be considered. For example, running experiments at different frequencies may produce data discernible of frequency dependent stress-strain behavior. Dr. Marks has continued testing specimen 1 to over 1.7 million cycles for a loading from 100-400 MPa without failure. This lead us to conclusively believe that at peak loads of 400 MPa [23], the material is safe. See Appendix A for the full fatigue tests report.

Costing Analysis

All aspects of our project are fully funded by Arevo Labs. Since Arevo is not charging us for the printing of the frame, and they do not want to print 2 full bike frame designs, we will not have a full scale prototype to run tests on. However, we will be printing several small sections of the frame where we feel the frame has the greatest chance to fail and can run tests on these pieces. Arevo Labs will not be charging us for the expenses of the materials used for these prints and the time to print. Not knowing the exact volume of material we will use to print our full frame also makes it difficult to know the price to print the final frame.

Business Plan

Executive Summary

The commercialization plan revolves around the design and manufacturing of sufficiently strong mountain bike frames with as little material as possible as to reduce weight and cost. The frames will be printed using 3D continuous carbon fiber printers. The frames will be cheaper than typical high end carbon fiber mountain bike frames, and as demand increases, our company will purchase more printers as to expand. The product will be sold to individual buyers and retailers, offering baseline models and the capability for user customization if desired.

Introduction

The product is a 3D-printed carbon fiber electric mountain bike frame featuring dual shock suspension systems. The market for bicycles with these unique features is limited, therefore, our targeted market are bicycle dealers and suppliers. In doing this, the goal is to allow consumers the opportunity to customize their bikes, rather than buying generic bicycles. The personnel required include a team of designers, a 3D-printer operator, and an assembly team to create and finish the bicycle. Our competition would be other small scale bicycle companies specializing in customized and personalized frames.

Goals and Objectives

The main goal of our team is quickly and efficiently design manufacture, and finish customized bicycle frames that are competitive with other high end, carbon fiber frames. Our objective is for these frames to be extremely durable, lightweight, and relatively affordable. The frame will be printed in two days and through holidays because the machine does not need to be continuously manned. It will be durable, meaning, the frame will outlast the rider. The frame, including the chain stays, will be no more than 2.5 kg. Lastly, the frames will be priced at $4,600 initially, but will drop over the course of company growth.

Product Description

The key technology for this design is utilizing the unique capabilities of Arevo's continuous carbon fiber 3D-printer. Printing the frame allows for complex geometries that are not capable through common molding techniques. Molds are also fixed to a shape whereas the printer can take different paths on each print by simply changing the spline model in the printer's program. This allows for customizable frame designs that are not possible with molding techniques. The continuous carbon fibers are also significantly stronger than the generic chopped fibers found in the bicycle frame market today. Finally, the frames will last considerably longer than metal frames, allowing for an ideal life-cycle assessment from the buyer.

Potential Markets

We imagine the typical buyer of our end-product to be prosumer-level mountain bikers. Our product will be sold in small volumes with a competitive compared to other, non-printed models, but to counteract the high-price penalty, we will offer additional services throughout the design process for a single frame. Because of the unique manufacturing process we are employing, we can offer customization options usually relegated to world-class competitors such tailored frame dimensions and cosmetic features. This is in addition to larger orders of less expensive, standardized models to high end bike retailers.

Based on our experience designing and manufacturing a prototype frame over the last year, we will move forward with the following assumptions:

- Five round-the-clock dedicated 3D printing machines, one of which is reserved for customized orders

- An average printing and assembly job time of three business days

- Enough demand to merit continuous back to back printing jobs

- 15-20% direct-to-consumer, of which, 1-3 per month include customization options. Remaining percentage go to resellers.

With the above assumptions, we envision a monthly output of 25-35 frames to buyers. As discussed, there are two main avenues of sale: direct to consumer and through authorized retailers. We expect a initially low volume of consumer-direct sales, which will grow with time as we establish rapport and a reputation in the marketplace. Our approach to resellers will be more aggressive, as the majority of our units will be sold through them. Our growth strategies include:

- Purchasing more printers

- Optimizing the printing and design processes to maximize output per printer

- Building reputation and developing a wide reseller network

- Continuous development and refinement of our standardized designs

Manufacturing Plans

The manufacturing process for the frame and the chain-stays will be much faster than traditional carbon fiber frame processes. Due to the innovative 3D printing technology the frame and chain-stays can both be printed and finished within 3-4 days once the design is finalized. This printing process requires far fewer employees and managers to oversee the manufacturing process, since it can be printed overnight with no supervision. Our frame and chain-stays will be printed at Arevo Labs using their continuous carbon fiber printer, and can be finished and post-processed in their machine shop as well.

The inventory needed is the carbon fiber filament material, the printer, and post-processing machines such as a belt sander and a milling machine. The printer itself is in the million dollars range, and with the other machines and the material the start up cost will be somewhere around 1.1 million dollars. The upfront cost, however, will pay off in the sense that these machines do not require a lot of upkeep and last for thousands of prints without needing new parts. Thus, the only other costs as the company commercializes and expands will be the cost of materials, the minor cost of machine upkeep, personal changes and hiring, and other day to day expenses such as sanding paper and milling tools.

Product Cost and Price

The material costs about $400 per kilogram, and this includes labor and running printer time cost. Each mountain bike frame is expected to weigh around one kilogram, which will be much greater than any other bike frame style. Thus all frames are estimated to cost $400 or less from design finalization to finished product. The chain-stays total about 0.5 kilograms and thus will cost about $200 total.

Assuming that the frame and chain-stays can be printed and finished in four days, with one printer our company can print about five frames a month. With a unit price of $4,600 for a baseline design to a direct customer, $5,000 for custom design orders, and $4,000 wholesale, we estimate a profit of about $20,000 a month. The price for our product reflects the reason that the additional printers needed for commercialization and expansion require a large revenue, and as such an average of $4,000 profit per unit is reasonable to support expansion, personnel, equipment, and material costs. Further, using the $4,000 Specialized S-Works Demo 8 frame as a baseline and considering the lower cost required to manufacture a frame using carbon fiber molding processes, the price per unit utilizing our technology reflects a reasonable production profit.

Service and Warranties

Each bike frame and chain-stay is expected to outlast the rider. They will only be replaced when the rider has decided to purchase a new bike due to newer technologies or designs. Due to this, our company will offer a lifetime warranty that guarantees money back or a bike replacement if the rider can break the frame under normal riding conditions. This means that our team will examine the broken frame to ensure our warranty policy is not being taken advantage of. Our team has a high confidence in our product based upon material testing and simulations with exceptionally high rider and loading conditions.

Since our team doesn't expect our product to break under normal riding conditions we will not have a service sector in our company. This means that the product will not be fixed if broken, but rather the new frame will be printed and exchanged for the broken product, or the customer will receive their money back.

Financial Plan and ROI

As discussed, the up front cost will be large as to purchase the printers and necessary processing equipment and material. Thus, a large sum of money will be needed from investors to get the company up and running. This sum would be almost the grand total of the initial upfront cost, or about 1.1 million dollars. Assuming our company will make about $20,000 a month on frame sales, it would take about four years for us to begin turning a profit. However, with the increased interest in 3D printed composites, it is safe to say that interest in the product will increase over these four years. Thus more investors will be on board, and more printers can be purchased. With an increase in demand and more printers, our company should be able to reduce the time line for income to half the initially anticipated time. With an increased need for composites in numerous industries, we believe our company will offer a high return on investment and earn a large profit within the five year mark.

Engineering Standards and Realistic Constraints

Manufacturability

Manufacturability is a central concern of this project. With the goal of showcasing Arevo's continuous carbon fiber printing technology, the capabilities of the 3D printer determine the scope of our designs. Printing carbon fiber composites shares many similarities with existing thermoplastic printers. A filament is melted through a heated element or zone and deposited on a build surface in a path determined by a pre-programmed software file. Though relatively pliable in this heated state, the stiff properties of carbon fiber limit the smallest radius of a curvilinear path the machine can extrude. Because of this, the majority of the printed part's structures will consist of layers of extrusions where each layer's fibers run parallel to each other. The carbon fiber possesses excellent axial stiffness, however suffers from a poor orthogonal loading capability. To mitigate this, layers of fibers will be extruded at relative angles to each other to introduce quasi-isotropic properties to the frame along the axis defining the extrusion planes.

Also, our designs considered the additive nature of 3D printing. The best prints results when the part has a large, flat face built up first that provides a material foundation for subsequent extrusion layers. To this end, we designed our parts to be extrusions of outline profiles to minimize the presence of cantilevered regions with respect to the printer's z axis.

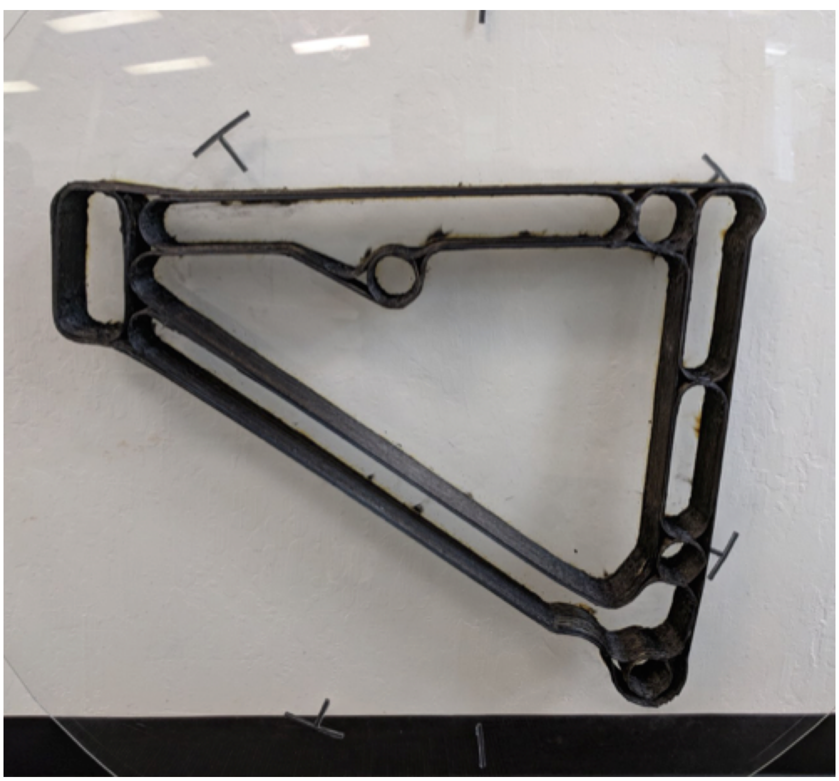


Figure 31: Skeleton Frame, printed at Arevo.

Despite this, we required some post-printing processing and refinement. We were unable to print all of the frame as expected in previous talks with the Arevo team. The rear stays, and the walls of the main frame would have simply taken too long to print. Figure 31 shows what was able to be printed given the time and labor constraints of the company. Our team decided to describe this print as the skeleton frame because it is not a complete quasi-isotropic frame. To ensure strength and give the frame a quasi-isotropic layup, we hand wrapped our frame. This process, and subsequent refining processes in the frame such as sanding and machining, required health and safety measures, explained in that section.

Because of the printing limitations, our team had to machine certain fixtures and spacers for the rear stays, motor, and shock pivot points. We machined these parts out of 6061 aluminum. The members of our team who were responsible for creating these parts had been trained in a basic instructional and safety course for nearly all machines in the school's shop.

Figure 32: Hand Wrapped Frame and Rear Stays.

We had originally planned on bonding the rear stays with industrial epoxy adhesive and have the joints reinforced with layers of composite tape. Rotational interfaces of parts were to be printed with slightly smaller radii than the design calls for to allow reaming via subtractive machining, and every part would have had its volume slightly overprinted and reduced to a smooth finish via sanding. Instead, we machined parts to size based on printing dimensions and glued them in place when needed with epoxy. We also created our rear stays out of acrylic, foam, and wrapped carbon sheets with resin. Figure 32 shows the bike with all of the components (minus suspension) that our team manufactured.

Health & Safety

In recent years, many countries are advocating for the increased use of bicycles for standard transportation. This will increase the health and quality of life of riders as well as decrease the negative environmental impact transportation currently induces. Additionally, there has been an increasing trend in the manufacture and sale of electric bikes (ebikes). Because of this trend of increased usage, our design requires all the safety consideration that go with usage of existing ebikes. Users will need to wear a helmet and proper protective clothing, especially when the pedal assist system is engaged the rider moved at faster than normal speeds over hazardous terrain. The frame must be able to dynamically support loadings both from rider body forces and environmental shocks with a wide factor of safety of at least 2.0.

The eBike system also represents some unique engineering constraints. Though our choices of battery all come with a durable, weather-sealed exterior, we design assuming the battery will eventually undergo a shock or collision. To reduce the chance of a battery rupture during an impact event, we will likely design the frame/battery interface to be broken and displaced rather than held rigid to absorb the collision forces.

Additionally, Congress has defined what a low-speed electric bike entails. For our team to say that we have created a true eMTN bike, then these parameters need to be met. A low speed electric bike as defined in section 38(b) of the Consumer Product safety Act, ”means a two or three-wheeled vehicle with fully operable pedals and an electric motor of less than 750 watts (1 h.p), whose maximum speed on a paved level surface, when powered solely by such a motor while ridden by an operator who weighs 170 pounds, is less than 20 mph” [20].

After printing the main frame, we were left with an incomplete bike. Wrapping, sanding, machining, and troubleshooting became repetitive processes to finish the frame. These were processes that required a great deal of vigilance. Hand wrapping with carbon fiber sheets and resin can be dangerous. The fumes from the resin should be avoided breathing as well as general exposure to skin. Team members wore ventilator masks and gloves when hand wrapping the bike. The safety measures that went into sanding were quite similar. Gloves to protect against carbon fiber splinters and particulate masks to avoid inhaling small pieces of material were worn. In order to create the necessary fixtures and spacers for the shock, motor, and rear stays, members of our team used Santa Clara University’s machine shop. In order to be able to use the machine shop, we were required to take a basic training and safety course, MECH 101L, taught by Don MacCubbin. We were then required to take an advanced safety test. Those unable to receive a perfect score on this safety test were not allowed to use the school’s machine shop for senior design purposes. Once ready to use the shop, detailed drawings need be presented and approved by Mr. MacCubbin. Only at this juncture, were students then allowed to work in the machine shop under supervision.

