Design of a Carbon Fiber Frame for Metrofiets Cargo Bikes

by
Sam J. Conklin

A PROJECT

submitted to

Oregon State University

University Honors College

in partial fulfillment of
the requirements for the
degree of

Honors Baccalaureate of Science in Mechanical Engineering
(Honors Scholar)

Presented June 2, 2015
Commencement June 2015

AN ABSTRACT OF THE THESIS OF

Sam J. Conklin for the degree of Honors Baccalaureate of Science in Mechanical Engineering presented on June 2, 2015. Title: Design of a Carbon Fiber Frame for Metrofiets Cargo Bikes .

Abstract approved:

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Nancy Squires PhD

Cargo bikes are increasingly being adopted as an alternative mode of transportation by families and businesses as they are capable of easily transporting 400 pounds of rider and cargo. Metrofiets is a leading manufacturer of hand built cargo bikes in Portland, Oregon and requested a design for a carbon fiber frame to be incorporated on a concept bike. A design was developed utilizing pre-made carbon fiber tubes joined by wet layup of carbon fiber fabric over 3D printed molds. Material testing was completed to characterize the carbon fiber before a test section of the frame was fabricated and subjected to physical testing to validate the strength and stiffness of the design. The test section exhibited exceptional structural integrity and the design suggests a 42% reduction in frame weight. The material cost for the frame is estimated at $1,400. Further testing of joints would be required before a production model is manufactured; however, the results of this preliminary study indicate that a high quality carbon fiber cargo bike can feasibly be fabricated with the selected manufacturing method.

Key Words: Composites, Carbon Fiber, Bicycle, Product Design

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APPROVED:

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Roberto Albertani PhD, Committee Member, representing Mechanical Engineering

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Toni Doolen, Dean, University Honors College

I understand that my project will become part of the permanent collection of Oregon State University, University Honors College. My signature below authorizes release of my project to any reader upon request.

Sam J. Conklin, Author

To my family,

For their endless support of curiosity

Contents

Introduction

Metrofiets is a Portland, Oregon based bicycle company that designs and manufactures bicycles in the Dutch cargo bike style. These bicycles are capable of carrying four hundred pounds of payload and rider weight. They provide a viable transportation alternative to families, merchants or individuals who demand more carrying capacity than is feasible on traditional bicycles. Metrofiets would like to diversify its product line by offering a carbon fiber frame which will be an industry first for cargo bikes.

Carbon fiber has been established as the material of choice for many performance bike frames due to its superior stiffness to weight ratio and the freedom to design non-traditional geometries. Developing a carbon fiber cargo bike will provide riders with a lighter, stiffer, and stronger vehicle capable of efficiently porting cargo.

Figure 1 Metrofiets, The Standard

Bicycle Commuting on the Rise

As congestion in cities increases and individuals and companies become more aware of their carbon footprint, using bicycles as a utilitarian form of transportation is becoming more common. According to Dan Powell, owner of Portland Design Works, one of the most promising and fastest growing sectors of the cycling industry is non-recreational bicycles intended for daily use [1]. This represents a paradigm shift for an industry whose innovations have been primarily driven by achieving small efficiency gains in high end racing bikes for the last 20 years. Copenhagen, Denmark, elected as the first UCI Bike City by the International Cyclist Union (UCI) in 2008 [2], has already adopted this mentality and fifty percent of all citizens working or studying in the city commute by bike every day [3]. The city encourages ridership by maintaining 400 kilometers of bike lanes and offering ample bike storage and services. Copenhagen also boasts a highly successful bike share service that allows users to pick up and drop off rental bicycles at designated locations dispersed throughout the city. In addition to standard, upright bicycles Copenhagen supports a large population of cargo bike riders. Based on sales numbers in 2011, it was estimated that 40,000 cargo bikes are ridden in Copenhagen every day [4]. Further, it is estimated that twenty five percent of families with at least two children own a cargo bike [3]. Bicycles are a way of life in Copenhagen and the culture rides on the infrastructure and bicycle options necessary to support it.

Faced with growing populations, worsening traffic, and excessive carbon emissions, progressive American cities have begun to follow the lead of the Danish capital in order to improve ridership. This has been accomplished by making improvements to the roadways that make cycling safer and more comfortable. For example, the designated green "bike boxes" near intersections (Figure 2 Gree*n Bike Box in Portland, OR [27]*) and the bike lanes located adjacent to parked cars are appearing in San Francisco, New York, and Portland. Both of these traffic control strategies were originally developed and tested in Copenhagen, Denmark.

*Figure 2 Gree*n Bike Box in Portland, OR [27]

The efforts of American cities are making an impact as bicycle commuting has significantly increased in popularity across the country in the last twenty years. The League of American Bicyclists collects data on the numbers of bicycle commuters in cities across America and reported their findings on the percentage of bike commuters per city and the percent increase from 1990 to 2011:

City	Bicycle Commuter Share			Percent increase from 1990 to 2011
	1990	2000	2011	
Austin, TX	0.8%	0.9%	1.9%	142.0%
Boston, MA	0.9%	1.0%	1.7%	98.0%
Denver, CO	0.9%	1.0%	2.4%	183.0%
Lexington, KY	0.3%	0.6%	1.8%	435.0%
Minneapolis, MN	1.6%	1.9%	3.4%	108.0%
Portland, OR	1.2%	1.8%	6.3%	443.0%
San Francisco, CA	1.0%	2.0%	3.4%	258.0%
Washington, D.C.	0.8%	1.2%	3.2%	315.0%

Table 1 The Growth of Bike Commuting [5]

In addition to implementing changes to the infrastructure, San Francisco is further incentivizing bike commuting by offering tax benefits to companies who compensate their employees for riding a bike to work. The minimum employee benefit consists of a monthly $20 stipend intended to be used for bicycle related expenses [6]. The health, financial, and environmental benefits in addition to improved infrastructure and accommodations in the workplace are facilitating a measurable rise in bike commuting across America. Innovative bicycle designs will encourage a car free or car reduced lifestyle.

Cargo Bikes in America

While falling short of the usage in Copenhagen, Denmark, the popularity of cargo bikes has seen an increase in recent years in the United States. With the growth of cargo bike companies in urban areas, and many businesses have been adopting them for daily deliveries. HUB Hopworks Urban Brewery (Figure 3), Old Town Pizza, and Trailhead Coffee Roasters (Figure 4) are just three examples of Oregon companies that have incorporated cargo bikes into their business model. The international shipping companies UPS and FED-Ex have also implemented cargo bikes to make package deliveries in urban areas.

Figure 3 HUB Hopworks Urban Brewery Beer+ Bike, Custom Metrofiets [7]

Figure 4 Trailhead Coffee Roasters, Custom Metrofiets [7]

While most cargo bikes are still imported from European brands, a higher demand for them in the United States has allowed a number of American companies to specialize in the cargo bike market. These companies are small compared to the international corporations that lead the production of traditional frames; however, each company is supported by riders passionate about their product. The most popular front loading cargo bikes available in the United States are compared here.

Bakfiets.nl

Figure 5 Bakfiets.nl Cargo Bike

The Bakfiets brand, meaning Box Bike in Dutch, is the most popular cargo bike in the Netherlands and is common in the United States as well. The Bakfiets are specifically marketed to families looking to transport multiple children. Each box is fitted with fold down bench seats and seat belts. In the US, Bakfiets are available for $3,500 in three different sizes capable of carrying two to four children. The Bakfiets is a sturdy frame, weighing 90 pounds fully built with a wood box. To allow bike sharing, it is designed to fit a wide variety of riders between heights of 5' and 6'4". The extreme frame weight and upright position makes the Bakfiets a very poor hill climber which is a problem for many cities with steeper terrain than The Netherlands. The Bakfiets is designed for slow moving, stable trips with lots of cargo.

Larry vs Harry, Bullitt Bike

In contrast to the more casually paced Bakfiets, the Bullitt, by Larry vs Harry Cycles, is marketed as a fast and sporty cargo option and is extremely popular in the United States as well as Europe. The Copenhagen based company sources Taiwanese manufacturing plants and sells through dealers around the world. A ready to ride frame with Shimano Alfine components costs

$3,300. The optional wood cargo box costs an additional $365 [7]. The Bullitt is constructed with welded aluminum tubes and box beams and utilizes an aluminum honeycomb structure sandwiched between two aluminum sheets to create the front cargo deck. A fully outfitted bike with a cargo box weighs 58 pounds (Bullitt Model 8-speed with Side Panel Kit). It is also capable of hauling 400 pounds including the rider [8]. Reviews of the Bullitt claim that it has a quick, responsive feel but the road vibrations due to the stiff aluminum frame can become tiring after a long ride. The Bullitt also has significant trouble with steering stability making it unwieldy in stop and go traffic, on bumpy terrain, and at high speed. Larry vs Harry offers an aftermarket steering damper marketed to aggressive riders or those carrying large loads. The damper is a pneumatic cylinder linking the fork to the frame.

Cetma Cargo

Cetma Cargo founded in Eugene, Oregon, started as a rack manufacturer and released a line of cargo bikes in 2007. Cetma offers three frame sizes that differ in length and width of the cargo area. The mid-sized option costs $3,900 fully built with a box. Each frame is bi-partable just behind the steering tube which makes them easy to ship and store, a common problem for cargo bikes. The mid-size frame weighs 50 pounds, without the cargo box. According to ride reviews, the Cetma also has a learning curve associated with riding the new geometry. It is a comfortable bike and handles well with practice. Cetma utilizes welded 4130 steel tubing and a steering linkage connected to the bottom of the fork with a spherical bearing. All three models are equipped with a 26 inch rear wheel and a 20 inch front wheel.