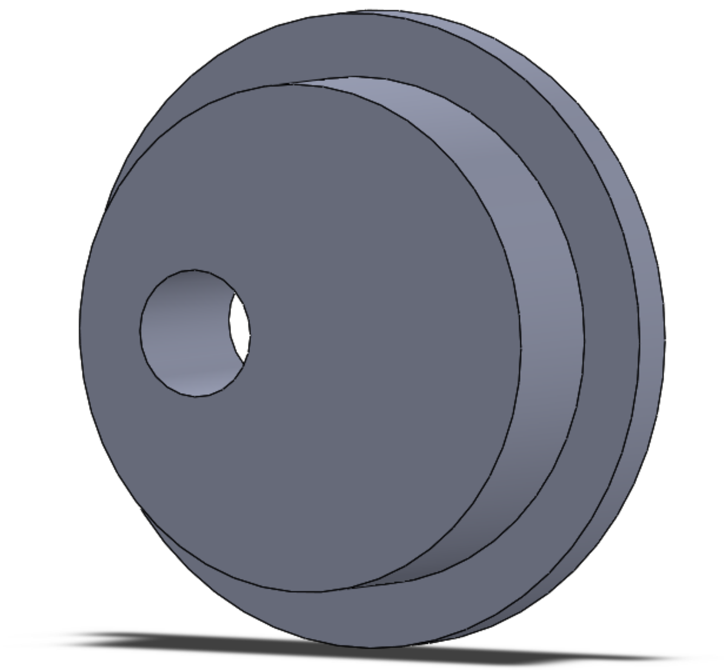


Figure 33: CAD Illustration of Shock Pivot Cup Part.

Social

The social aspect of biking played a role in our early choice to pursue a ebike system. Up until the advent of relatively affordable ebike systems, a necessary high degree athletic ability prevented many individuals from participating in the sport of mountain biking. With a pedal assist feature, physically unfit or otherwise unable individuals can now ride alongside more practiced mountain bike riders, widening the potential audience for our final product. Though some may prefer the challenge of non-assisted mountain biking, an electric bike also may represent an entrance opportunity for individuals who otherwise would never have the impetus to try the sport.

Another aspect of this project that has a large stake in human developments and engineering in general is Arevo's additive manufacturing process. The continuous printing process that Arevo has developed is revolutionary because of the strength and versatility of its application. Carbon fiber composites can be used in aerospace, automotive, robotics, high intensity sports equipment, and many other industries. The benefit of the widespread implementation of this manufacturing process has great potential. We live in a day and age where we have to be conscious of the materials we use and the way that we use them. Current carbon sheet methods of manufacturing waste a large portion to sizing. Printing has little waste.

Environmental Impact and Sustainability

There are two areas of environmental impact which this project implicates directly. The first is the benefit of electrically powered transportation. There has been a major cultural and business trend in this area with most major automotive companies developing and releasing electric cars along with a host startups and established companies producing electric-power assisted bicycles, skateboards, scooters, etc. Although, the electric mountain bike directly fits into this category and very well could add to the continued cultural push for non-fuel consuming vehicles, trail riding is traditionally dominated by human power already. This makes it challenging to quantify any impact the bike would have.

The second area stems from disrupting the manufacturing processes of carbon fiber components using additive techniques as opposed to pressurized molding or just wrapping. This is much more quantifiable.

The parts of our assembly that will need to be replaced most often will be the tires, and battery. The recycle and replacement of tires is standard procedure since bicycles have been around for such a long time. The recycle of lithium ion batteries poses a bigger issue. The battery will likely need to be replaced every two or three years. Al batteries are considered hazardous waste in California when they are discarded. This means that proper disposal is necessary. California offers a multitude of options because the local government understands the hazard. Calling 1-800-CLEAN-UP (253-2687) can find the nearest recycling center to properly dispose of lithium ion batteries.

Despite its relative newness as a manufacturing material, carbon fiber boasts strong recyclability. Carbon is capable of retaining "a significant portion" of its virgin properties, even after a second round of reclamation [6]. In fact, Boeing, one of the largest industrial consumers of carbon fiber composites in their airframes, estimate that the composites can be recycled at 70% the cost of producing the original fiber at $8-12 per lb vs 15-30 per lb to produce, and requiring less than 5% of the energy needed for manufacturing (1.3 to 4.5 kWH/lb vs. 25 to 75 kWH/lb).

On a global scale, the manufacture and use of ebikes has long lasting sustainability benefits. It is said that a region, community, or people who use their resources to effectively prolong life can be sustainable. In the act of creating and using ebikes, more people are likely to ride instead of drive to work, wear and tear on roads will be reduced, and people will be living more active lives, promoting health and quality of life. Ebikes promote a sustainable lifestyle by saving gas, reducing necessary materials required to fix roads, and reducing CO_2 emissions from cars. Unfortunately, the production of carbon fiber is an energy intensive multistage process. The majority of carbon fiber (90%) is made from polyacrylonitrile while the rest comes from a rayon or pitch-based precursor. The steps can be broken down as follows [1]:

1. **Polymerization:** Stirring of the precursor with a catalyst at a proprietary temperature and pressure to create long-chain polymers, followed by washing and drying in a solvent.
2. **Spinning:** The fibers are oriented by extrusion through a spinneret followed by drying and stretching with rollers.
3. **Oxidation:** Oxygen is combined with the fibers in an oven which promotes polymer chain cross

linking, effectively increasing the fiber density.
4. **Carbonization:** The fibers are carried through a series of furnaces in an inert process to promote crystallization.
5. **Sizing/Surface Treatment:** The fibers are treated in a bath to rough the surface, creating a better bonding surface for the matrix resin. Sizing is a coating which is applied to protect the fibers during handling and weaving.
This entire process is highly proprietary, requires a lot of specific machinery, and consumes a lot of energy. The process consumes approximately 14 times as much energy as the production of steel [2], however due to excellent corrosion resistance and fatigue life, it has the potential of a much longer life-cycle. Additionally, the same part for a car, airplane, etc. can be made much lighter using carbon fiber, so over time the energy savings from weight could potentially surpass the production costs.

Economic

The economics of this project center on printing time and material usage. Additive printing is distinct from subtractive manufacturing from the ratio of material usage to material waste; with the exception of rafts, some support structures, and sanding, virtually all the carbon fiber fed through the extruder will end up in the final product. However, the carbon fiber filament remains an expensive material to purchase. This imposes a design constraint on material usage concerning support structures and infill. A member printed with a crystalline interior support structure will be stronger than one without, at the cost of increased weight and significantly increased printing time. This is also true concerning concerning the printing of external structures to support cantilevered features.

The infill factor will be heavily influenced by the external geometry of the pieces. We planned to design parts to minimize the use of infill structures, however some infill was necessary to reinforce thinner members. Figure 32 reveals the print design beneath the wrap. The infill seen in this photo is necessary to have a continuous tool path as well as for the housing of fixtures. Because of our printing time constraints, our print took a very small amount of time and used little material. The costly portion of this project was the motor, battery, and HUD.

Our team was lucky enough to be fully sponsored by Arevo.

Summary and Conclusions

This project was a very rewarding experience for our team as a whole, allowing us to utilize and showcase what we have learned over the past 4 years here at Santa Clara University. While we were able to accomplish our main goal of printing a bicycle frame out of continuous carbon fiber, we were unable to complete our fully assembled ridable bicycle. Moving forward there are several corrections to be made in order to create a fully assembled and ridable e-bike.

One of the biggest issues that our group faced was the print time required for the complete frame. As mentioned earlier, we were able to print a skeleton frame, which saved approximately 2 days of print time, and then wrapped this skeleton frame in carbon fiber. What we found is that carbon fiber is not an easy material to work with once it is dipped in the resin and hardener mixture which meant that our initial layer of wrap had numerous holes and bubbles that caused imperfections on the surfaces of the frame. Due to this difficulty of working with carbon fiber wrap, we were forced to apply numerous layers onto the frame adding weight which defeated the purpose of wrapping as this took us several days of work, whereas the printer would have been capable of completing this in 2 days. This also meant that we were working hands on with dangerous chemicals and were required to wear protective masks. Due to the fact that the wrap actually took us longer to finish than the printer would have and poses potential risks to those working with the wrap, we would not recommend this approach again. If we were to print another frame, the entire frame, including the walls, would be printed using the continuous carbon fiber printer.

The next issue that we faced were several problems with our rear stays. As mentioned before, due to time constraints on the printer we were forced to design our rear stays out of acrylic and foam and then wrapped this in carbon fiber to provide the strength necessary to support a rider. This again took several days to wrap, defeating the purpose of not printing these 2 rear stays. We also found that these components were not capable of supporting a rider since the stress from the weight of a rider was concentrated in the foam and not the carbon fiber wrap. The other option that was suggested to us by Arevo Labs was to have a metal mold of our rear stays that could then be wrapped in carbon fiber for aesthetic purposes. However, due to time and budget constraints, we were unable to contact any companies that could supply us with these our rear stay designs in a reasonable time. However, we do believe that this method would be capable of supporting a rider. Our preferred method would be to print the rear stays using a chopped carbon fiber printer since this allows for printing tighter radii than the continuous carbon fiber printer. It also maintains the lightweight characteristics that we hoped for in our bike and would provide us with plenty of strength for our design.

Another issue was we found several problems that we had to overcome during the assembly process of the bike. One of the first issues that we faced was that we did not take into account the extra material that would be added to the frame from the carbon fiber wrap, which gave us difficulty in attaching the electric motor. With the extra material we did not have clearance to install the motor, which meant we had to find a way to remove this extra layer of carbon fiber. We determined that the best way to remove of the extra material was to use a Dremel tool and remove the several wrapped layers where the motor was meant to be inserted. In the future, the frame would be completely printed and sanded down which would allow an ample amount of clearance for the motor to be installed.

The other major issue that we faced during the assembly process was that the holes in our rear stays were not perfectly aligned. This was due to the fact that there were no level surfaces on the rear stays after we wrapped them making it impossible to clamp the rear stays together in perfect alignment. This meant that after our initial drilling we had to re-drill the holes on one of the stays to be slightly larger than we had intended in order to insert the rod and connect all the components. As previously mentioned, using a continuous carbon fiber printer would allow us to print these holes, rather than using a mill to create these holes. However, if these holes were too small to be printed, the printer would still provide us with level walls making it possible to clamp the stays together and then mill these holes so that they would be perfectly aligned.

Bibliography

[1] Anderson Jr., J. “Introduction to Flight: Eighth Edition.” *McGraw-Hill Education*, New York (2016).

[2] Latta, E. G., 1888, “Velocipede.” U.S. Patent 378253.

[3] Garford, A. L., 1891, “Safety Bicycle.” U.S. Patent 457080.

[4] Chamberlain, L., 2010, “Bicycle assembly with rear shock.” U.S., Patent 20100327556 A1.

[5] Liu, Y., Tsay, T., Wang, T., and Liu, C. “Analyzing the influences of bicycle suspension systems on pedaling forces and human body vibration.” *Journal of Vibroengineering* Vol. 16, No. 5 (2014): pp. 2527-2535.

[6] Yan, B., Zhongxia, X., Tian, H., Xu, Z., and Xinghua, W. “Optimal design and dynamic simulation of mountain bike with rear suspension” *Chinese Journal of Mechanical Engineering* Vol. 22, No. 1 (2009): pp. 21-26.

[7] Bhuyan, M., Rahman, R., Chetia, A., Das, S., and Rajkhowa, S. “A Typical Approach to Design and Analysis of Foldable Bicycle.” *IUP Journal Of Mechanical Engineering* vol. 11, no. 1 (2018): pp. 7-27.

[8] Agrawal, S., Singh, K., and Sarkar, P. “Impact damage on fibre-reinforced polymer matrix composite – A review.” *Journal of Composite Materials* Vol. 48, No. 3 (2014) pp.317-332.

[9] Usamentiaga, R., Clemente I., Matthieu K., Xavier M., Jeroen P., and Alvaro S. “Nondestructive Evaluation of Carbon Fiber Bicycle Frames Using Infrared Thermography.” *Sensors* (14248220), Vol. 17, no. 11 (2017): pp. 1-16.

[10] Yang, C., Tian, X., Liu, T,, Cao, Y,, and Li, D. “3D printing for continuous fiber reinforced thermoplastic composites: mechanism and performance.” *Rapid Prototyping Journal*, Vol. 23, Iss. 1 (2017): pp. 209-215.

[11] Archibald, Mark. “Design of Human-Powered Vehicles.” *ASME Press*, 2016.

[12] Filippov, A., et al. ”Application of 3D Computed Microtomography for Investigating the Microstructural Defects of Carbon Fiber Reinforced Composite Made by 3D-Printing.” *Key Engineering Materials*, vol. 712, July 2016, pp. 324-327.

[13] Hšchtl, F., et al. ”A Method for Quantifying Impact Loads from Stone Impact in Mountain Biking.” *Procedia Engineering*, vol. 34, iss. ENGINEERING OF SPORT CONFERENCE 2012, 01 Jan. 2012, pp. 415-420.

[14] Lewicki, James P. et al. “3D-Printing of Meso-Structurally Ordered Carbon Fiber/Polymer Composites with Unprecedented Orthotropic Physical Properties.” *Scientific Reports*, vol. 7, 2017.

[15] RONTESCU, C., et al. ”Choosing the Optimum Material for Making a Bicycle Frame.” *Metalurgija*, vol. 54, no. 4, Oct. 2015, pp. 679-682.

[16] Bheda, H., 2014, “Reinforced fused-deposition modeling.” U.S., Patent 20140232035 A1.

[17] Mark, G. and Gozdz S., 2015, “Three Dimensional Printer with Composite Filament Fabrication.” U.S., Patent 9156205 B2.

[18] Dumitrache, F., Romanca, M., Pana, G. “E-bike Electronic Control Unit.” *Optimization of Electrical and Electronic Equipment (OPTIM) & 2017 Intl Aegean Conference on Electrical Machines and Power Electronics*, (2017): pp. 687-692.

[19] Joseph, J., Kuriakose, J., Benny, A., John, D., and K., C. “Effortless Hybrid Bicycle with PMDC Motor and Solar Assembly.” *Grenze International Journal of Engineering and Technology (GIJET)*, vol. 3, 2017: pp. 18-26.

[20] United States. Cong House. Energy and Commerce. Senate. Commerce, SCience, and Transportation. “Consumer Product Safety Act of 2002”. 107th Cong. 1st sess. H. Rept. 107-5. *The Library of Congress.* Web. 21 May 2018.

[21] Schepers, J.P., Fishman, E., den Hertog, P., Klein Wolt, K., and Schwab, A.L.. “The safety of electrically assisted bicycles compared to classic bicycles.” *Elsevier: Accident Analysis and Prevention* Vol. 73, (2014): pp. 174-180.

[22] Rontescu, C., Cicic, T.D., Amza, C. G. Chivu, O., and Dobrota, D. C. “Choosing the Optimum Material for Making a Bicycle Frame.” *Metalurgija*, Vol. 54, Iss. 4 (2015): Pp 679-682.

[23] Marks, R., ”Fatigue Data Report for Arevo Labs.” 2018.

Appendices

Appendix A: Decision Matrices

Scoring Criteria

Project:	Car6on	
System:	Suspention Type	
Date:	8-Nov-16	
	Criterion	FACTOR
1	Simplicity	7
2	Easy of Analysis	9
3	Easy of Assembly	8
4	Aesthetics	10
5	Interest Level	15
6	Comfort	25
7	System Integration	6
8		
9		
10		
11		
12		
Time		10
Cost		10
SUM		100
Target		100
difference		0

(a) Suspension criteria

Project:	Car6on	
System:	Front System	
Date:	8-Nov-16	
	Criterion	FACTOR
1	Weight (by intuition)	11
2	Strength (by intuition)	12
3	Simplicity	4
4	Printability	13
5	Machining Required	6
6	Ease of Analysis	9
7	Easy of Assembly	5
8	Aesthetics	10
9	Innovativeness	8
10	Marketability for Arevo	7
11		
12		
Time		13
Cost		2
SUM		100
Target		100
difference		0

(b) Main-frame design criteria

Project:	Car6on	
System:	Rear System	
Date:	8-Nov-16	
	Criterion	FACTOR
1	Weight (by intuition)	11
2	Strength (by intuition)	12
3	Simplicity	4
4	Printability	13
5	Machining Required	6
6	Ease of Analysis	9
7	Easy of Assembly	5
8	Aesthetics	10
9	Innovativeness	8
10	Marketability for Arevo	7
11		
12		
Time		13
Cost		2
SUM		100
Target		100
difference		0

(c) Sub-frame design criteria

Figure 34: Weighted criteria used to choose between the trade-offs shown in the following decision matrices.

Matrices

Design Project = Car6on   System= Suspention Type

	TARGET or	DESIGN IDEAS							
CRITERIA	FACTOR	1 = Baseline		No Suspension		Suspension Fork		Full Suspension	
Time – Design	10	10		0		10		20	
Time – Build	5	5		0		5		10	
Time – Test	10	10		5		10		15	
Time weighting	10		10		1.67		10.00		18.33
Cost – Prototype	400	$ 400.00		$ -		$ 400.00		$ 600.00	
Cost – Production	200	$ 200.00		$ -		$ 200.00		$ 300.00	
Cost weighting	10		10		0.00		10.00		15.00
Simplicity	7	3	21	5	35	3	21	2	14
Easy of Analysis	9	3	27	5	45	3	27	1	9
Easy of Assembly	8	3	24	5	40	3	24	2	16
Aesthetics	10	3	30	1	10	3	30	4	40
Interest Level	15	3	45	1	15	3	45	4	60
Comfort	25	3	75	1	25	3	75	5	125
System Integration	6	3	18	1	6	3	18	3	18
	TOTAL		240.0		194.3		240.0		268.7
	RANK								
	% MAX		89.3%		72.3%		89.3%		100.0%
	MAX	268.7							

NOTE: User fills in Purple areas, gold areas are calculated or fixed
Light blue areas filled from prioritizing matrix

BASELINE = Standard Hardtail with Front Suspension Fork

Design Idea Descriptions

2 No Suspension
3 Same as Baseline
4 Full Suspension

Figure 35: Decision matrix, used to score and help choose the suspension system for the bike.

Design Project = Car6on   System= Front System

CRITERIA	TARGET or FACTOR	DESIGN IDEAS 1 = Baseline		Simple Triangle		Cantilever Seat		Supported Seat Post	
Time – Design	15	15		12		20		17	
Time – Build	15	15		15		15		16	
Time – Test	15	15		15		20		15	
Time weighting	13		13		12.13		15.89		13.87
Cost – Prototype	200	$ 200.00		$ 100.00		$ 110.00		$ 120.00	
Cost – Production	100	$ 100.00		$ 50.00		$ 55.00		$ 60.00	
Cost weighting	2		2		1.00		1.10		1.20
Weight (by intuition)	11	3	33	3	33	3	33	2	22
Strength (by intuition)	12	3	36	3	36	2	24	4	48
Simplicity	4	3	12	3	12	2	8	2	8
Printability	13	3	39	3	39	3	39	3	39
Machining Required	6	3	18	3	18	3	18	2	12
Ease of Analysis	9	3	27	3	27	2	18	2	18
Easy of Assembly	5	3	15	3	15	3	15	3	15
Aesthetics	10	3	30	3	30	4	40	4	40
Innovativeness	8	3	24	2	16	5	40	4	32
Marketability for Arevo	7	3	21	2	14	4	28	3	21
0	0	3	0		0		0		0
0	0	3	0		0		0		0
	TOTAL		255.0		241.9		261.0		254.9
	RANK								
	% MAX		97.7%		92.7%		100.0%		97.7%
	MAX	261.0							

NOTE: User fills in Purple areas, gold areas are calculated or fixed
Light blue areas filled from prioritizing matrix

BASELINE = Standard Basic Triangular Mountain Bike Front

Design Idea Descriptions

2	Basic triangular shape with points at head tube, seat tube, and bottom bracket.
3	Triangle is more obtuse and the seat tube is cantelevered away from top tube.
4	Triangle is more obtuse with a higher seat tube supported by a diagonal from top tube.

Figure 36: Decision matrix, used to score and help choose the design of the main-frame of the bike.

Design Project = Car6on System= Rear System

CRITERIA	TARGET or FACTOR	DESIGN IDEAS: 1 = Baseline		V-Shape		Triangle		Chain-Stay Only	
Time – Design	15	15		20		18		25	
Time – Build	10	10		10		12		10	
Time – Test	15	15		15		15		20	
Time weighting	13		13		14.44		14.73		17.33
Cost – Prototype	200	$ 200.00		$ 100.00		$ 120.00		$ 80.00	
Cost – Production	100	$ 100.00		$ 50.00		$ 60.00		$ 40.00	
Cost weighting	2		2		1.00		1.20		0.80
Weight (by intuition)	11	3	33	2.5	27.5	2	22	4	44
Strength (by intuition)	12	3	36	3	36	4	48	1	12
Simplicity	4	3	12	3	12	4	16	2	8
Printability	13	3	39	3	39	3	39	3	39
Machining Required	6	3	18	2	12	2	12	2	12
Ease of Analysis	9	3	27	3	27	3	27	3	27
Easy of Assembly	5	3	15	3	15	3	15	3	15
Aesthetics	10	3	30	3	30	2	20	4	40
Innovativeness	8	3	24	3	24	3	24	4	32
Marketability for Arevo	7	3	21	3	21	3	21	4	28
0	0	3	0		0		0		0
0	0	3	0		0		0		0
	TOTAL		255.0		243.1		243.1		253.9
	RANK								
	% MAX		100.0%		95.3%		95.3%		99.6%
	MAX	**255.0**							

NOTE: User fills in Purple areas, gold areas are calculated or fixed
Light blue areas filled from prioritizing matrix

BASELINE = Standard Mountain Bike Chain and Rear Stay System

Design Idea Descriptions

2	V shape with point at wheel and two ends fastened individually to system.
3	Full triangle with point at wheel and side fastened to system.
4	Rear stay ommited from system. Chain stay acts as cantilevered beam.

Figure 37: Decision matrix, used to score and help choose the design of the sub-frame of the bike.

Appendix B: Sketches

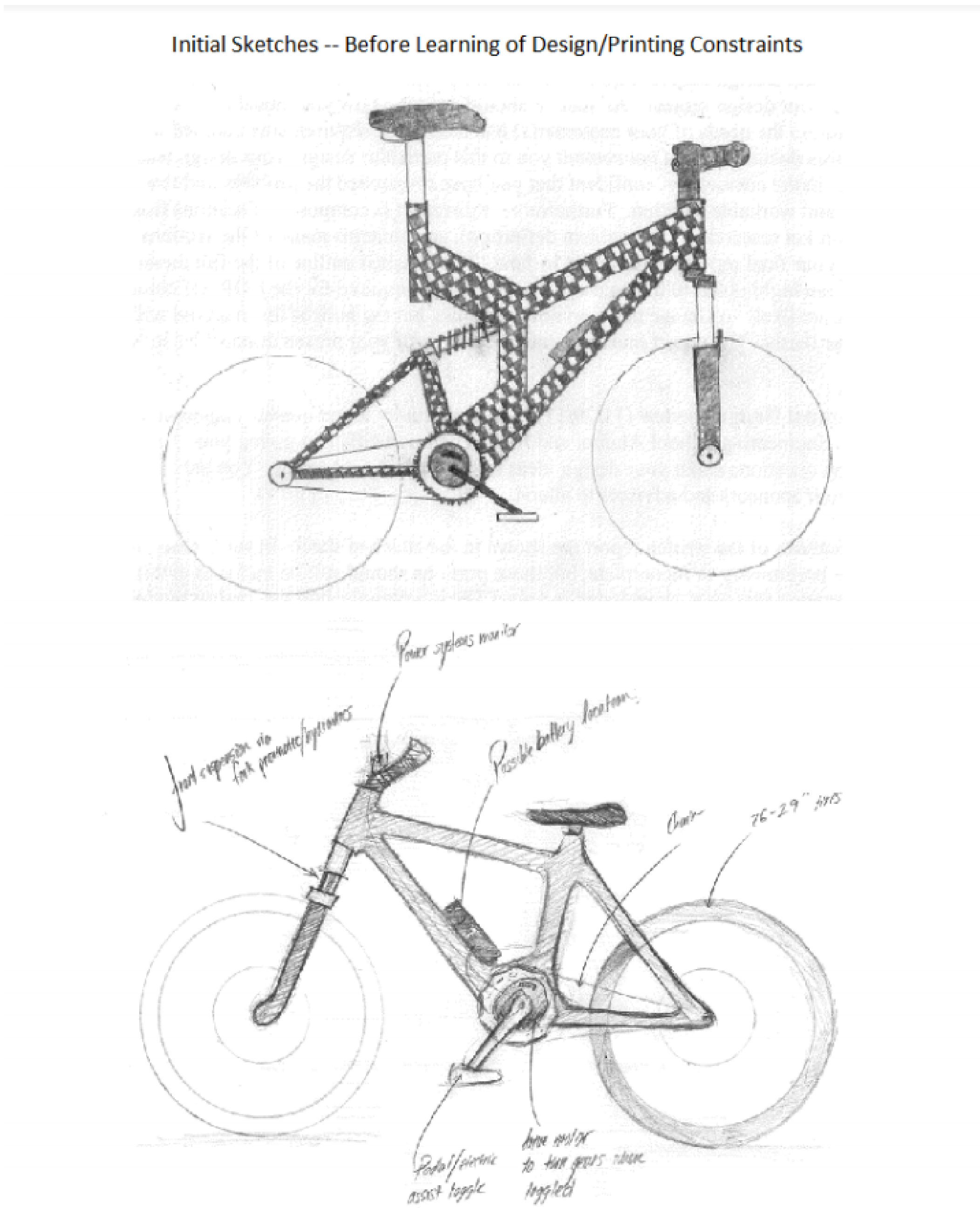


Figure 38: Initial sketches used to make basic conceptual decisions about the design of the frame.

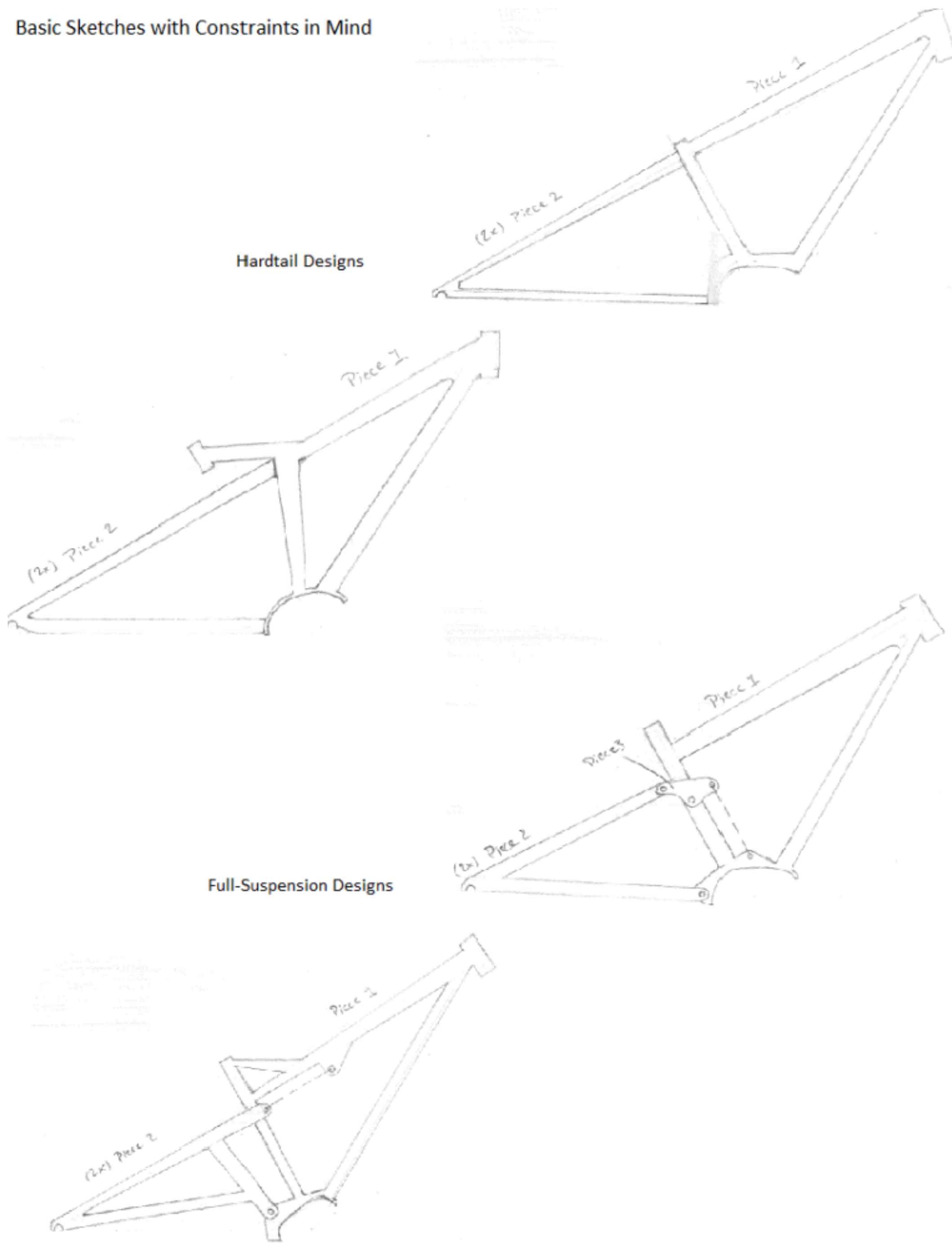


Figure 39: Sketches made to decide between major subsystem concepts for the frame.