Current State of the Metrofiets Cargo Bike

Metrofiets cargo bikes are hand built in Portland and are marketed as artisan built bicycles. Metrofiets was founded in 2007 by Phillip Ross and Jamie Nichols. The current frame design is called The Standard and is offered with a variety of optional accessories including seatbelts in the cargo box, an electric assist drivetrain, and a rain shelter for the cargo box. The frame can also be custom ordered in seven different colors. The base model weighs 68 pounds and costs $3970. It is available for sale online as well as through dealers located across the United States and Canada. In addition, Metrofiets has select distributors in Amsterdam and New Zealand.

A main feature of The Standard is its ability to comfortably fit a range of riders between 4'5" and 6'7". This makes sharing a bike within a family very easy. Another attribute that sets Metrofiets apart is the 24" front wheel. As opposed to the typical 20" wheel used on most cargo bikes, the larger wheel provides more stable handling and rolls over obstacles more easily. This does come at the cost of a longer front boom tube arm which contributes to the frame's flexibility, often a critique of the Metrofiets. This flexibility provides improved comfort in the form of ride compliance but at the cost of pedaling efficiency. The Standard is constructed, almost entirely, from chromoly steel which makes it a heavier frame than the aluminum Bullitt.

In order to assess areas of possible improvement in the current Metrofiets design, a test ride of The Standard was made in both the loaded and unloaded conditions. Following are the observations:

- Difficult to lift and turn around when in a narrow driveway.
- Very intuitive steering and balance, unlike other frames.
- Head tube deflects considerably (1/2" in each direction) when turning.
- Head tube deflects backwards when loaded (1/4") and even more when riding loaded (1").
- Very smooth over rough surfaces.
- Minimal vibration in steering at high speeds or on rough surfaces.
- Bike is compliant laterally which seems to reduce efficiency.
- Takes significantly more energy than a traditional bike, even when unloaded.

The test ride was helpful for understanding what parameters were significant in the design of a new frame and what areas could use improvement. The Standard is a constant work in progress and improvements are always being made to the design.

When designing The Standard, two important factors were safety and longevity. Jamie Nichols wanted to design a bike that would last 100 years and subsequently designed parts with significant factors of safety to avoid fatigue failure. So far, Nichols has been successful and has not had any bikes come back that have failed prematurely. Beyond normal wear and tear, another unfortunate reality of bicycle riding are collisions with automobiles and damaged frames have been returned to Metrofiets for insurance and safety assessments. No riders have been seriously injured in crashes involving cars while riding a Metrofiets and Nichols attributes that to a number of safety features including:

- Bend in steering rod that acts as a crumple zone in the case of a front wheel impact. This limits the force that can be translated to the handlebars.
- Cargo box can detach from the frame to protect rider and cargo in the case of a side impact.
- The upright riding position makes riders more aware and visible.

Not all the features and functionality of The Standard were achieved in the first frame Nichols built. The frame was designed based on intuition and improved with trial and error of multiple test frames before the first Metrofiets was sold. One major problem in early models was the excessive flexibility of the frame and the handling problems this induced. The first attempt to fix this was to apply a laser cut rib welded to the bottom of the boom tube. This helped the vertical rigidity but the torsional and horizontal rigidity was still too low. The final solution, present on the frames today, was the addition of boom tube staples that make up the three bar section underneath the cargo box. This improved stiffness and provided a large platform to mount the cargo box and kickstand.

The steering linkage was another system that required multiple iterations. Nichols recognized that it was important for the steering rod to flex with the frame to keep the relative lengths of the frame and steering rod equal as they flexed while riding. This required the steering link to be attached with a rigid bushing to constrain non-steering related rotation. Significant effort went into the development of this connection and a self-lubricating, repair friendly solution was achieved which sets The Standard apart from other cargo bikes.

Manufacturing The Standard

Nearly all of the components on The Standard are custom made, either in house or at Portland fabrication shops.   provides names, material, and manufacturing steps involved for the major frame pieces.

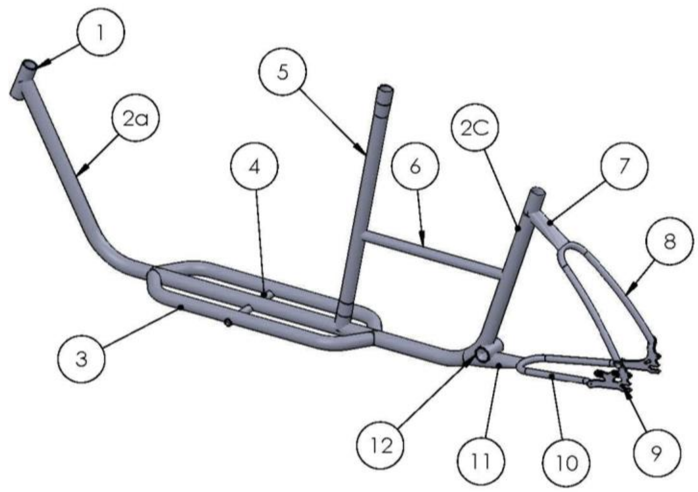


Figure 6 The Standard by Metrofiets

Part #	Name	Material	Manufacturing Operation
1	Head Tube	1.50” 4130 Tube	Ends turned on lathe
2	Boom Tube	1.50” 4130 Tube	Machine bent, single piece
2a	Front Boom Tube Arm	“ “	Laser cut miter to head tube
2b	Boom Tube Pierce	“ “	Drilled vertical hole for steering shaft
2c	Seat Tube	“ “	End turned on lathe
3	Boom Tube Staple	1.50” 4130 Tube	Machine bent, laser cut miters
4	Kick Stand Tube	0.75” 4130 Tube	Laser cut miters
5	Steering Tube	1.38” 4130 Tube	End turned on lathe, laser cut miter
6	Top Tube	1.00” 4130 Tube	Laser cut miters
7	Seat Stay Bracket	1.50” 4130 Tube	Hand forged tube, annealed
8	Seat Stay	0.63” 4130 Tube	Hand bent
9	Rear Dropouts	0.25” 4130 Plate	Laser cut, tabs bent
10	Chain Stay	0.63” 4130 Tube	Hand bent, threaded plugs welded in ends
11	Chain Stay Bracket	1.50” 4130 Tube	Hand forged tube, annealed
12	Bottom Bracket	1.63” 4130 Tube	Ends turned on lathe

Table 2 The Standard materials and manufacturing

Design Requirements

Each year, the International Cargo Bike Festival is held in Copenhagen, Denmark. This is an event where cargo bike companies from around the world release new products and trends for the upcoming years are established. Metrofiets intends to build a carbon fiber concept bike and unveil it at a future show. No other cargo bike companies offer a carbon fiber frame and a successful build would draw significant attention at the festival. This would highlight the hand built craftsmanship and innovation that is at the core of Metrofiets' mission. In the case that a marketable design and sufficient interest is generated, a carbon fiber frame could be added to the Metrofiets product line at low production levels.

To guide the design of the special edition Metrofiets cargo bike, parameters were established based on positive and negative characteristics of The Standard as well as special requirements associated with designing a striking show bike. These parameters can be divided into three categories: marketing appeal, frame weight and ride feel.

Marketing

Marketing is a significant factor in the design of this bike as there is a high probability that initially only one will be made and its sole purpose will be for advertising. In order for this bike to be an effective marketing tool, it must attract attention and remain consistent with the Metrofiets brand. Carbon fiber is the primary direction the cycling industry is moving toward and represents an expectation of high performance. Using carbon fiber as the primary frame material is a strong desire of Metrofiets.

It is critical that the finished design represents an aesthetically pleasing form that stands out from competitors and is recognizable as a Metrofiets product. The Standard has a stylized form reminiscent of frames built in the 1930's and 40's that should be maintained. This Art Nouveau style is typified by smooth lines of organic nature which can be seen in the curvature of the steering rod, the rising upper edge of the cargo box, and the bulging silhouette of the seat stays. Additionally, careful attention must be paid to the surface finish and craftsmanship of the final product. This may dictate the selection of certain manufacturing methods based on the desired visual aesthetic. Beyond the bikes appearance, it is also critical that the bicycle delivers tangible improvements in frame weight and ride quality while providing the same load carrying functionality as The Standard.

Frame Weight

The frame weight of The Standard, without any accessories or components is 27 pounds. The significant weight of the fully built bike (68 pounds) makes it difficult for many customers to move the bike in storage or lifting situations. The increased weight also affects efficiency as it requires more force to accelerate and climb hills. The goal was set at reducing the frame weight to a maximum of 18 pounds which would represent a 33% decrease in frame weight. Additional weight savings could be made by redesigning other parts of the bike such as the wood cargo box (10 pounds), however, the scope of this project was limited to frame design.

Ride Feel

The rider experience on a bike is difficult to quantify as it encompasses qualities such as body position, handling at various speeds, and response to road bumps. These behaviors are affected by a variety of design decisions ranging from component selection to frame stiffness and frame geometry. In order to maintain the range of rider sizes and rider positions of The Standard, the frame geometry will be kept the same. This entails:

- Head Tube Angle: 70°
- Steering Tube Angle: 81°
- Seat Tube Angle: 73°
- Bottom Bracket Drop: 1.75” (vertical distance below rear axle)
- Wheel Base: 80.9”
- Rear Wheel 26”
- Front Wheel: 24”

By keeping the frame geometry and rider contact points unchanged, many of the problems associated with designing a nontraditional bike frame will be avoided.

Steering

Stability and handling is a common problem for cargo bikes as the steering linkage and head tube angle must be well tuned. The Standard has an advanced steering system that remains stable at all load levels and speeds, making a change in this area undesirable. The existing design runs the steering shaft (inside the steering tube) through a transverse hole in the boom tube. This hole, referred to as the boom tube pierce, is located near the middle of the frame. This is a point of high loading in the frame which could cause a significant stress concentration. Care must be taken to design a suitable support in this area to maintain stiffness and structural integrity.

Stiffness

Frame stiffness makes a significant contribution to ride feel and efficiency. A rigid frame allows maximum transfer of energy from the rider to the rear wheel but also makes for a much rougher ride by transmitting road vibrations directly to the rider without any compliance. A balance of the these factors can be achieved by applying stiffness in designed locations with the end goal being a ride feel and efficiency that match the bike’s intended use. The Standard provides a compliant ride that has been viewed as overly flexible to some riders. In the carbon fiber frame, a frame stiffness increase of 10% is desired.

In a document released by Cervélo focusing on frame stiffness and industry standards, Will Chan, a Cervélo composites engineer identifies the three primary stiffness modes that affect rider experience as: torsional stiffness, bottom bracket stiffness, and vertical stiffness [9].

Torsional Stiffness

Torsional stiffness primarily contributes to ride quality by affecting responsiveness through turns. In any cornering scenario lateral forces are generated on the front wheel contact patch when the handlebars are turned. This is an active process requiring constant correction throughout a turn. The rider counteracts this imbalance by leaning over into the turn and force is transferred through the handlebars, seat, and the rear wheel contact patch. This mode of torsion is especially significant for the Dutch style cargo bikes because the distance between the front and rear wheels allows more torsional deflection. This propagates a lag in turning response and a noticeable lateral deflection of the head tube when making quick turns on the Metrofiets Standard.

Bottom Bracket Stiffness

Bottom bracket stiffness is at the root of pedaling efficiency as it measures the stiffness between the load applied to the pedals and the resisting force at the rear wheel contact patch. Energy absorbed by deflecting frame material is directly deducted from the energy intended to propel the rider forward. In the most common high power output situation, the rider assumes a standing position and leans the bicycle away from the down stroke pedal. This typically creates a bending moment about the axis of the seat tube due to the lateral load applied at the bottom bracket and the supporting reactions at each of the tire contact patches.

Vertical Stiffness

Vertical stiffness is most closely associated with ride comfort as this is the mode that road vibrations are transmitted. The mass of the rider being applied at the seat, pedals, and handlebars is acting directly against the perturbations of the road through the wheel contact patches. A common critique of carbon fiber frames is the associated “road buzz” due to the increased stiffness over traditional metal frames. Steel is widely accepted as the smoothest riding material followed by titanium, aluminum, and finally carbon fiber. Bicycle designs compensate for this by reducing stiffness of the seat stays and occasionally design curves into the stays to act as a spring. Vertical stiffness is of extra importance to cargo bikes due to the high loads that must be carried. If stiffness is too low, the load will deflect the frame considerably and can develop a resonance with the pedal strokes. If stiffness is too high, large irregularities in the road surface, such as a pothole, could transmit potentially damaging forces to the frame.

Strength and Government Standards

Unlike stiffness, the strength of a frame has no effect on ride quality and only defines the maximum load capabilities of the frame. The increased weight capacity and extended geometry of a cargo bike increase the maximum forces experienced, making strength a critical consideration. Observed frame failures of cargo bikes include failed welds at the head tube/boom tube joint following a front wheel impact and failure at the boom tube pierce.

The forces of concern are induced by the pedaling action of the rider and the response of the rider and cargo mass to accelerations. The pedaling of the rider induces a downward force on the pedals at a distance out from the centerline of the bicycle. The distance between the feet is referred to as the Q factor and is measured as the distance between the connection points of the pedals to the cranks. This moment about the bicycle centerline is counteracted by the rider at the seat and the handlebars. In the extreme case, it is assumed that the rider is in the standing, sprinting position which removes the reaction force at the seat. The force applied to the pedals is subsequently translated through the drive chain and resisted at the tire contact patch. This creates tension in the chain which must be counteracted by the chain stays. Cervélo was able to determine the average pedaling force versus the crank position for a full revolution using strain gauges on an instrumented road bike.

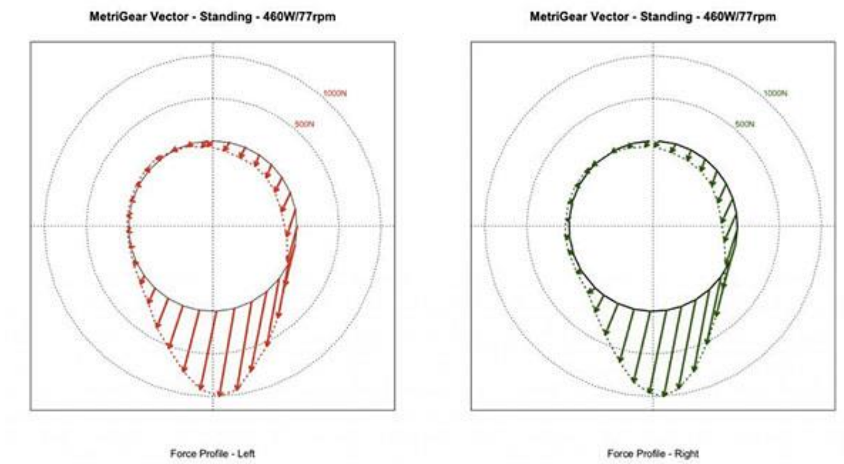


Figure 7 Load Application vs. Pedal Position [9]

The Consumer Product Safety Commission (CPSC 1512) [10] , along with the American Society for Testing and Standards (ASTM F2868) [11], has developed standards that govern the design of all bicycles sold in the United States. Section 1512.8 applies to the drivetrain and mandates that the tensile strength of the drive chain must withstand at least 1,800 pounds force of tension. This can be assumed as the maximum force transmitted through the drivetrain.

While pedaling is a nearly constant force and a source of fatigue, it is typically not the highest load contributor. Greater forces are seen during deceleration (braking and front impact) and vertical drops. To regulate this, the CPSC has developed tests to validate fork strength and frame strength in these situations:

- CPSC 1512.6 (b) mandates that handlebars must withstand a 450lbf load, applied in line with the primary axis of the bike at a 45^{o} angle below horizontal (see Figure 8).

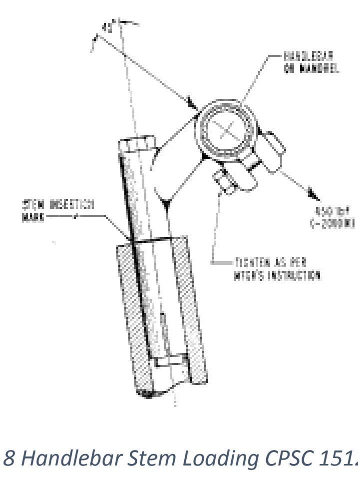


Figure 8 Handlebar Stem Loading CPSC 1512.6(b)

- CPSC 1512.14 tests the fork and frame assembly by placing the bike vertically, fixing the rear axle and dropping a mass on the front axle. The frame and fork must absorb 350in-lb of energy without taking on a permanent deflection greater than 1.57in.

- While these standards provide a good basis for design, the maximum loads associated with cargo bikes are difficult to predict and are not equivalent to loads experienced by traditional frames. Recognizing the uncertainty, it was decided that designing a frame with equivalent strength to the steel frame of The Standard would be the safest option. Each designed frame section must demonstrate equivalent strength to the corresponding steel members.

Design Requirements Summary

- Equal or greater strength than the steel frame
- 10% increase in frame stiffness
- 30% reduction in frame weight
- Maintain the Metrofiets aesthetic

Exploration of Manufacturing Methods

In the carbon bike industry, a variety of techniques have been developed and each company touts the benefits of their individual process. Typically, high production bikes are made with pre-preg carbon fiber (carbon fabric impregnated with uncured epoxy) in steel molds.

Trek

When building the carbon fiber trek Madone, Trek stacks sheets of unidirectional carbon fiber before cutting them out with a CNC ply cutter. These stacks are anywhere between three and forty plies depending on the final location and each ply is oriented to place the fibers in the appropriate direction. The collection of cutouts, known as a kit, is then pressed into two open halves of a steel mold. Finally, before the mold is closed an inflation bag is placed in the hollow interior to apply pressure to the carbon while the part is curing in an oven. Rather than laying up the whole frame at once, Trek fabricates various sections of the frame and uses a mixture of epoxy and .004in glass beads in a secondary bonding process (bonding after parts are cured). To improve the bond strength, Trek developed the *Step Joint Technology*, where each joint is molded with steps at three different thicknesses to generate a more even distribution of load through the thickness of the joint. The assembled frame is then placed in a jig and subjected to a second oven cure cycle [12].

Felt

Felt Bicycles uses two main manufacturing processes to fabricate their frames, Modular Monocoque and Dynamic Monocoque. In the Modular Monocoque process Felt lays up sheets of unidirectional pre-preg and cures the entire front triangle in a single, two part mold before inserting the rear stays. A full global ply of carbon is then applied to the frame and co-molded to create a more continuous final layer. The Dynamic Monocoque technique which is Felt's latest advancement is similar to Trek's method in which smaller sections of the frame are constructed and then bonded together. This allows improved placement of the inflation bladders to minimize buildups of epoxy on the interior of the frame. In addition, Felt uses a polyurethane internal mold to evenly distribute the pressure from the bladder and provide a smooth internal finish by eliminating the effects of vacuum bag wrinkling [13].