Appendix C: Budget

Table 5: Budget

Bafang Electric Motor Kit	$440
Bottle Battery	$220
Shock	$80
Front Fork	$86
Wheels & Handlebars	$260
Apoxie Sculpt	$45
Foam & Acrylic	$80
Resin & Hardener	$170
Cylindrical Metals	$200
Print Materials & Time	$???
Carbon Fiber Cloth	$???
TOTAL	**$1581 + x**

Appendix D: Timeline

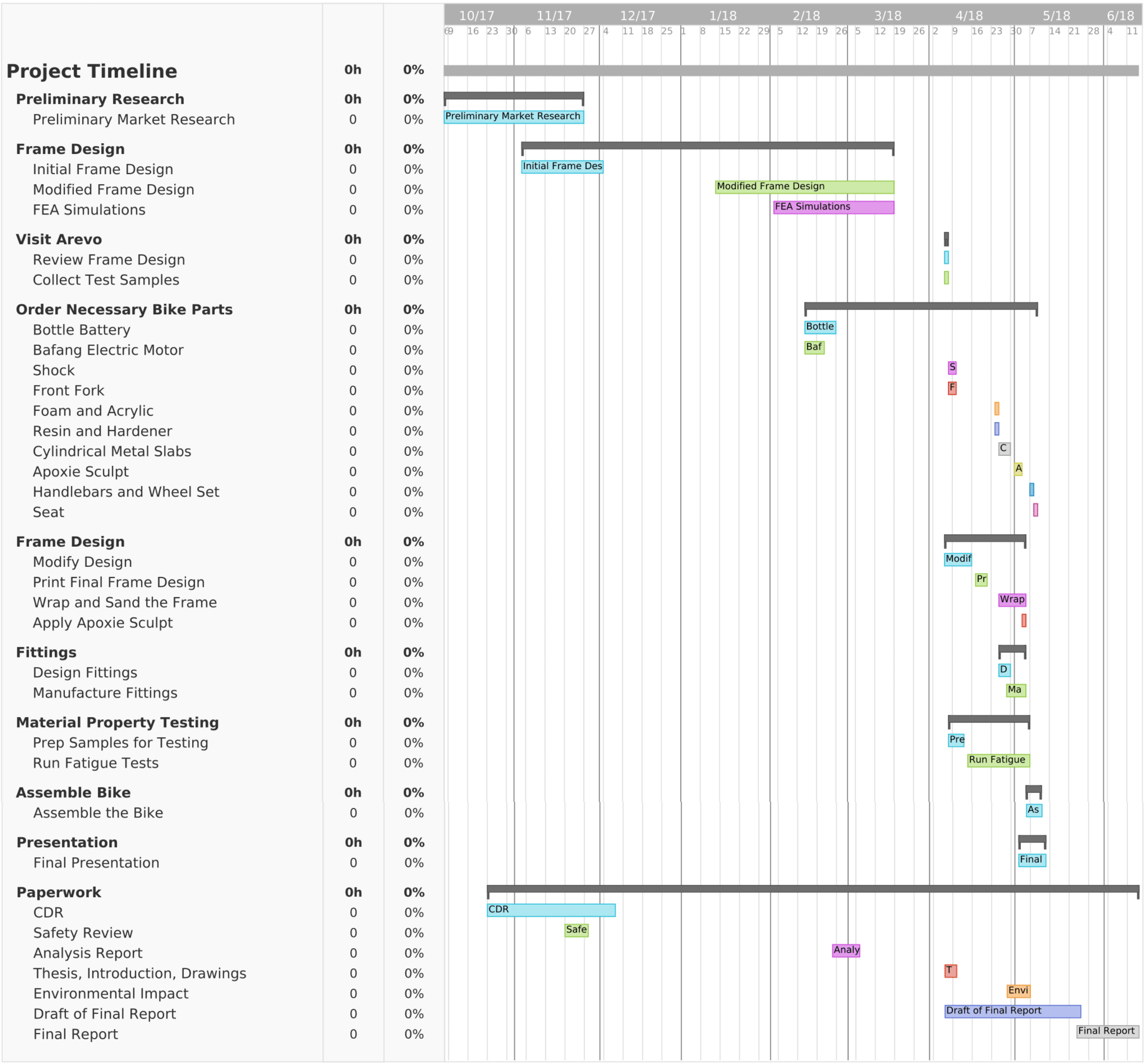


Figure 40: Timeline maintained throughout the design and manufacturing processes of the project.

Appendix E: Environmental Impact Report

Environmental Impact Report for a 3D Printed Carbon Fiber Bike Frame

Introduction to the Project and the Areas it Impacts

This paper discusses the environmental impacts of the creation of a electric mountain bike frame using 3D-printed continuous carbon fiber. The frame was printed using Arevo, INC's proprietary continuous carbon fiber printing technology. The company uses a constantly fed, unidirectional strand of fiber filament which is impregnated into a matrix polymer within the printer head, heated, and then laid onto a build plate in the pre-specified geometry. The frame geometry was designed based on industry proven concepts, iterations using finite element analysis, and the requirements and current capabilities of the printer. In order to significantly reduce the printing time required for the frame, the left and right faces were omitted from the print. A wrapping process using carbon fiber weave and composite resin was performed to finish the frame.

There are two areas of environmental impact which this project implicates directly. The first is the benefit of electrically powered transportation. There has been a major cultural and business trend in this area with most major automotive companies developing and releasing electric cars along with a host startups and established companies producing electric-power assisted bicycles, skateboards, scooters, etc. Although, the electric mountain bike directly fits into this category and very well could add to the continued cultural push for non-fuel consuming vehicles, trail riding is traditionally dominated by human power already. This makes it challenging to quantify any impact the bike would have.

The second area stems from disrupting the manufacturing processes of carbon fiber components using additive techniques as opposed to pressurized molding or just wrapping. This is much more quantifiable and will be the focus of the report.

Background and Contemporary Manufacturing Techniques

There are three main phases which contribute to the environmental impact of a carbon fiber project:

- Material production and preparation
- Manufacturing process
- Machining / Component finishing

Each of these carries a significant load of the total impact which will be broken down further in the following sections. This continuous fiber stands used in the 3D-printing for this project are no different from those that are weaved together in prepreg meshes for conventional manufacturing. So, unlike the manufacturing and finishing phases, the production of the fibers is not a point of difference. However, it still adds to the total footprint of a part and will be discussed briefly.

Carbon Fiber Production:

The production of carbon fiber is an energy intensive multistage process. The majority of carbon fiber (90%) is made from polyacrylonitrile while the rest comes from a rayon or pitch-based precursor. The steps can be broken down as follows [1]:

1. **Polymerization**: Stirring of the precursor with a catalyst at a proprietary temperature and pressure to create long-chain polymers, followed by washing and drying in a solvent.
2. **Spinning**: The fibers are oriented by extrusion through a spinneret followed by drying and stretching with rollers.
3. **Oxidation**: Oxygen is combined with the fibers in an oven which promotes polymer chain crosslinking, effectively increasing the fiber density.
4. **Carbonization**: The fibers are carried through a series of furnaces in an inert process to promote crystallization.
5. **Sizing/Surface Treatment**: The fibers are treated in a bath to rough the surface, creating a better bonding surface for the matrix resin. Sizing is a coating which is applied to protect the fibers during handling and weaving.

This entire process is highly proprietary, requires a lot of specific machinery, and consumes a lot of energy. The process consumes approximately 14 times as much energy as the production of steel [2], however due to excellent corrosion resistance and fatigue life, it has the potential of a much longer life-cycle. Additionally, the same part for a car, airplane, etc. can be made much lighter using carbon fiber, so over time the energy savings from weight could potentially surpass the production costs.

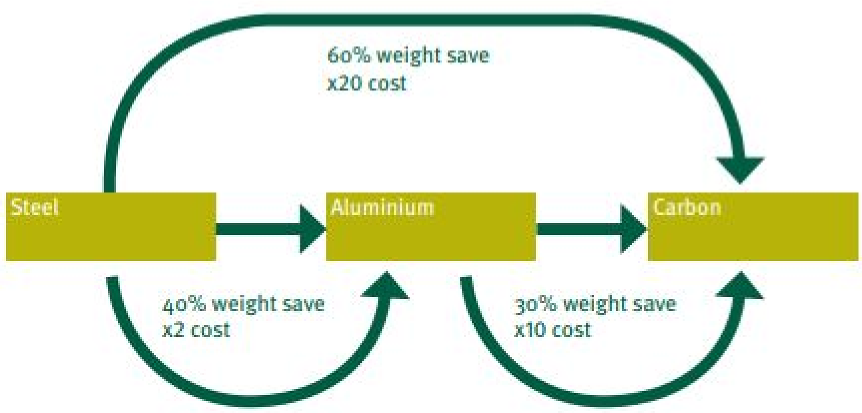


Figure 41: Image describing the weight saving vs cost increase when choosing between carbon fiber, aluminum, and steel [3].

Unfortunately, in the bicycle industry, weight savings do not apply quite as directly to energy savings. Instead, lightweight bikes are desires for the extra speed they are capable. It can be argued that making a more desirable and quicker bike will draw more people away from fuel consuming cars, but that is an abstract and challenging to prove statement.

Current Manufacturing Techniques:

Current carbon fiber manufacturing techniques are time, material, energy, and labor intensive. Numerous methods exist, however in the bicycle industry the vast majority of manufacturers have adopted the monocoque method [4]. To create custom part geometry, a CNC machine cuts out initial carbon fiber shapes that will become the frame components. Each part then requires an aluminum mold of the final desired geometry, in which a latex bladder is inserted and inflated [5]. This bladder is wrapped with layers of carbon fiber composite, and encased in the mold. The entire mold is heated and pressed, and the carbon fiber composite cures. After this process, additional refinements are made, usually via sanding, before each individual part is bonded to the next with industrial adhesive. While the entire process can take place in a single manufacturing location, the cutting/molding/curing process can be replaced almost entirely by a single 3D printing job.

Recyclability/Reclaimability:

Despite its relative newness as a manufacturing material, carbon fiber boasts strong recyclability. Carbon is capable of retaining “a significant portion” of its virgin properties, even after a second round of reclamation [6]. In fact, Boeing, one of the largest industrial consumers of carbon fiber composites in their airframes, estimate that the composites can be recycled at 70% the cost of producing the original fiber at $8-12 per lb vs 15-30 per lb to produce, and requiring less than 5% of the energy needed for manufacturing (1.3 to 4.5 kWH/lb vs. 25 to 75 kWH/lb)

This is pertinent to our project; as the production of 3D printed carbon fiber parts rises, so will the necessity of proper disposal of unneeded parts and prototypes. Carbon fiber is estimated to be 14 times more energy intensive than steel to produce [2], placing a greater emphasis on the need for recyclability and reusability. Luckily, carbon fiber does not corrode or degrade the same way as traditional steel and aluminum bikes. Barring impact, the largest factor contributing to their deterioration is UV radiation weakening the epoxy bonds of the composite [7], and this is easily mitigated with commercial UV protective topcoating products.

It is estimated that of about 50,000 tons of carbon fiber produced in 2017, 10,000 went directly to waste without ever making it into a product [8]. Unfortunately, carbon fiber currently is not as recyclable as steel and aluminum. Where the latter may melted down and reformed virtually any number of times, recycled continuous filament carbon fiber invariably [9] returns in a chopped and shortened form. This is the main issue. While still useable, chopped carbon fiber composite loses the load bearing ability of its continuous form. A lot of research money and time is currently being poured into the process of realigning recycled fibers in order to achieve close to the original characteristics [3].

Assumptions Used to Quantify the Project’s Potential Impact

In order to quantify the potential environmental impact our project carries, some key assumptions are being made. The assumptions relating the the carbon fiber printing are that of an idealized process, which does not perfectly reflect our project. However, this is the direction that carbon-fiber 3D printing must go in order to be viable for market production of goods. These assumptions are very rough, but they are necessary to quantify the impact and sufficient to draw general conclusions. The assumptions are below:

1. Printing capabilities:
    a. The printed bike passes safety and strength regulations without needing additional material
    b. The printer/printers will produce 1000 bikes in a year
    c. The finished bike will have less than 0.5 mm removed from the outside by sanding/milling
    d. All holes will be captured during printing, so there will be no drilling necessary
    e. No material is wasted during the printing process
2. Steel Frames:
    a. Making 1 kg of carbon fiber uses 14 times the energy of 1 kg of steel
    b. A carbon fiber part can weigh 60% less than the same steel part
    c. Manufacturing a steel frame produces no significant amount of waste because it is all recycled
3. Molding Carbon Fiber:
    a. Approximately 1/5 of the raw fiber cloth used to mold a bike frame becomes unusable scrap when cut to size
    b. Less than 10% of the wall thickness will be sanded away when finishing a molded part
4. Any wasted carbon fiber will be considered unusable because the current recycling process cannot realign the fibers to make high-strength parts
5. The difference in energy used to actually produce the finished bike frame via 3D-printing carbon fiber, molding carbon fiber, or extruding and welding metal tubes is negligible.

Note: Assumption 5 is clearly false. However, finding accurate numbers for the different manufacturing processes proved problematic, so the assumption was necessary to move forward.

Quantitative Results of the Potential Impact

In this section the impact of creating a 3D printed carbon fiber bike frame will be compared to both a carbon fiber frame made with traditional methods and a steel bike frame. The impact is viewed in terms of energy to produce the bike and the material wasted.

Our 3D Printed Frame:

- The entire printed bike frame weight approximately 4 lbs and had 3 mm thick walls.
- From 1c in the assumptions 0.5 mm will be taken away from those walls which is 1/6 of the total material.
- Other than this there is no wasted material, therefore 2/3 lbs of carbon fiber will be sent to the landfill.

Molded Carbon Fiber:

- Traditional carbon fiber bike frames weight around 2 lbs.
- From assumption 3a, 2/5 lbs of fiber cloth is wasted before molding a frame.
- From 3b, another 1/5 lbs of finished material will be removed after molding.
- Therefore, 3/5 lbs of carbon fiber composite will go to the landfill

Steel:

- Carbon fiber uses 14 times more energy than steel but saves 60% of the weight
- This means that a traditional steel frame will weigh around 2/0.6 or 3.3 lbs (this is consistent with most road bikes)
- Then the material for our bike used 14*(4/3.3) or 16.8 times more energy to create than a standard steel frame

Table 6 shows the comparison between our printed carbon fiber bike and a standard carbon fiber bike or a steel bike.

Table 6: Comparison of the environmental impact of 3D printed carbon fiber bike frames vs molded carbon fiber bike frames and steel bike frames after producing 1000 bikes.