Colnago Bicycles

Colnago, based in Italy, uses a somewhat different process to construct their frames. Instead of using unidirectional pre-preg and molds to make their tubes, Colnago purchases filament wound tubes and cuts and miters them before assembling into carbon fiber lugs. A portable oven is then dropped over the frame jig to cure the bonds [14].

Calfee Bicycles

Calfee makes a variety of carbon fiber products in addition to their line of bicycles and also offers custom frame sizes. Their bicycle tubes are purchased from ENVE Composites and use dry fiber, rather than pre-preg, to fabricate all their lugs. On the Tetra, a carbon fiber tandem, the tubes are jigged in place and then wrapped with wetted out carbon tow (non-woven carbon strands). The resulting joint is then pressed with a metal die to compress the layers into its final shape and remove excess epoxy [15].

TIME

Located outside Lyon, France, Time bicycles is a small manufacturer that has a very different manufacturing method. Dry carbon tow is woven into braided sleeves with specific weaves and materials. These sleeves are then cut to size and slid over wax molds before being placed in a mold and injected with epoxy in a resin transfer molding process. The frame is then wrapped with a single layer of pre-preg for aesthetic appearance and placed in an oven to cure the epoxy and melt out the recyclable wax [16].

Figure 9 Carbon fiber loom making sleeves at TIME

Design Selection

Based on the requirements established by Metrofiets, a variety of designs using different manufacturing methods were considered. These options were compared using cost, weight, and feasibility and are presented in chronological order.

Pre-preg and Steel Tooling

As it is the most common method employed for making frames, designing a frame using pre-preg carbon and metal tooling was initially considered. This would allow many frames to be built with consistency of quality. It would also be the lowest weight option due to the low fiber volume ratios achievable with pre-preg. Unfortunately this option was ruled out due to the extremely high initial investment. During a factory tour with Steve Maier, President and Founder of Innovative Composites Engineering (ICE) in Hood River, Oregon, Mr. Maier estimated that a full tooling package would cost $280,000 and each frame would cost $2,000 [17]. ICE currently builds frames for Argonaut Cycles based in Portland, Oregon.

Benefits:

- Improved frame quality
- Reduced weight
- Flexibility for producing more complicated frame geometry

Limitations:

- Extremely high startup cost ($280,000)
- Marginal chance of success in first iteration
- Would require a third party manufacturer
- Increased demands for composite design capabilities
- Long lead time before first frame would be ready

Purchased Carbon Tubing and Metal Lugs

Appreciating that a full tooling package fell outside the budget and needs for the project, Steve Maier recommended building a frame with carbon fiber tubes and metal lugs. This would allow Metrofiets to fabricate in house and would be a more economical option than steel tooling and pre-preg carbon.

To determine the feasibility of this design, pre-fabricated carbon fiber tubes were researched to determine weight, stiffness, and strength. Rockwest, based in Salt Lake City, Utah, provides a wide selection of roll wrapped and filament wound tubing available in small quantities. Based on standard tubing sizes, the material properties of the carbon fiber tubes did not permit a direct replacement of steel tubes with carbon tubes of similar diameter. In order to achieve equivalent bending and torsional stiffness, carbon fiber tubes with an outer diameter of 2.125” and a wall thickness of .125” are necessary.

The deficiencies of this design came as a surprise due to the success of other traditional bike frames which use this same construction method. The primary difference lies in the geometry of the frame and how stresses are carried. The triangular nature of traditional bicycle geometry limits the stresses in each member to axial tension and compression, similar to a truss. While some bending moment is induced by out of plane loads, like pedaling and cornering, the tubes are not subjected to significant amounts of torsion. Carbon fiber tubes used on traditional geometry can therefore be designed with fibers running primarily along its length (0°) for tensile and bending stiffness, and around the circumference (90°) for compressive stiffness. To achieve a similar torsional stiffness to the steel tubing, a significant number of off axis plies (typically 30°, 45°, or 60°) need to be included.

Originally, it was considered that sections from The Standard could be used as the steel frame lugs which would result in considerable savings in manufacturing and development time. However, due to the large size of the necessary carbon fiber tubing, metal joints could not be made with the materials or fixtures commonly used by Metrofiets. In addition, it was determined that a cargo frame with carbon fiber tubes and steel lugs would not be received by the cycling community as a significant advancement and would create too little impact as a marketing tool.

Benefits:

- Assembly does not require significant training or experience
- Reduction in labor hours
- Known properties of materials at joints

Limitations:

- Large diameter carbon tubes are required and metal tubing of an equivalent size would be required for joint fabrication
- Low marketing appeal
- Risk of delamination and corrosion affecting bonds over time

Wet Layup of Full Frame

While pre-impregnated carbon and steel tooling is the predominant method used in the carbon fiber industry for performance products, wet layup is an alternative process that allows the creation of complex carbon fiber forms with fewer facility demands. Wet layup is the process of spreading uncured matrix (the binding agent, often epoxy) into fiber reinforcement before placing on a form to cure. This is the process used by surfboard shapers to create a fiberglass shell around a light weight foam or wood core. For small scale and hobbyist applications, wet layup of carbon fiber is typically done with a two part epoxy and a woven fabric. Two part epoxy is beneficial due to its high strength and ability to cure at room temperature without an oven.

A number of hobbyists have created frames using this method and documented their work on the internet. Mark King has fabricated two bikes using wet layup and created detailed tutorials [18]. The first frame was fabricated by wrapping carbon fabric over a shaped foam core. King used a hotwire to cut the foam cores and created individual carbon tubes before assembling them into the complete frame. The second bike was built with fiberglass, negative molds made to form two complete halves of the frame that were later bonded together. While the second frame, using negative molds, had a more uniform surface, the added complexity of bonding the two halves together is not an option for the cargo bike.

Another method utilized by hobbyists looking to minimize cost is to generate compression of plies with tight wraps of electrical tape over the wetted out plies during curing. The tape can be perforated with a needle before application to allow egress of epoxy with the compression. This eliminates the need to purchase a vacuum pump and the associated vacuum bagging materials. This method is similar to a technique used by composite tube manufacturers who wrap the composite tubes with a heat shrink tape before curing [17].

Using the method of wrapping carbon fiber over foam cores permits the creation of irregular shapes that are better designed to carry the anticipated loads. A basic boom tube concept was generated to meet some of the special needs of the cargo bike.

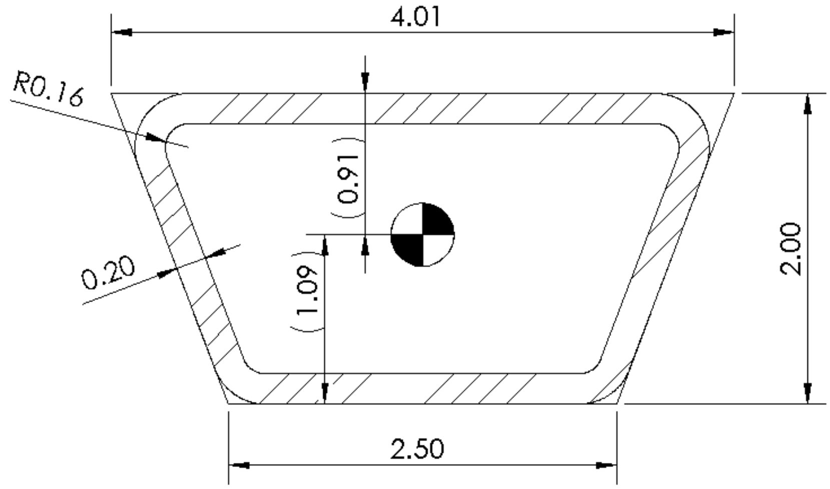


Figure 10 Cross section of angular boom tube concept

This boom tube concept was designed with a flat upper surface to provide a stable mounting face for the cargo box. The asymmetric geometry also reduces the stress in the upper wall of the beam where compression is greatest without dramatically increasing the vertical depth. Uniform carbon fiber tubes subjected to bending consistently fail at the upper most point on the beam due to compression and interlaminar ply buckling. This is partially because a typical carbon fiber reinforced polymer (CFRP) can exhibit maximum compressive failure strength 10% lower than the maximum tensile strength [19]. The maximum compressive stress in the upper surface of this asymmetric beam is approximately 10% lower than the maximum tensile stress carried in the bottom of the beam.

This boom tube cross section was included in a preliminary design of the full frame. This design utilized a combination of wet layup over foam cores and purchased tubing. The premade tubing was specified for the steering tube and top tube. This design retained the overall geometry of The Standard but included a single boom tube concept (Figure 11). It was later determined that a single boom tube of acceptable size and material allocation would not provide sufficient stiffness compared to the steel, triple tube design. A comparison of stiffness values can be found in Table 4 Stiffness comparison of forward boom tube designs.

Additionally, it was determined that the weight benefit associated with replacing the steel rear triangle was not worth the added complexity in design, manufacturing, and safety analysis involved in developing a carbon fiber rear triangle. The rear triangle is an especially critical part of a frame dimensionally and structurally as it supports the drivetrain and rear wheel where many forces are concentrated. It was also recognized that a steel rear triangle would help reduce the road vibration often associated with carbon fiber bikes. This same conclusion was reached when considering designing a new, carbon fiber front fork. Failure of carbon fiber forks plagued the carbon bike movement in its early years and the risk associated with redesigning a composite fork is too high.

Figure 11 Single boom concept frame

A small test section of the boom tube was shaped from foam to determine the feasibility of creating sacrificial foam plugs to be wrapped in carbon. High density insulation foam was selected for its low cost and weight, availability, and shaping characteristics. The core was cut on a table saw and the corners filleted by hand. The edge radii were verified using a 3D printed gauge to ensure a uniform fillet along the length of the beam. The resulting foam core and corner gauge can be seen in Figure 12 and Figure 13.

Figure 12 Foam core for concept boom tube

Figure 13 3D printed gauge for foam boom tube shaping

The shaping of the foam plug went smoothly, however, it was determined that achieving symmetry on more complex sections would be extremely difficult by hand. Additionally, the foam core was easily damaged and retained dents incurred during processing and storage.

These concerns were verified in a meeting with Shawn Small of Ruckus Composites, a custom composites shop in Portland [20]. Various detrimental characteristics of a full wet layup were discussed that altered the direction of the frame design and manufacturing method. The deciding factors that eliminated this design option included:

Benefits:

- Freedom to create unique geometry
- Lower cost than steel tooling and pre-preg
- Inexpensive facility requirements
- Potential for completing manufacturing in-house

Limitations:

- Excessive man-hours required for the labor intensive wet layup process
- Highly variable material properties for entire frame
- Pre-made tubes from a composites company can offer significantly higher specific strength and stiffness compared to wet layup
- Foam cores do not provide dimensional stability throughout the manufacturing process and may sag during layup
- Tape compaction only works on convex surfaces and is difficult on anything more complex than a tube

Based on these drawbacks, the design was revised to reduce manufacturing time, improve final quality, and reduce weight. Certain aspects of the design were maintained and valuable information was acquired in the exploration of this concept.

Combination of Purchased Tubing and Wet Layup

With the information garnered from Ruckus Composites, a final design concept was generated that replaces the long sections of wet layup (boom tube, steering tube, top tube) with pre-made carbon fiber tubing. The rear triangle was kept as the original steel design from The Standard and all connecting joints fabricated with wet layup. Ruckus is experimenting with using 3D printing to generate low weight cores of complicated geometry. Compared to shaping cores by hand or sourcing a CNC to machine cores, the decision to use a personal 3D printer was made to reduce cost and lead time of cores, and permit more flexibility for design changes. Vacuum bagging was also incorporated into the manufacturing process to maximize the surface quality and fiber volume ratio of the wet layup.

Benefits:

- Known material properties in major stress bearing members of the frame
- Reduced manufacturing time
- Improved surface finish
- Maintains Metrofiets aesthetic

Limitations:

- Restricted to commercially available tube sizes unless higher cost custom tubes are ordered
- Material properties of wet layup carbon fiber need to be defined
- Areas of wet layup will still be time consuming and will require validation through testing

Final Design Development

To finalize the design, the following aspects needed to be accounted for and each of these aspects is discussed in detail below.

- Selection of carbon fiber tubes
- Selection of wet layup materials
- Design of laminates at joints
- Integration of steel components
- Design of 3D printed cores.

Selection of Carbon Fiber Tubes

As the purchased carbon fiber tubes represent the largest part of the frame by volume, they have a significant effect on stiffness, weight, and cost, each of which must be accounted for in the selection. As the geometry of the frame is remaining relatively unchanged, each potential tube was evaluated for stiffness by direct comparison to the steel tube, or group of tubes, it will be replacing. Stiffness was assessed based on the necessary pounds per inch of deflection for bending and inch- pounds per degree of rotation for torsion. Equation sets 1 and 2 have been derived to compare stiffness between beams of varying materials and geometry. The majority of composites suppliers are reluctant to release mechanical property data for their products due to liability; however, Rockwest Composites was willing to calculate certain elasticity properties for select tubes. Table 3 shows the stiffness, weight, and cost comparison for each tube with the stiffness normalized to the corresponding steel tube on The Standard.

	Part No.	Normalized Torsional Stiffness	Normalized Bending Stiffness	Length	Linear density (lb/ft)	Weight (lb)	Cost
Boom Tube	35043-A	1.40	1.62	24.7	0.55	1.1	$ 123
Staples	35051	1.40	1.62	35.5	0.20	0.6	$ 82
Steering Tube	35051	0.52	2.49	25.9	0.20	0.4	$ 60
Top Tube	45244	1.15	2.05	17.8	0.18	0.3	$ 37
Head Tube	45202	no data	no data	4.0	0.49	0.2	$ 22
Front Arm	35043-A	1.40	1.62	16.9	0.55	0.8	$ 84

Table 3 Rockwest carbon fiber tubes, stiffness normalized to corresponding steel tube

Special consideration was given to the triple beam section that sits below the cargo box due to the complex geometry and high stiffness needs. As discussed earlier, in regards to the design of the square single boom tube design, it was determined that a single boom tube of reasonable size would not provide enough stiffness. Table 4 presents the results of a study analyzing the stiffness of a variety of boom tube assemblies with varying materials and geometry. Equation sets 3 and 4 in the equations section detail the analysis process used.

	Center Tube	Outer Tubes	Tube Spacing (in)	Normalized Torsional Stiffness (CF/Steel)	Normalized Vertical Stiffness (CF/Steel)	Normalized Horizontal Stiffness (CF/Steel)
The Standard	Steel	Steel	4"	1.00	1.00	1.00
Single Box Beam	Wet layup	No Tube	-	2.12	1.48	0.14
Single 2" CF	35043-A	No Tube	-	0.46	0.54	0.02
1- 2", 2- 1.25"	35043-A	45244	4"	0.60	0.78	0.44
1- 2", 2- 1.5"	35043-A	35051	4"	0.66	0.84	0.39
3- 2" CF (4" spacing)	35043-A	35043-A	4"	1.40	1.62	0.84
3- 2" CF (6" spacing)	35043-A	35043-A	6"	1.41	1.62	1.83
3- 2" CF (4.6" spacing)	35043-A	35043-A	4.6“	1.40	1.62	1.1

Table 4 Stiffness comparison of forward boom tube designs (CF= Carbon Fiber)

Using the steel triple boom tube design as a base line, normalized stiffness results are presented for each potential carbon fiber replacement option. One unexpected finding was that the bending stiffness of the outer tubes and spacing between tubes made very little difference in the torsional stiffness of the assembly. However, the tube spacing did have a significant effect on the horizontal stiffness as can be seen in the last three lines of the table where the tube assembly was kept the same and the spacing was adjusted. A three tube assembly of 2 inch carbon fiber tubes spaced 4.6 inches apart provides the desired stiffness in all directions and was selected for the final design.

Selection of Wet Layup Materials

When designing a composite, a wide range of materials is available that affects the manufacturing process as well as the final product. The selection of fiber reinforcement, laminating epoxy (also referred to as matrix), and vacuum bagging materials is discussed in this section.

Carbon Fiber Reinforcement

Carbon fiber fabric is offered in a variety of thicknesses, weaves, and fiber properties, each of which affect the manufacturing process as well as the properties of the cured laminate (Figure 14). Fiber modulus, the stiffness of the fibers, is an important value in the bicycle industry and is often used as a marketing buzzword. Ultra-high modulus carbon has become synonymous with performance as it can provide high stiffness with a small amount of material. While increased carbon modulus can be very beneficial, all production bikes use a combination of materials and only use the high-modulus fiber in select areas to reinforce other plies. At the recommendation of Ruckus Composites, a single, intermediate modulus carbon fiber was selected to be used for all layers in all joints. With limited composite design and layup experience, a single fabric type was the safest option. The intermediate modulus fibers selected provide an element of safety by providing a greater strength to stiffness ratio, reducing the risk of ultimate failure of an adequately stiff frame. Additionally, the intermediate modulus carbon is less susceptible to impact damage, a very common cause of failure for carbon bikes.

The weave of the fabric is another important trait and three primary options, plain weave, twill, and satin are readily available for purchase. The characteristics affected by the type of weave most important for this application are drape, crimp, wet out, and stability.

- Drape - A fabric's ability to conform to complex curves without bridging or wrinkling.
- Crimp- The amount of distortion experienced by each strand as it goes over and under the perpendicular fibers. Fabrics with reduced crimp exhibit higher material properties in cured composites due to reduced shear stresses induced by the weave as the fibers are put in tension. Crimp is also directly related to surface smoothness.
- Wet out- The ease with which epoxy can be spread into the fabric; tighter weaves are typically more difficult to uniformly saturate.
- Stability- The propensity for cut edges of the fabric to unravel during manufacturing which limits the complexity of ply profiles, finished surface appearance, and care required when wetting out.

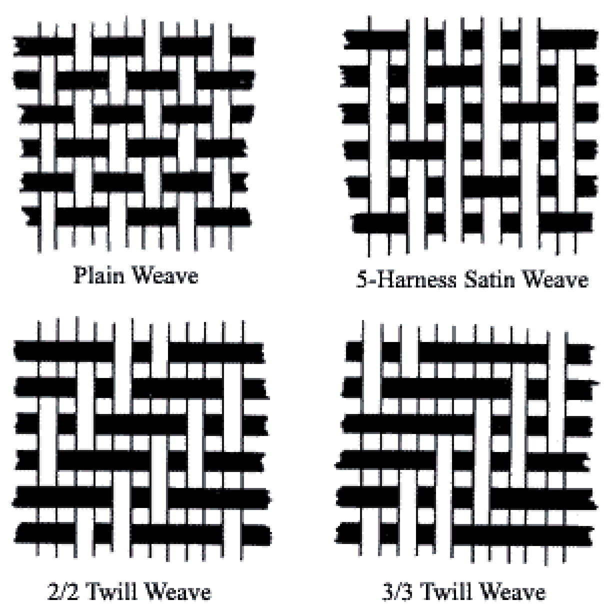


Figure 14 Representations of common weaves used for carbon fiber fabrics

While a satin weave provides superior properties in drape, crimp, and wet out, the joints of the bike will require plies cut to tight radii and the low stability of satin would be detrimental. Instead, a 2 X 2 twill weave was selected as it performs better than plain weave and has improved stability over satin. Additionally, twill has a classic carbon fiber appearance that adds to the final aesthetic.