Environmental Impact Type	**Carbon Fiber:** 3D printed	**Carbon Fiber:** Molded	**Steel:** Extruded
Waste:	667 lbs carbon fiber	600 lbs carbon fiber	Negligible
Energy Consumption (normalized with respect to steel)**:**	16.8 times the steel process	8.4 times the steel process (½ of 3D printing)	1

Conclusion

The quantitative results show that manufacturing a carbon composite bike frame using any technology is much more costly to the environment than a steel frame. The numbers comparing an aluminum frame are slightly different but convey the same message. This was expected when the project began. There exists a tradeoff for many novel manufacturing materials between the mechanical benefits and the potential damage to our environment. A lot of this impact is due to the fact that all of the initial research of novel materials goes into producing it with the best possible properties. It takes a long time for research into recyclability and cutting down production waste can catch up. There is a strong trend in this direction as companies such as Boeing are funding large movements to recycle 90% of their carbon fiber parts, and fiber producers are trying to cut down energy costs by as much as 30%.

When comparing the 3D printing process with molding, there is little significant difference between the two. Both processes produce similar amounts of waste and consume a lot of energy while making a part. Table 1 shows that in the current state, 3D printing is slightly behind molding in terms of impact, but these numbers do not tell the whole story. One key difference in 3D printing's favor is that the matrix polymer must be a thermoplastic instead of a thermoset plastic so that the printed part hardens as it cools. Thermoplastics themselves are recyclable, so more of the total part is not wasted. In contrast thermoset plastic composites must be incinerated away from the fibers in order to have a chance at recycling the carbon fiber itself. This releases harmful gases and requires that more plastics are created for additional parts.

When the reduction in impact catches up with the benefits of carbon fiber composites, it will be a much more attractive option more many industries. However, in its current state only certain industries can sufficiently justify its use. For instance, aerospace and automotive applications benefit a lot from reduced fuel consumption due to lighter-weight components. The bicycle industry does not have quite as strong of a justification, but there is still a growing popularity in carbon bikes due to the desire to have the fastest equipment. The argument can be made that lighter bikes draw more people away from cars, and that carbon composites can last longer than metal, but these justifications are not concrete.

Appendix F: PDSO

Introduction

In September, our team reached out to Pete Woytowitz, the Director of Modeling and Algorithms at Arevo Labs, in regards to exploring 3D printing technology. He informed us that we could help the company showcase their potential to revolutionize the carbon fiber manufacturing and 3D printing industries. In order to achieve this, we agreed that designing and building a bicycle frame would be a relatable product for consumers which would effectively demonstrate Arevo's technology.

Arevo provided preliminary material strength information including material strength properties for modulus of elasticity, shear modulus, poisson's ratio, as well as maximum stresses in the xx, yy, zz, xy, xz, yz directions. Additionally, we performed fatigue tests with printed samples to provide us with a conservative S-N curve approximation for the material. All of this data allowed us to design and iterate a CAD model based upon FEA analysis to ensure that our frame would not fail under circumstantial loading typical of a mount
ain bike.

In general, carbon fiber composites do not behave like a standard isotropic material, which behave equivalently in all directions. Instead, the material is much stronger along the axis of its fiber than orthogonal to it. This can be an issue when designing a part, but it can also be taken advantage of with 3D printing by intelligently manipulating the tool path. The material was assumed to behave equivalently in all directions in the X-Y plane, which is be accomplished by layering different angles of fibers on top of each other. This is called quasi-isotropic, and is most often achieved by using fibers at 0, 45, and 90 degrees stacked on top of each other.

After finishing the design process for the chosen frame and meeting with the engineers at Arevo, it was determined that printing the whole frame as designed would take too much time. In order to maximize the resources available while maintaining the unique ability to print complex continuous shapes it was decided to printing only the inner and outer walls of the frame, and omitting the flat left and right sides. Then, after printing we used carbon fiber fabric and epoxy to wrap the walls together, achieving virtually the same end result. Although this process added some unnecessary weight to the design, it also greatly improved the out of plane strength of the frame. Finally, the bike was assembled with standard purchased hardware along with the electric components that the frame was designed around.

Problem Definition

There is an untapped market of 3D carbon fiber printed products. Current carbon fiber bike frame manufacturing processes have plateaued and Arevo Labs believes public interest could be spiked by showcasing their technology. Continuous carbon fiber offers much higher strength in the axial direction and thus can optimize the strength of the bike under common loading scenarios felt by mountain bikes while minimizing the weight compared to a bike manufactured from chopped carbon fiber.

System Level Sketch

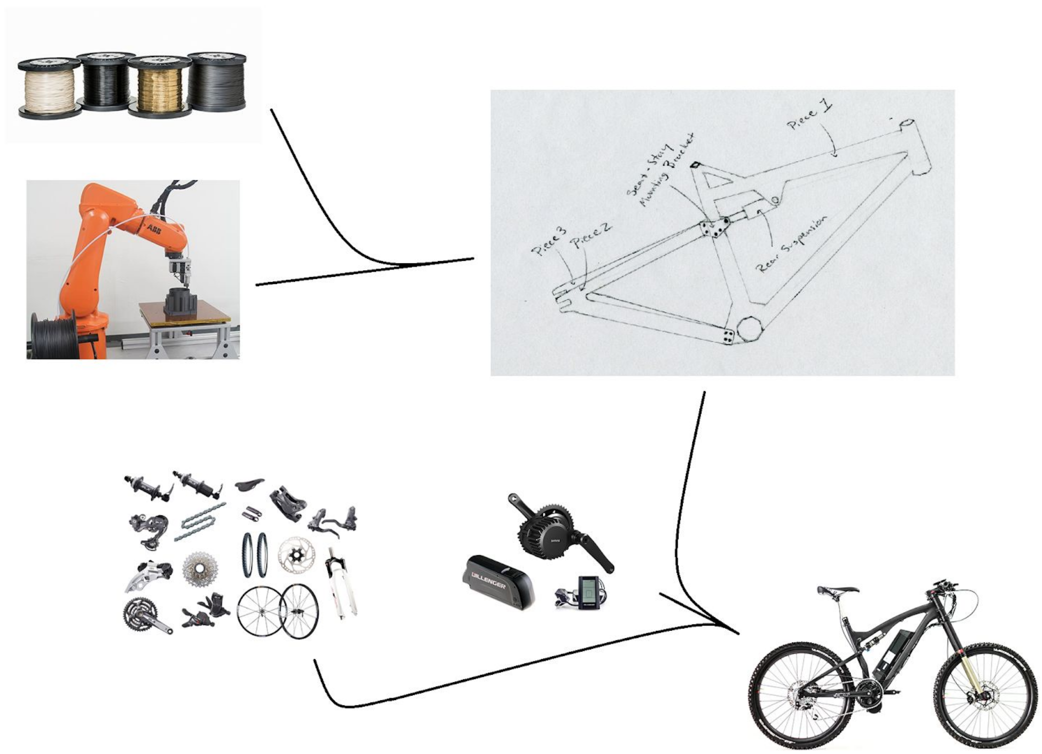


Figure 42: System level sketch of a 3D-printed carbon fiber electric mountain bike

Product Design Specification

The major design criteria for this project is focused around the printability of the bike frame and the competitiveness of the product in its market. First, the geometry required in order to print the frame using AREVO labs' printer it must be made of rectangular tubing with at least 4mm material thickness. Additionally, the frame must fit in a 1m^2 rectangular build plate. This size constraint is satisfied by the standard size of mountain bike frames. Next, in order to be competitive in a carbon fiber bike market, the frame must fall below a certain weight but offer incredible strength and a high level of safety.

The weight goal for the frame is to fall below the average for a carbon fiber mountain bike, which is 15 lbs. Being a mountain bike, our design required a geometry such that areas of high static and dynamic loads can be supplemented with extra material taken from areas of lower stress concentrations. The complex dynamic loading scenarios experienced by a mountain bike adds a level of ambiguity to simulating realistic riding conditions, and thus requires a high factor of safety to ensure unexpected loads or impacts are insufficient for failure. After many iterations and geometry optimizations from simulations and finite element analysis, the team was able to design a sufficiently sturdy frame weighing 12 lbs capable of withstanding numerous complex dynamic and static loading scenarios with a factor of safety of 2. The factor of safety was decided to be sufficient compared to the industry standard of 1.5 for mountain bikes. Further, all simulations were run at exceptionally high loads and drop heights and did not include the suspension system.

Goals

- Design cost efficient product
- Conduct finite element analysis
- Stress/strain analysis
- Fatigue testing of material
- Ride the bike
- Adhere to timeline
- Market projection
- Fully explore 3D printer processes

Table 7: List of product specifications with datums and targets.

Elements / Requirements	Units	Parameters Datum	Target / Range
Price	US Dollars	$799.99	$500
Manufacturing Process	techniques	Pressure Molding	3-D Printing
Size	meters	0.43-0.56 in	0.43-0.56 in
Mass	grams	1360-1820 g	1330-1500 g
Maintenance	N/A	Carbon Fiber tape or sheet wrap	Carbon Fiber tape or sheet wrap
Aesthetics	N/A	Matte Black/Silver, Round Tubing	Matte Black, Rectagular Tubing
Packing	kilograms	2.3 kg	< 2 kg
Quality & Testing	Properties Tested	Fatigue, Stress, Impact, and Visual	Fatigue, Stress, Impact, and Visual
Operation Environment	Environment Conditions	Dust, Mud, Impact Prone, Rain	Dust, Mud, Impact Prone, Rain
Lifetime	years	> 100 years	> 100 years
Tensile Strength at 90deg (same as compressive)	Mpa	600	600
Tensile Strength at 45deg (same as compressive)	Mpa	110	110
In Plane Shear Strength at 90deg	Mpa	90	
In Plane Shear Strength at 45 deg	Mpa	260	260
Density	grams/cm^3	1.6	1.6
Young's Modulus	Gpa	70	70

Appendix G: Safety Review

SANTA CLARA UNIVERSITY
ME194 ADVANCED DESIGN I

Car6on Project Safety Review

Chris Edwards, Fionn Ruder, Joseph Hurley, Micah Thomas, Mitch Spinelli, Parker Gribb
Technical Advisor: Dr. Robert Marks
11/27/2017

Manufacture:

There are an innumerable amount of risks involved in the 3D printing process. The robotic, multi axis 3D printer wields precision lasers, has many high temperature parts, and emits harmful chemicals as it prints. Fortunately, our team members will not be using this technology or be anywhere within within risk of danger while it is in action. We will leave this to the certified professionals at Arevo Labs. The engineers and lab technicians have taken all safety precautions like proper ventilation, personal protective equipment, and many others to prevent catastrophe. In addition to producing the frame, the outer surface will need to be finished through machining, mainly for aesthetic purposes. This finishing work will not be performed by our team but will be instead handled by AREVO.

Assembly:

During assembly, team members will be operating manual and powered hand tools in order to attach all subsystems into a complete electric bike. The main safety concern during assembly is the proper handling of equipment. Standard safety precautions will be followed as laid out during light fabrication training. This includes but is not limited to: always wearing safety goggles, closed toed shoes, and long pants; always having at least two members people present along with supervision if working in the university machine shop, proper securing of parts, etc. Some of the system components, such as the motor, will be heavy and should be handled and transported with care. Lastly, the electrical wiring of the battery, motor, and any added electrical components (i.e. regenerative braking, speedometer) pose a safety risk. All of these will be purchased as part of a kit, and no needed alterations are foreseen. However, if any changes are deemed necessary, approval and supervision will be attained. If soldering is necessary, the technician will need to guard themselves against burns and fumes. Care must be taken to ensure proper wiring to prevent any short circuits, and all exposed wire must be wrapped and secured against catching.

Test/Operation:

Various tests will be performed at different points in the design process of the bicycle. Some initial wafer samples and square tubes of the carbon composite will be tested early in the Winter. Heavy machinery will be used to test tensile and compressive strength and toughness. In order to ensure safety while operating these machines, supervision from a lab manager or technician will be needed along with proper clothing, footwear, and eye-protection. At a later stage, once a full frame has been printed, it is likely that the team will attempt to outsource testing to an established bike company. Personal safety will not be a concern if this is done. Finally, once the complete electric bicycle has been manufactured and assembled, the prototype will be tested for full functionality. Put simply, a team member will ride the bike to make sure all the subsystems work together as intended. The safety precautions needed at this stage are identical to those of operation. The rider will wear safety gear to guard against a potential crash, and will operate the bike safely and within the comfort of their ability.

Display:

It was determined that there are no known risks or hazards in presenting the completed bike frame. It will be secured in a holder case or with an installed kickstand and not moving. The electric bike generator will not be turned on or in operation in the display so there is no inherent risk.

Storage:

Storage of the bicycle will be relatively safe. The bike itself should not be structurally compromised from long storage times, although the general quality of ride might degrade from a rusted chain or low tire pressure. The only real concern during storage is with the battery. If it is possible to easily remove the leads from the terminals of the battery chosen, this is an option. Otherwise, before riding again, the user should make sure that there are no signs of corrosion.

Disposal:

The only harmful component of the bike if it were to be disposed would be the battery powering the electric motor. This battery is considered “hazardous waste” in California and should be properly recycled, or taken to a hazardous waste disposal facility. The motor components aswell should be properly recycled or sold for scrap metal as they too can be harmful to the environment. The frame itself is designed to last indefinitely without the expectation of disposal, however, the carbon fiber can be recycled and used in non structural parts (only virgin carbon fiber is strong enough to be used in critical, structural components). The rest of the bike members (i.e. wheels, fork chain… etc) can be sold or recycled.

Appendix H: Fatigue Data Report

SPECIMEN #1

The following graph illustrates a sampling of data obtained from our first run of load cycling at 1 Hz. The inner and outer spans of the four-point bend fixture were set to 3 cm and 9 cm, respectively. It was our intention to cycle between 100 MPa and 250 MPa, but we need to increase the proportional gain so actual load keeps up with the command load. Also, 1,000 N is only 1% of the load cell capacity, so we should consider different specimen dimensions if there is extended interest in bend tests.