To determine the appropriate fabric thickness an estimate of the total laminate thickness was calculated and divided by a reasonable number of plies to be completed during layup. It was estimated that laying up ten plies would be practical with the available time and would still allow for reasonably thin plies. The reinforcement selected was a 10.9 Oz/yd^2 fabric with a cured thickness of 0.015 inches.

A suitable 2X2 Twill, 10.9 Oz, 6K, 33Msi Carbon Fiber Fabric was sourced from Fiberlay, a composites supply company located in Portland. Material properties can be found in Appendix E-1.

This material description indicates a variety of critical properties of this product:

- 2X2 Twill – Type of fabric weave.
- 10.9 Oz – Weight of the carbon per square yard.
- 6K – Number of individual carbon filaments per tow. A tow is a group of filaments gathered together and is visible within the weave.
- 33Msi – The tensile modulus of elasticity of the carbon fiber filaments.

Matrix

A two part, room temperature cure epoxy was selected to eliminate the need for a curing oven. Fiberlay ProGlas 1301 is a 4:1 resin to catalyst ratio epoxy with low viscosity and a slow set time. The low viscosity allows maximum removal of air and excess epoxy with wet layup and a vacuum bag. ProGlas is also highly resistant to ultraviolet degradation which is a requirement for any product that will primarily be used outdoors. In addition, this epoxy features 100 percent solids (no VOC's) which reduces the long term exposure risk. Material properties of the epoxy can be found in Appendix E – 3.

Vacuum Bag Materials

After applying the wetted out carbon fiber cloth to the cores, a vacuum bag is placed over the form to apply even pressure to the laminate, removing excess air and epoxy. This vacuum bag is composed of three different fabrics and a sealing tape.

- Vacuum Bag-Creates an airtight membrane over the part which can be evacuated of air. Careful use and construction of vacuum bags can permit multiple uses.
- Breather Fabric- A thick fibrous mat that allows flow of air through the assembly.
- Release Film- A strong, porous fabric that can be peeled off the laminate after curing is complete. This fabric is also referred to as peel ply. Certain release fabrics leave a roughened surface that is designed for improved bonding of subsequent layers. Only one layer of peel ply or release film is used for each curing cycle and cannot be reused.
- Vacuum Sealant Tape- Rolls of highly sticky putty used to seal the edges of the vacuum bag.

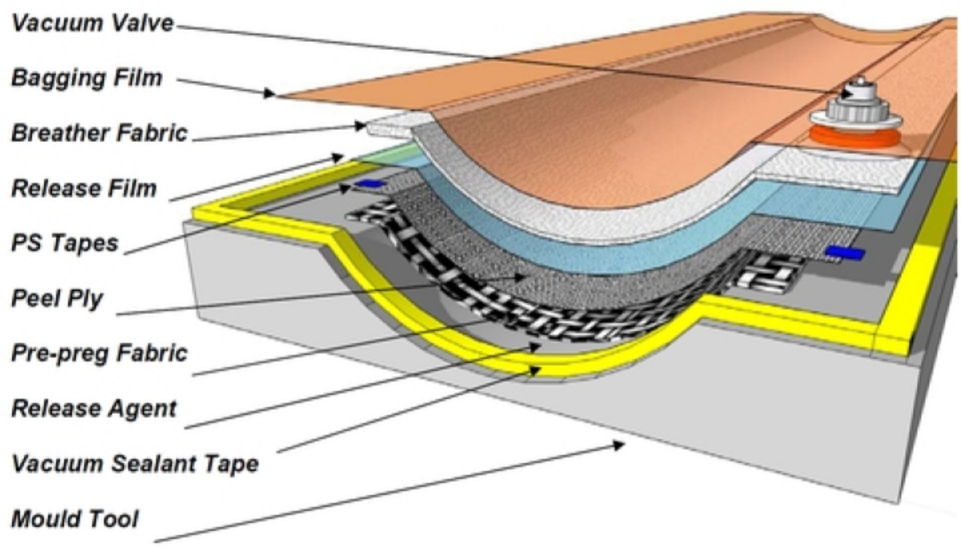


Figure 15 Vacuum bagging diagram [21]

The following materials were selected for the wet layup process and were purchased from Fiberlay.

Product Number	Product	Description	Unit Size	Price
100150010	Epoxy Resin 1301	2 Part, slow curing, low viscosity epoxy resin	1 gal	$ 126.31
100220108	Epoxy Hardener	Catalyst for the epoxy (4:1 ratio)	1 qt	$ 59.65
18040031	Breather Fabric	Allows free travel of resin under vacuum	60" x 1yd	$ 4.43
17210550	Carbon Fiber 10.9 OZ 2X2 Twill	Carbon fabric to bond joints	50" x 1yd	$ 58.75
18010491	Strechlon Film	Elastic vacuum bag	54" x 1yd	$ 4.59
18020011	Econolease	Permeable peel ply, leaves rough finish to minimize prep for next layer	60" x 1yd	$ 9.56
18030021	Sealant Tape	Seals edges of vacuum bag	1/8" x 25ft	$ 9.16
18050182	Release Film	Permeable peel ply, leaves smooth surface for last layer	60" x 1yd	$ 16.82

Table 5 Wet layup materials purchased from Fiberlay

Design of Laminates at Joints

With the fabrication materials selected, appropriate geometric and laminate designs were needed for the joints. This thesis focuses on the design and construction of the frame's tail section where the steel rear triangle meets the carbon tubing. This area was selected for preliminary testing due to the various geometric, bonding, and stress considerations, including:

- High bending moment and torsional loads carried through this section
- Complicated geometry of bottom bracket area requires intricate ply profiles to ensure even dispersion of seams and ply orientations
- Designing for stress risers at transition between steel and carbon
- Ensuring appropriate bonding of composites to steel

The design of the test section required characterization of materials, design of ply layup, and design of the geometric form. Each of these steps is discussed in the following section.

Material Testing

To effectively design the laminate, material properties needed to be determined for a representative composite sample using the same materials and manufacturing methods. Six tests are typically required to determine all material properties used in a complete composite design. Unfortunately, many of these tests require special test fixtures and coupon geometries that were not readily available or feasible. For that reason, only in-plane, uniaxial tension tests were completed on uniform laminates of 0°/90° orientation and ±45° orientation. From these tests, longitudinal modulus, longitudinal maximum tensile strength, and maximum in-plane shear strength were determined. These values allowed benchmarking against composites of similar construction and characteristics from which the remainder of the material properties could be estimated.

0°/90° Tensile Testing

The sample creation and testing procedures defined by ASTM Standard D3039 was followed to evaluate the in-plane tensile properties. This required ten, one inch wide, 3 ply laminate coupons with each ply oriented in the 0°/90° direction. Metal tabs were bonded to the ends of the coupons to reduce the risk of gripping failures. The tabs were adhered using 3M DP-420 Black, two part epoxy. A test procedure was created in the Instron control program, Bluehill 3, to run the test and capture strain data from an extensometer and load data from the load cell on the Instron tensile test frame.

On the first round of tensile samples, steel tabs were used and each of the coupons failed through the composite ¼ inch from the ends of the tabs, simultaneously at both ends. It is likely this failure was due to a stress riser induced by the high stiffness steel tabs and was not representative of the true maximum tensile strength of the fiber. For that reason, a second series of coupons was created using tapered aluminum tabs. This change successfully shifted the failure initiation site towards the middle of each sample and dramatically increased the measured maximum tensile strength. Results from each sample can be found in Appendix B-2 and an example of the tensile coupon can be seen in Figure 16.

Figure 16 3 ply, 0°/90° tensile coupon with aluminum tabs after material failure

±45° Tensile Testing

Maximum shear stress test specimens were made in a similar manner to the 0°/90° tensile test coupons using four layers of alternating ±45° plies. This test followed ASTM D3518. Equation 6.3 from Ishai, Daniel [19] was used to convert the 45° off axis stress to shear stress.

Steel to Carbon Bond Testing

ASTM D1002 was followed to determine the maximum shear strength of the two part bonding epoxy used at all interfaces between steel and carbon fiber. 4130 steel tabs were machined to half thickness at one tab end (to minimize bending moments) and bonded to a two ply, 0°/90° laminate. Specimens were loaded in tension to failure and all specimens successfully failed in bond shear.

Property	Average	Standard Dev.	Sample C.V.
Longitudinal Modulus	10.0 Msi	0.99 Msi	9.85%
Longitudinal Max Stress	89.7 ksi	4.29 ksi	4.79%
Maximum Shear Stress	6.36 ksi	2.07 ksi	32.6%
DP-420 Bond Shear	2.44 ksi	0.34 ksi	13.78%

Table 6 Material testing results of carbon fiber

Shape Design

The rear boom tube joint connects the primary load bearing beam, the boom tube, to the steel rear triangle. To reduce manufacturing time and avoid the need for additional jigs, the steel rear triangle uses the same geometry as The Standard with only small modifications. The manufacturing drawing (Appendix A-1) shows that a short section of the seat tube is welded to the rear triangle to provide a robust connection point. An additional change removes the typical miter cut used for coping the steel chain stay bracket (identified in Figure 17) to the steel boom tube. Leaving this material provides greater surface area for bonding the carbon and core material to the steel.

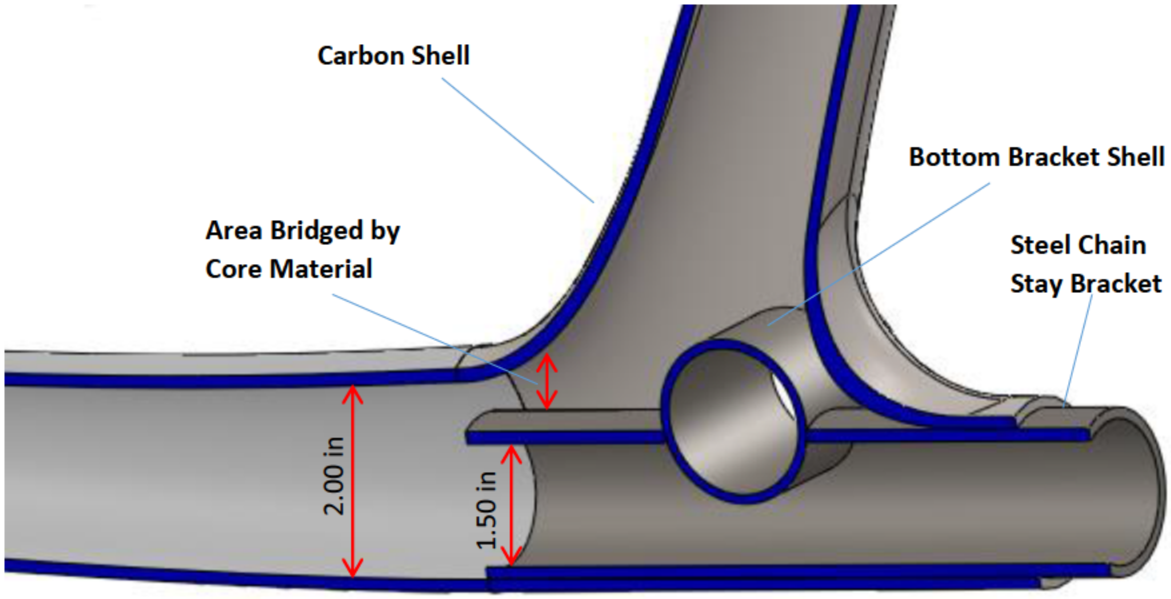


Figure 17 Bottom bracket cross section view

Designing the interface between the carbon fiber and the steel provided a unique challenge. While the specified carbon fiber boom tube available for purchase has an outer diameter of 2 inches, the chain stay bracket is made from 1.5 inch steel tubing. This demands that the carbon fiber joint smoothly transitions between the dissimilar diameters while still providing an adequate cross sectional area for stiffness without an excessively thick laminate. After making initial estimates for carbon fiber laminate properties, it was determined that a round, 1.5 inch diameter cross section at the bottom bracket would not provide sufficient vertical bending stiffness. To counteract this, the profile was elongated vertically to form an oval.

Designing around the minimum cross sectional areas at each point, the remainder of the geometric form was designed to facilitate easy layup of carbon and to promote in-plane transfer of loads through the laminate. Large radius curves worked to fulfill both of these requirements and aligned with the desired aesthetic form. The form was finalized in an iterative process between geometric design and laminate design to establish a compact composite beam that provided necessary torsion and bending stiffness while maintaining a realistic laminate thickness.

Laminate Design

Determining the stacking sequence of carbon fiber plies was the second major part of the design. A variety of methods were explored to analyze laminate properties including freeware computer programs, self-made Engineering Equation Solver (EES) code, Excel programs, and hand calculations. The eSuite composite analysis package developed by ESP Composites runs as a VBA in Microsoft Excel (interactive premade worksheet) and was determined to be the most user friendly and reliable method. When provided with material properties and a detailed layup schedule, this program uses classical laminate plate theory to calculate bulk properties for multidirectional laminates.

The carbon fiber frame is being designed to make at least a 10% improvement in stiffness over the steel frame. Based on beam bending and beam torsion equations, it was determined that the product of the area moment of inertia and the modulus of elasticity can be used to assess stiffness equivalency between beams. These quantities, *EI* and *GJ,* are referred to as flexural rigidity and torsional rigidity, respectively. These rigidity terms can be seen in the basic beam deflection equations listed in Section One of the attached equations.

ESP Composites was used to develop carpet plots which are graphical representations of the bulk laminate properties as a function of the ratios of 0°/90° and ±45°plies (Appendix D-2). Based on the area moments of inertia (*I* and *J)* defined by the tube geometry, a laminate containing 52% plies oriented in the ±45° direction provides the appropriate ratio of bending stiffness and torsional stiffness. Recognizing the limited number of plies that would be used in this laminate, exactly 52% could not be achieved and instead an equal number of plies oriented in each direction were used. A laminate of this type with fabric plies alternating between 0°/90° and ±45° is referred to as a quasi-isotropic laminate as it provides nearly equal material properties in every direction. The significant number of undefined forces acting on the bottom bracket area makes a quasi-isotropic laminate a safe choice. The following laminate was selected for the lower section of the boom tube:

$[(45°F/0°F)_6]$ (F= Fabric, 6= number of repetitions)

This twelve ply laminate will provide ample stiffness and a high quality appearance will be possible with the final ply oriented in the 0° direction. The rigidity terms for vertical, horizontal, and torsional deflection based on this layup are shown in comparison to the steel boom tube rigidity in Table 7.

	Flexural Rigidity Normalized to Steel Boom Tube (CF/Steel)		
	EI_{xx}	EI_{yy}	JG
Steel (base line)	1	1	1
Front (circle)	1.90	1.90	1.79
Rear (oval)	1.59	1.10	1.23

Table 7 Normalized flexural rigidity for carbon fiber boom tube joint

It can be seen that the stiffness is significantly greater at the front of the joint which reflects the increased moment experienced by this section of the frame. This moment gradient in the boom tube was visualized with a finite element model of the steel frame. The model was generated with Femap, a NASTRAN based Finite Element Analysis (FEA) package developed by Siemens that performs stress analysis on complex geometry. The model displayed in Figure 18 represents a 200 pound rider with a 250 pound payload distributed evenly across the floor of the cargo box. The pedaling forces were drawn from the Cervélo pedal force study as visualized in Figure 7.

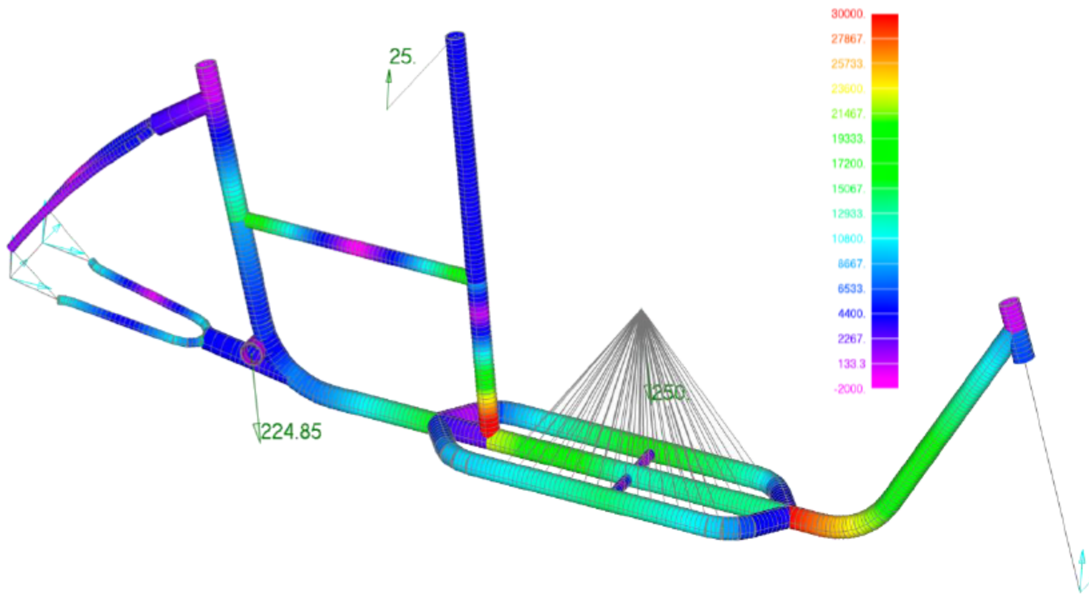


Figure 18 Femap model of The Standard, Maximum Combined Stress

This finite element model is constructed with beam elements and the cargo load is applied with Type 3 rigid bodies (RBE3) to evenly distribute the load. This model was verified by comparing FEA results with hand calculations estimating the stress in the front arm of the boom tube and the reaction forces at the contact points. A global mesh size of 0.25 inches was used for the beam element which falls far beyond the mesh quality convergence point for accurate results. This excessively fine mesh allows refined visualization and probing of information at many locations at a relatively low computational cost. The color map represents the maximum combined stress in each beam segment and the maximum and minimum levels have been scaled for improved visualization. While the loads generated by typical pedaling are relatively low, the proportions of stresses and distribution of loads are still useful and are similar to loads experienced during vertical drops and heavy cornering.