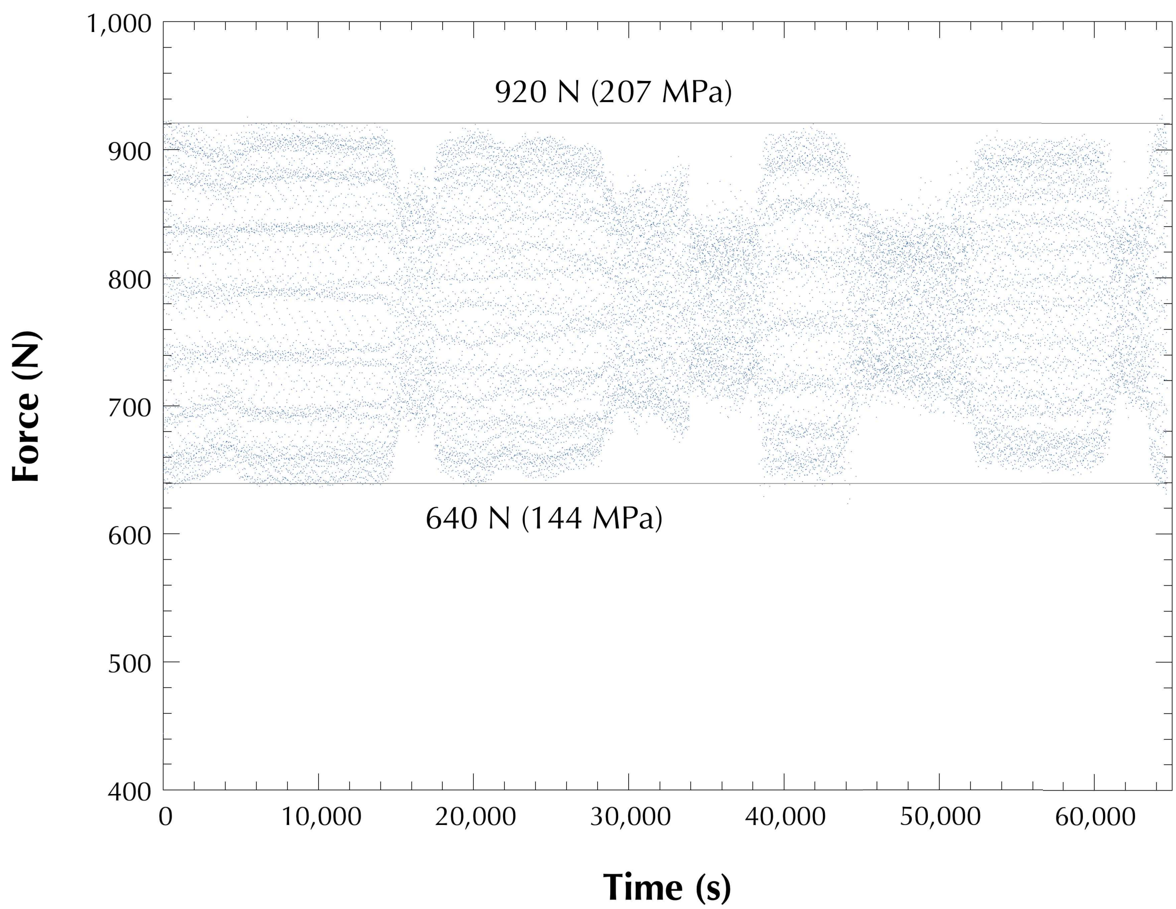


Figure 43: Four point bend data cycling Specimen 1 from 100 to 250 MPa at 1Hz.

It also appears that over some time periods, the load did not cycle between the typical ≈640 N and ≈920 N. To confirm that this was not an artifact of data not necessarily being sampled at load peaks and valleys, I produced the following graphs to examine the details of a few load cycles. Noise in the data is partially attributed to operating at a small fraction of load cell capacity.

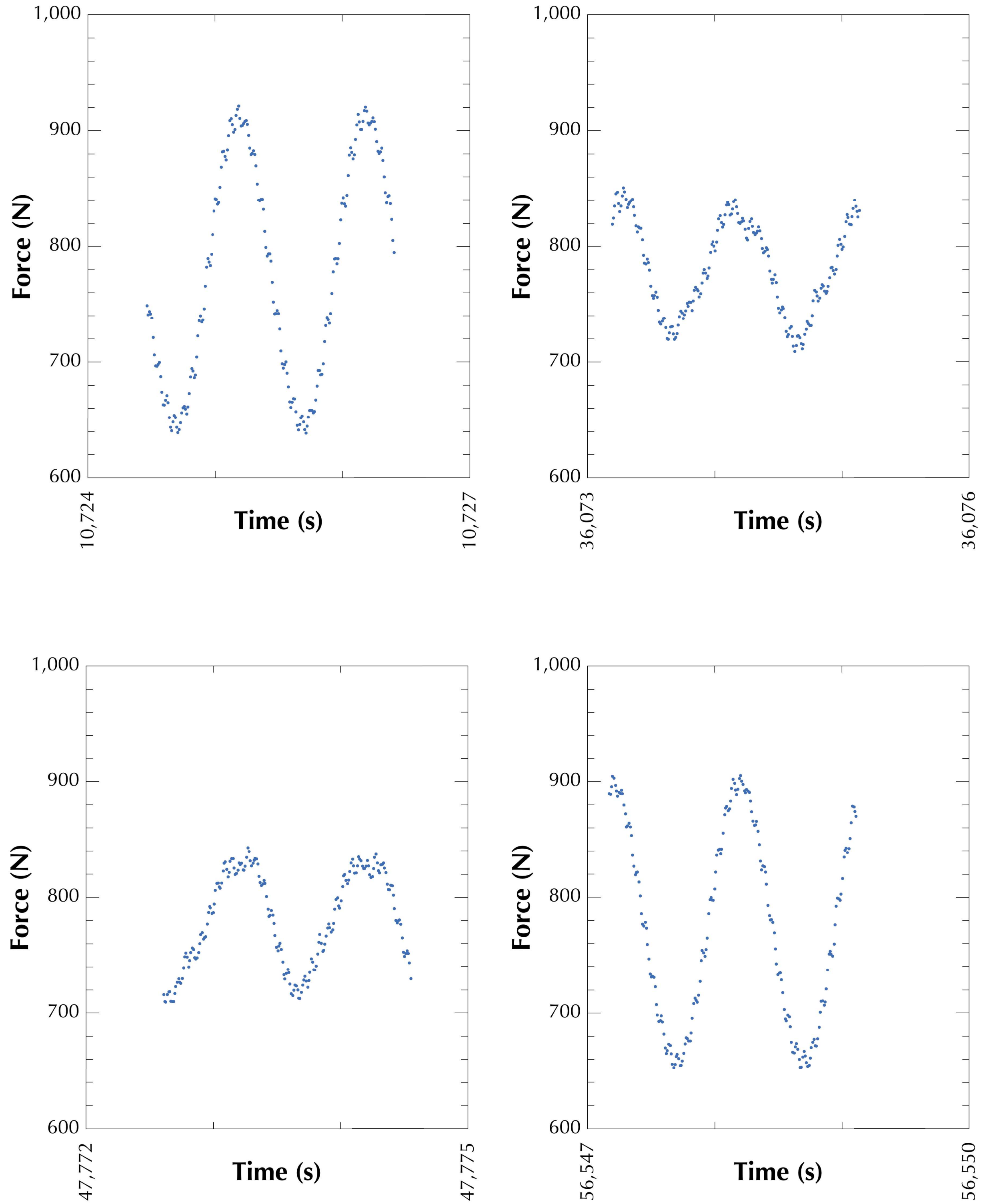


Figure 44: Zoomed in portions of Figure 43 to show load vs time details.

The following graph illustrates the force and position data for a few cycles; the slope of these lines is indicative of the specimen stiffness. There does not appear to be significant change in stiffness, as would be expected since this was not an extensive number of cycles for the stresses applied.

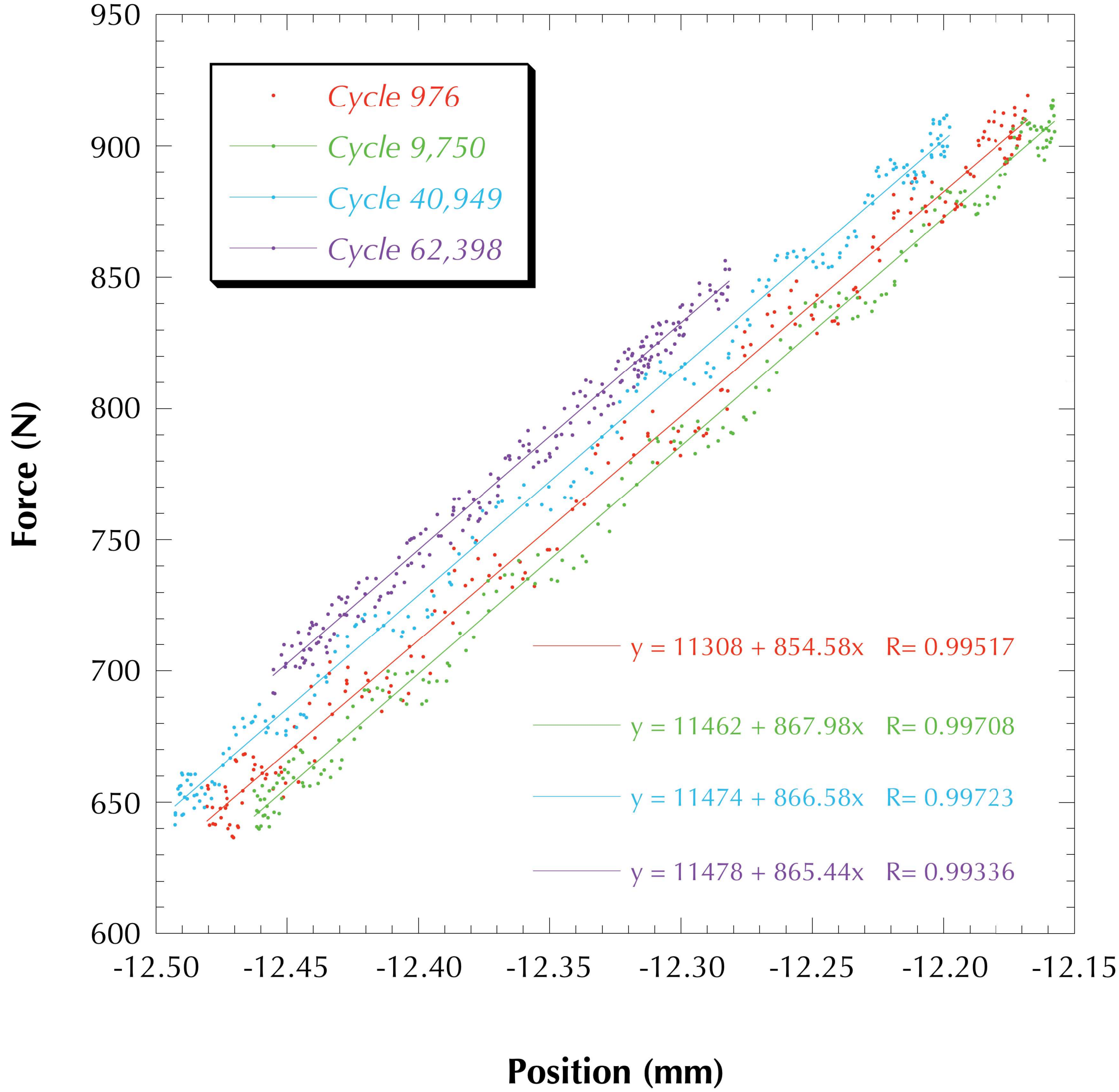


Figure 45: Plot of force vs position for a few cyles of Specimen 1 where the slope indicates stiffness.

Nevertheless, the decrease in slope (more compliant specimen) for the last three cycles graphed above caught my eye, and I decided to investigate whether this was an actual trend or simply due to typical noise in the data.

If I take out the first few data points, where the specimen appears to become stiffer with cycling, it appears there is a decline in stiffness, although the fit could be better. This should be investigated further, and we should also consider any effect of room temperature on load and position readings, especially since thermal overload on the hydraulic fluid pump is what caused the test to end after ≈65,000 cycles instead of the intended 200,000. Nevertheless, the data is so far encouraging and can be improved with a few simple refinements; *i.e.*, tuning the PID parameters and using air ventilation fan in the lab (forgot to turn this on before leaving last Friday 4/20).

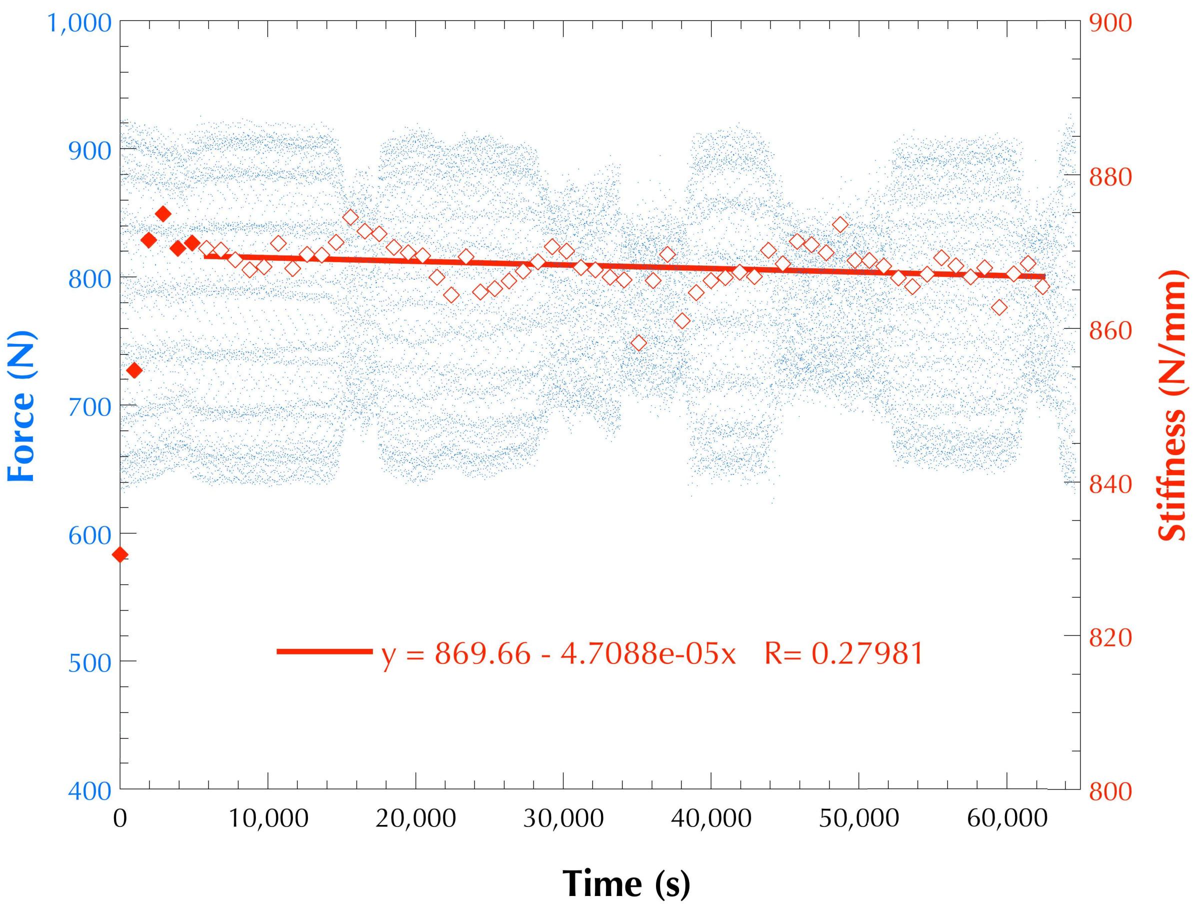


Figure 46: Force vs time graph for Specimen 1 with a linear regression showing a slight decline in stiffness.

SPECIMEN #2

On Friday, April 27, 2018, I loaded a new specimen and ran 60,000 cycles from 100 MPa to 400 MPa at 1.0 Hz. I tuned the proportional gain and integral gain some, using Specimen #1, and the load very consistently cycled between 444 N (100 MPa) and 1,778 N (400 MPa). It will be difficult to achieve a maximum-to-minimum stress ratio of 10 with the specimen dimensions we have. I will discuss this more later.

Data was recorded at 11.011 Hz instead of 102.40 Hz as in the prior specimen, so typically there were 11 data points per cycle from which I can extract a load vs. displacement slope (stiffness) value. I will only produce the final graph (stiffness vs. cycle #) since there are no obvious abnormalities in the load vs. time data. To reduce the number of data points, I sampled data in cycle increments of 10, starting with the first cycle; *i.e.*, 1, 11, 21, ... , 59,991. Before exporting the data, I actually graphed all 60,000 data points in *Mathematica*™, which is pretty good at handling larger data sets, and there is not significant difference with the sampling below.

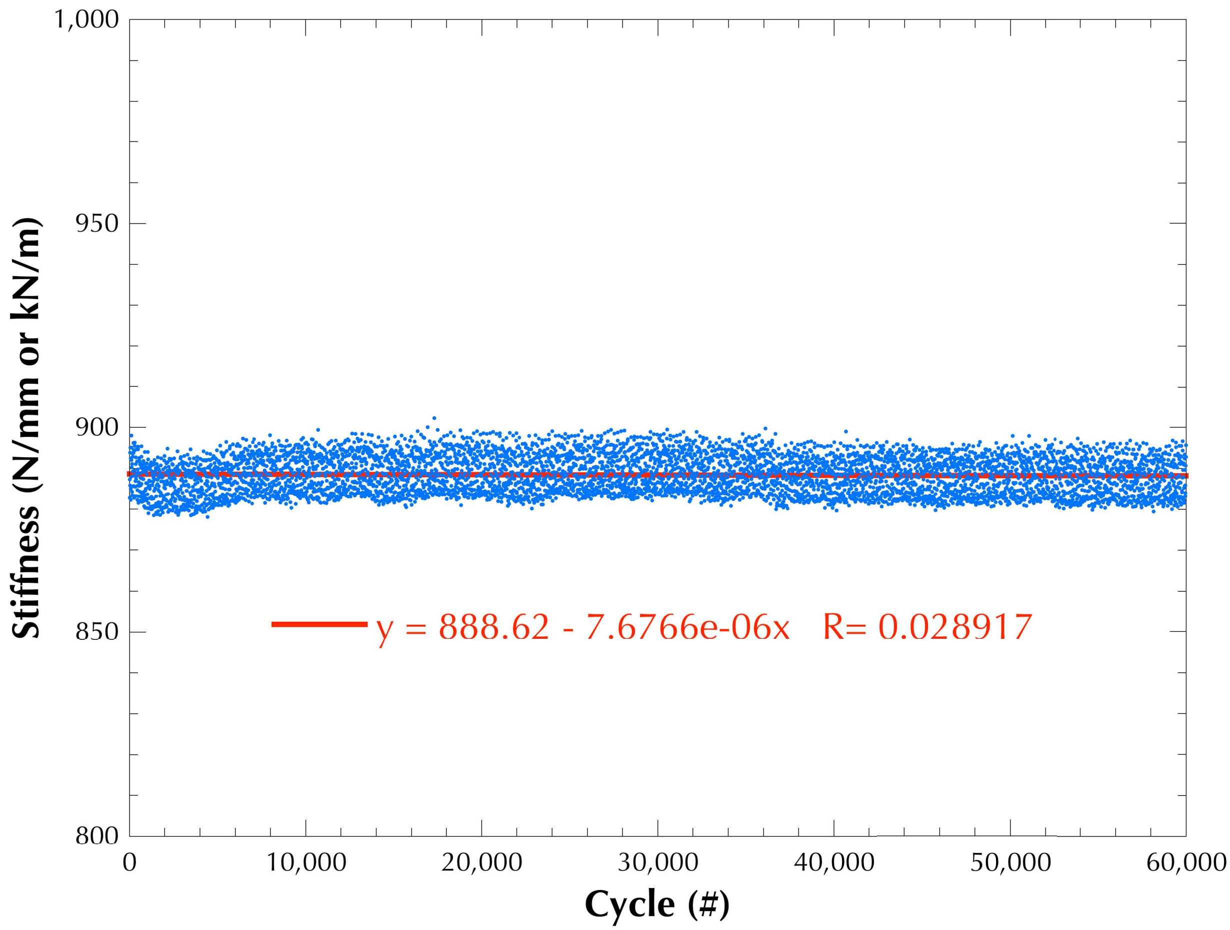


Figure 47: Stiffness vs cycles for Specimen 2 cycled from 100 to 400 MPa at 1 Hz.

There is a practically unnoticeable decline in stiffness, suggesting stresses up to 400 MPa are not inducing much damage in the specimen, at least for the short span of 60,000 cycles. Unfortunately, when I continued the test on Saturday (4/28/18), I overloaded the specimen while playing further with the tuning parameters. While the tuning was good during the above test (P = 30, I = 0.4, D = 0.0), I wanted to obtain a sense of how much leeway we have with these values, and there's not much, because it overshot the command once I set P = 150, which was about 100-200 cycles into the test. The failure was so quick, that I cannot see any data indicative of the load reached at failure. The way the program is set up is that if for any reason during a test the load goes outside the command range by say 10-20% (we can set these limits), the program immediately stops recording data and ends the test. I may put an extra DAQ step in there for future reference. For example, in this test, the command load cycled between 444 N and 1,778 N, and I set the limit range to 300 N and 2,000 N.

Images of the failed specimen are shown below. The upper image is the compressive face, and the lower image is the tensile face. Note that the side with better surface finish was chosen as the tensile face as there appears to be some type of scoring on the compressive face.

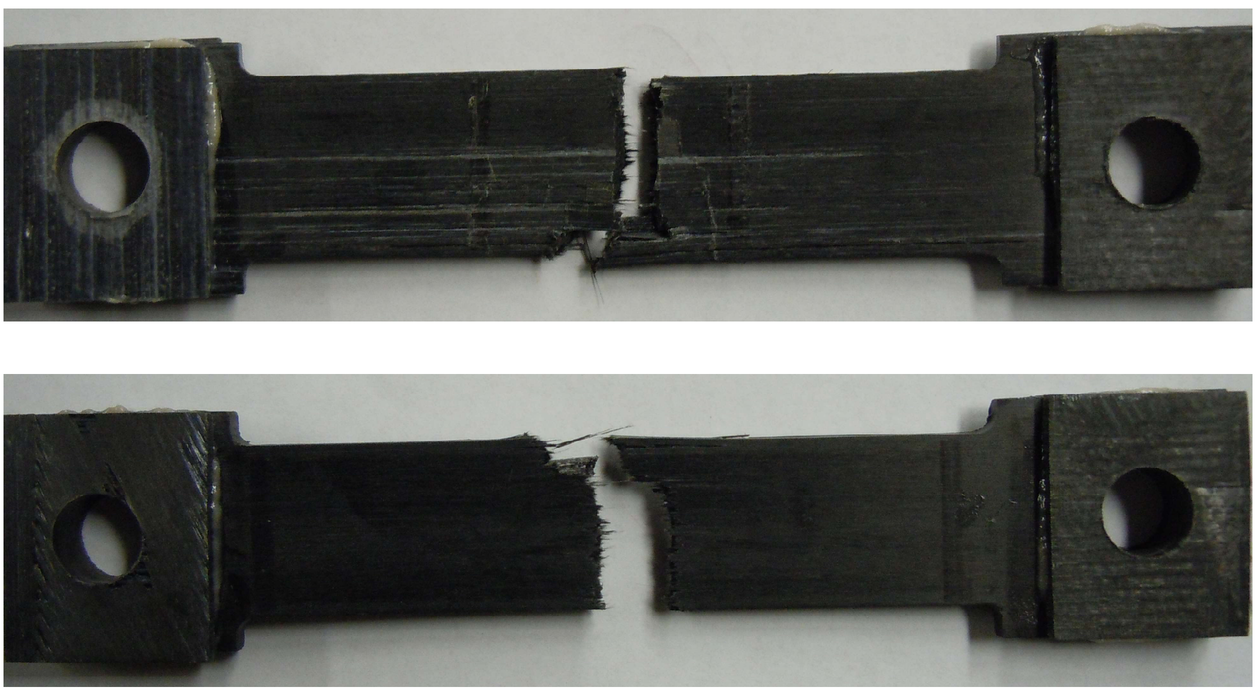


Figure 48: Front and back pictures of the first failed specimen caused by increasing the proportional gain.

SPECIMEN #3

After the failure of Specimen #2 and the idea that a lot of cycles were going to be required to observe significant change at 400 MPa, I decided to cycle Specimen #3 between 100 MPa and 600 MPa, all other conditions being the same. The following stiffness vs. cycle # data was obtained. The specimen failed after 388 cycles and this coincides with about a 20% decline in stiffness relative to the initial value. There was audible damage occurring during the test.

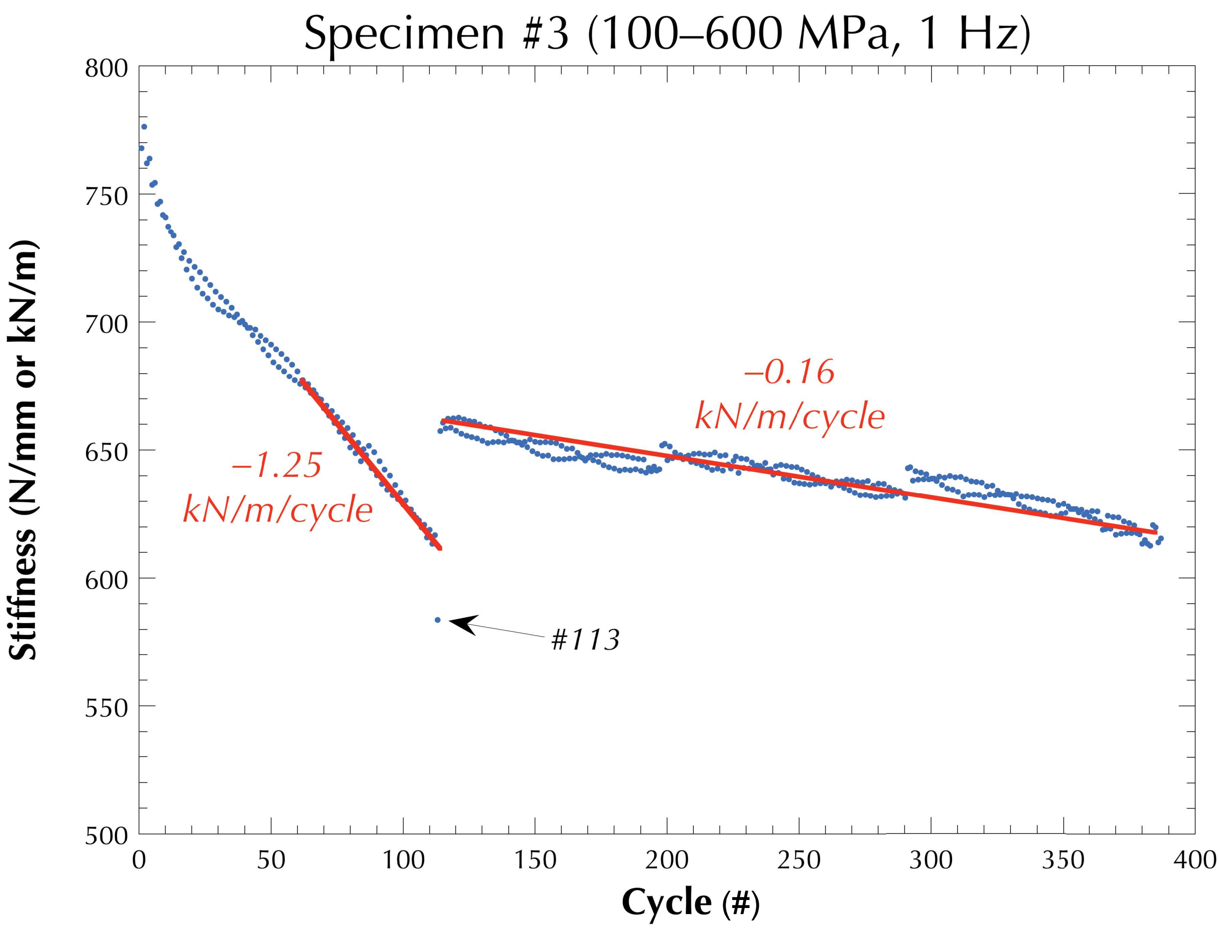


Figure 49: Stiffness vs cycles for Specimen 3 cycled between 100 and 600 MPa at 1 Hz.

Shortly after starting this test, I noticed the flexure of the beam was causing the outer contact rolls to push out by up to ≈3 mm on each side. In other words, the outer span worked it's way up to ≈96 mm from 90 mm during the first 112 cycles of the test, at which point I interrupted the test. I was able to reconfigure the bend jig to eliminate this problem. The images on the following page show the improper (top) and proper configuration (bottom). The fixture has springs that pull the contact rollers up against the stops; however, as can be envisioned from the top image, this may not be sufficient to hold them in position if sufficient downward force is applied to the middle of the beam. The problem is avoided by configuring as shown in the lower figure. For the inner span, the configuration should be as in the top figure (but at a different spacing) since bending of the beam would tend to push the contact cylinders toward the center of the fixture.

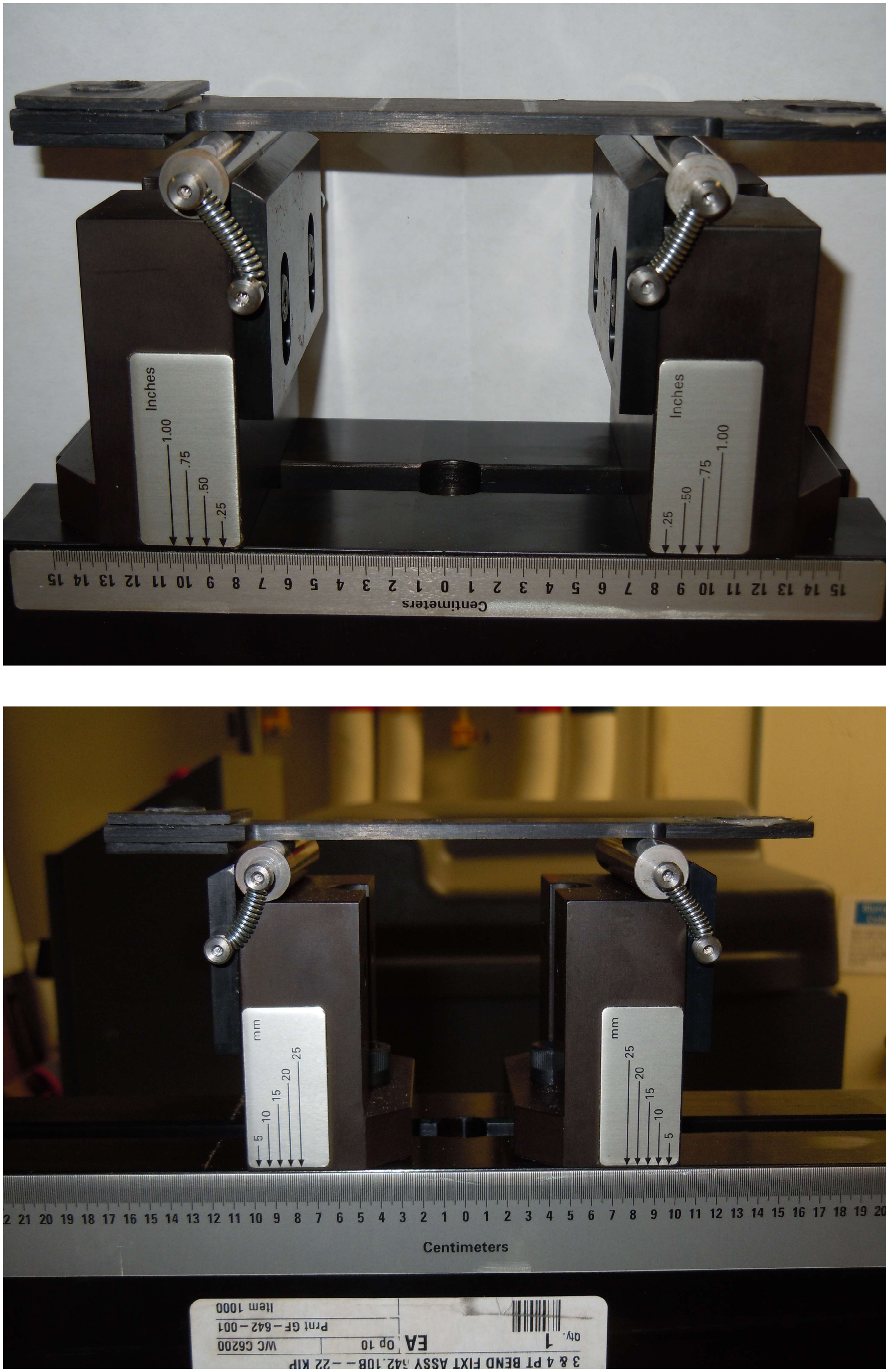


Figure 50: Pictures of the experimental four point bend test setup.

I believe the increase in span is the reason why the stiffness appears to drop more rapidly in the first part of the test compared to the latter. Using the formula for stress on the tensile face of the specimen between the inner span contacts, $\sigma_{max} = 3aP / bd^2$, where a is the spacing between one outer load contact and the nearest inner contact, P is the load, and b and d are the specimen width and thickness, respectively, I estimate the stress to be ≈10% larger; *i.e.*, a increased from 30 mm to ≈33 mm. This appears to be consistent with the discontinuity in data between cycle 112 and cycle 114. It also suggests that 600 MPa is a stress where the fatigue damage rate begins to increase rapidly (*i.e.*, flattening of the *S-N* curve near the UTS), due to the large difference in slope of the above graph before and after this event. Higher stresses in the first part of the test may have also contributed to the short lifespan of this specimen. The slope in the first region is about 8 times that for the latter portion of the test, so we might estimate that the higher stresses were equivalent to 8 times the number of cycles over this period; *i.e.*, 480 cycles instead of 60 cycles. Hence, the life span was shortened by ≈420 cycles, and the true lifespan for cycling from 100 MPa to 600 MPa may be more like 800 cycles instead of 388.

Additionally, when I interrupted the program, the specimen was quasi-statically loaded near 500 MPa for a minute or so until I could get into manual mode with the MTS software and manually lower the actuator ram. This extended static loading may be partially responsible for the short lifespan of this specimen if there is a significant time-dependent component to the stress-strain behavior of these materials. This could further be investigated with fatigue testing at different cycling frequencies.

Compressive (upper) and tensile (lower) faces of the failed specimen are shown below. Again, the surface of better finish was chosen as the tensile face.

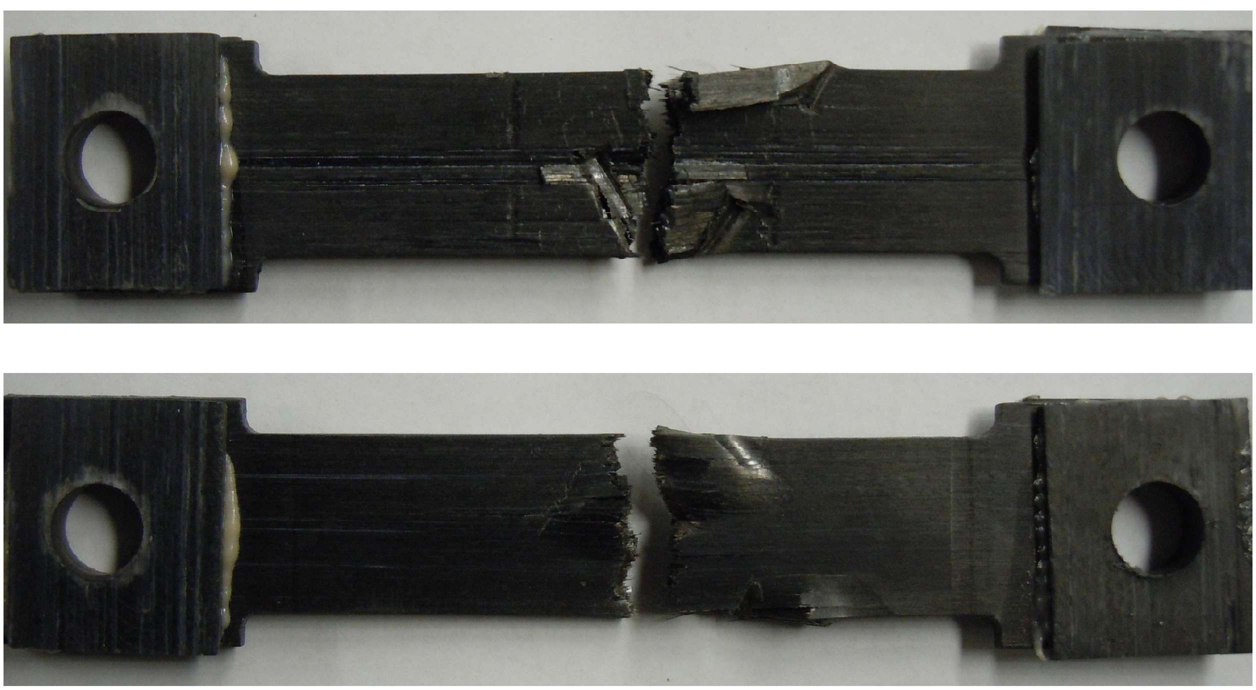


Figure 51: Front and back pictures of the second failed specimen.

The small discontinuities in ≈100 cycle intervals in the stiffness data appear to be an artifact of the data acquisition rate. Data was nominally recorded at 11 Hz; however the software automatically set the value to 11.011 Hz, which probably relates to whatever timing device is used to record the data. For the vast majority of cycles, 11 data points are recorded, but periodically 12 data points are actually recorded within the 1 second cycle interval. In fact, every time 12 data points were recorded, this apparent upshift in stiffness is computed.

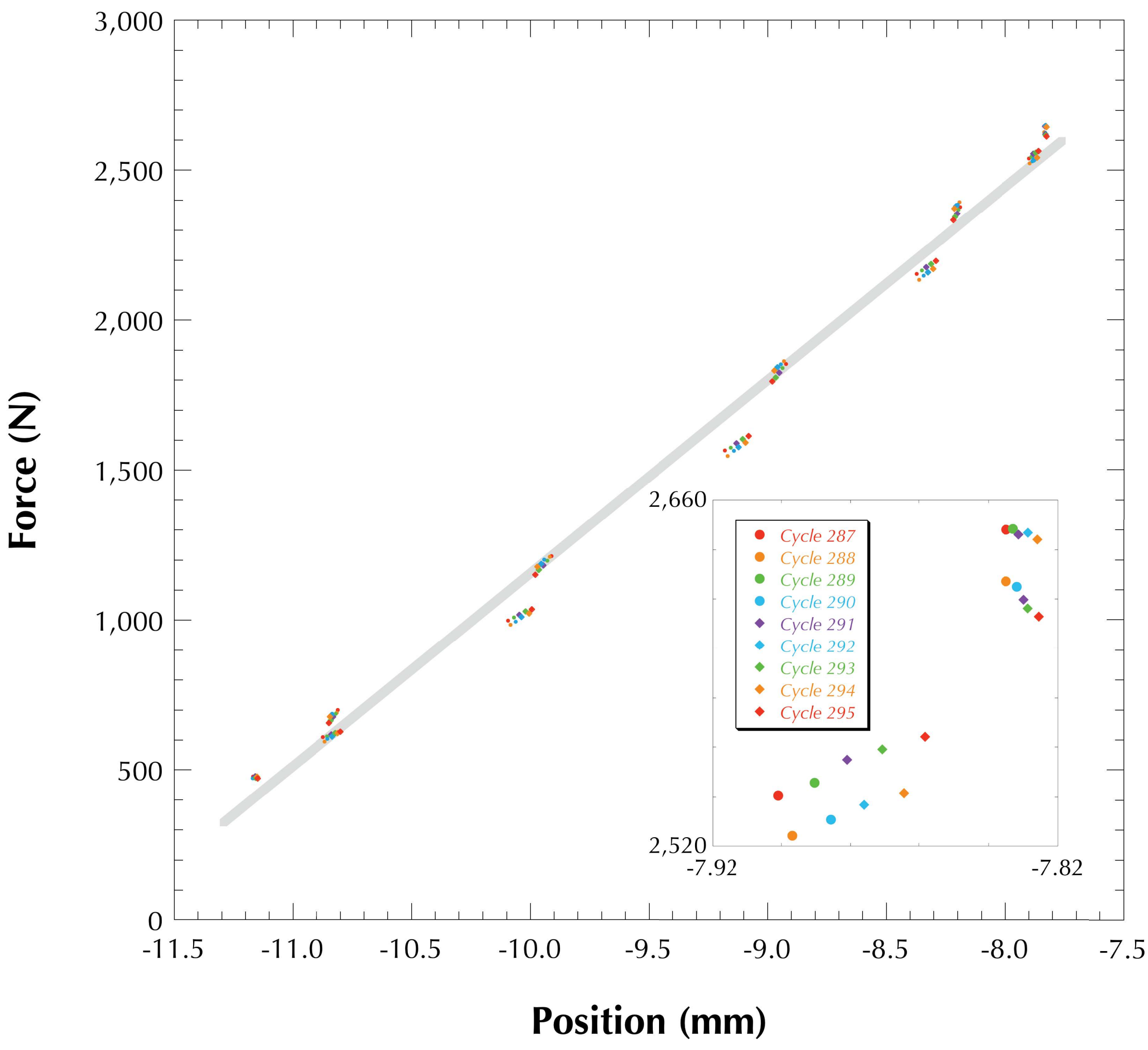


Figure 52: Plot of force vs position for a few cyles of Specimen 3 where the slope indicates stiffness.

In the force versus position graph above, it is apparent there is positive curvature to the data. Aside from the upper rightmost cluster of data points, each of the 11 clusters of data points contains exactly one point from each cycle. In the inset, the two upper rightmost clusters are shown in detail. It can be seen that the upper rightmost cluster has two data points for cycle #291; one of these is the 12th data point associated with this cycle. I believe this extra data point is weighting the linear fit more toward the steeper part of the data at these higher force values, resulting in an apparent increase in stiffness. Graphs similar to that above were obtained for cycles in the vicinity of the other upshifts in stiffness, namely at cycles 87, 198, and 384, each which has 12 data points.

I do not know the reason for the smaller periodic variation in the data occurring every ≈25–30 cycles, but it appears the stiffness alternates from high to low values each cycle, merging back to an intermediate value every 25–30 cycles. This may also be related to the data acquisition rate, or there may be some systematic deviation of the force over time from the ideal sine wave that occurs over periods longer than one cycle. There isn't an immediately obvious trend in the data at this point. If these features persist and are of concern, further consideration of data acquisition rates may be warranted.

FURTHER RECOMMENDATIONS

Since we are operating at such a small fraction of machine and load cell capacity (100,000 N), I am not comfortable cycling to loads lower than about 444 N (100 MPa) during these tests. In fact, the load cell reading does drift somewhat over the course of a day or so, say by ≈200 N. The load cell is zeroed prior to contacting the specimen; however, after the 60,000 cycles on Specimen #2, it read ≈200 N after the test had completed and the specimen was unloaded. It may also drift in the other direction (negative readings), and based on experience, I believe the drift may be attributed to the effect of room temperature on the electronics. Nevertheless, this implies if we were to reduce the load to 222 N (50 MPa), we might not actually have contact with the specimen, and it may shift as a result, causing aberrations in data.

Back to testing Specimen#1.

Table 8: Dated history of Specimen 1 with fatigue cycling data and notes.

SPECIMEN #1 HISTORY

Date	Stress Range (MPa)	Number of Cycles	Frequency (Hz)	Intended Cycles	Notes
4/20/18	150–200	≈65,000	1.0	200,000	Thermal Overload
4/28/18	100–600	≈100	1.0	≈100	after breaking Specimen #2, I was planning on using Specimen #1 as a tuning specimen, anticipating a much longer test with Specimen #3.
4/28/18	100–400	26,873	1.0	165,000	P = 30, I = 0.4, D = 0.0 Thermal Overload
5/4/18	100–400		2.0	500,000	P = 40, I = 0.4, D = 0.0