Based on the finite element analysis results, it was determined that the forces carried in the seat tube are significantly lower than those in the boom tube and strictly act in bending, no torsion. With this in mind, the laminate designed for the seat tube was reduced to a 10 ply, quasi-isotropic laminate of the construction:

$$[(45°F/0°F)_5]$$

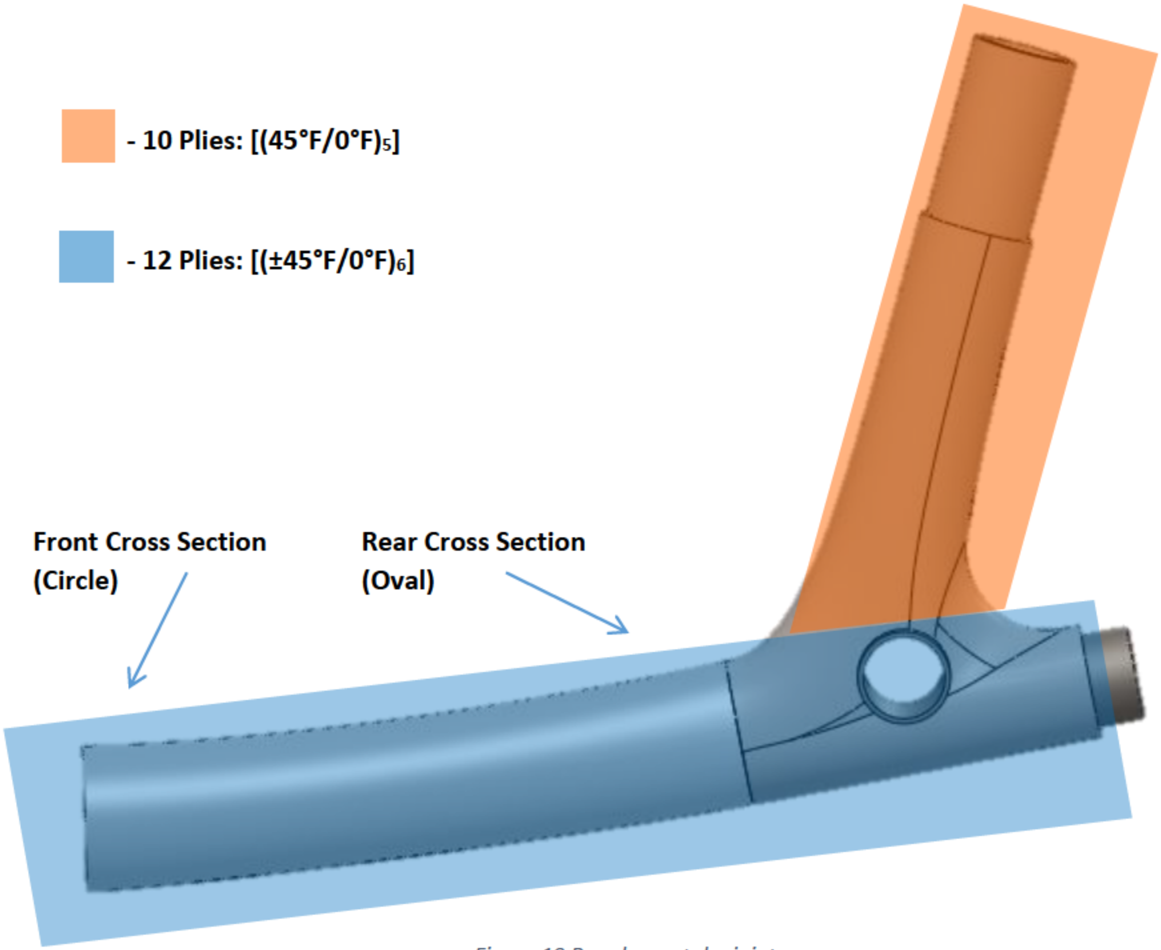


Figure 19 Rear boom tube joint

The initial laminate design was driven by stiffness, however, it must be confirmed that the joint will provide adequate strength as well. To establish the minimum necessary strength for the laminate, the bending and torsion loads necessary to fail a steel boom tube were determined. This was done with beam equations and a maximum stress failure criterion and can be found in Appendix D-3. The response of each carbon fiber section was then analyzed when subjected to the bending and torsion loads and the stress and strain in each individual ply was determined using ESP Composites. Maximum Strain and Tsai-Hill failure criteria were used to determine the factor of safety for each ply. A factor of safety less than one would indicate material failure. The lowest factor of safety out of all plies in the laminate is reported in Table 8 and Table 9 for the front and rear cross sections under each loading case.

Bending Factor of Safety	Max-Strain	Tsai-Hill
Front Cross Section	1.63	1.57
Rear Cross Section	1.55	1.49

Table 8 Bending factor of safety for carbon fiber lower boom tube joint

Torsion Factor of Safety	Max-Strain	Tsai-Hill
Front Cross Section	2.07	2.07
Rear Cross Section (Testing)	0.72	0.72
Rear Cross Section (Book)	2.25	1.22

Table 9 Torsion factor of safety for carbon fiber lower boom tube joint

This method theoretically ensures that the carbon fiber frame has at least equal strength to the steel frame. ESP Composites was used to determine the factors of safety and the equations used to determine max load cases and resultant laminate stresses are found in section 5 of the equations. Additionally, the individual rigidity constants and area moments of inertia for each section can be found in Appendix C-1.

It can be seen that the torsional factor of safety for the rear cross section falls below one. This is due to a discrepancy in the material properties used in the original design. The maximum shear failure strength had to be taken from a similar laminate in Daniel, Ishai [19] due to insufficient test data after the first run of material testing. Material testing was repeated and reliable values were collected.

Design of Connections

Complicated interfaces between different materials and shapes are a common problem in mechanical design. The rear boom tube joint is no exception and makes four key connections with external bodies. These connections are:

- Integration of steel chain stay bracket with carbon fiber boom tube joint
- Forward connection to purchased carbon fiber boom tube (steel test fixture in the case of the test piece)
- Bonding between carbon fiber seat tube and steel seat tube
- Interface between purchased carbon fiber top tube and carbon fiber seat tube

Each of these joints requires special consideration of the local stresses as well as materials. The bottom bracket interface is where the majority of the design time was spent as it envelops two different materials, complex geometry, and high loads. While an aluminum rear triangle was briefly considered for its low weight properties, the rapid oxidation of aluminum is a common source of bond failure. Additionally, aluminum must be chemically etched prior to bonding which introduces a toxic manufacturing step. Steel is a much more stable material that can produce strong, corrosion resistant bonds that will last the lifetime of the bike.

As previously discussed in the shape design section, the rear cross section of the lower tube of the boom tube joint was elongated vertically to provide greater vertical stiffness. This created a discontinuity between the carbon fiber profile and the round 1.5 inch steel tube. To bridge the gap between the elongated beam depth and the steel tube, core material was added directly to the top of the chain stay bracket allowing the vertical depth of the joint to stay at 2 inches for its entire length. This was a heavily deliberated decision as it dramatically reduces the available contact area for direct bonding between the carbon and the steel. It was determined that core material in this area would primarily be put in compression during a vertical loading scenario and bond shear should not be an issue as any load carried through the carbon shell should be resisted by the carbon wrapping around the seat tube. As an additional safety measure, epoxy mixed with glass microbeads was used instead of 3D printed ABS plastic to withstand the potentially greater loads.

To improve surface bonding to the steel, a single ply of carbon fabric was wetted out with ProGlas and wrapped around the bottom bracket and chain stay bracket with a bonding layer of 3M DP-420, two part epoxy before applying the glass filled fairing epoxy. This method of applying DP420 underneath the first layer was used at every interface between carbon fiber and steel. This bridged area is indicated in the cross section in Figure 17 Bottom bracket cross section view above and the physical result is shown in Figure 20 below.

Figure 20 Chain stay bracket with shaped epoxy core next to 3D printed boom tube core

An additional consideration at the bonds between steel and carbon fiber is the potential stress riser that can occur as a result of the dramatic increase in stiffness where the materials are overlapped. To reduce this effect, the steel tube was ground down to a ~5° taper spanning the length of the bonding area. This was completed at all interfaces between carbon and steel. At the bottom bracket interface, additional strengthening of the joint occurred as a byproduct of overlapping the plies from the seat tube and the lower boom tube. Each full layer of the boom tube was completed with only two separate plies and wrapping of the bottom bracket alternated between the seat tube ply and the boom tube ply. This prevented the excessive buildup of plies by alternating the location of the overlap area.

Where the wet layup carbon fiber joints meet the pre purchased tubes will require careful design and craftsmanship as well. Ruckus Composites recommends sanding down the ends of the tubes at a 5° taper, as was done with the steel, and laying up the carbon with successive plies stepping up the length of the taper [20]. In composites repair and manufacturing, this is called a scarf joint [22].

Fabrication

In order to evaluate the feasibility of this manufacturing method as well as the accuracy of the design, a physical test section was built. This piece is as accurate of a representation of the geometric and laminate design detailed above as possible. The steps required to fabricate a section of a carbon fiber frame are discussed below. In all manufacturing steps, the appropriate personal protection equipment is mandatory. This includes, a well ventilated space, dust and vapor masks when appropriate, protection from skin irritants, and protection for eyes and ears. A major factor in the success of composite manufacturing is the cleanliness of the work area and materials. Contaminants such as grease, hand oils, and dust degrade the quality of the bonds and the structural integrity of the final piece. Powder-free latex gloves and a sterile work surface are a requirement for any step involving uncured epoxy or parts that are intended for further lamination.

Fabrication of Steel Triangle

The fabrication of the steel triangle was completed by Metrofiets. The triangle weighed 4.9 pounds and was built with quality craftsmanship, providing substantial rigidity and contribuiting to the Metrofiets aesthetic.

3D Printing of Cores

The plastic cores were printed using ABS plastic on a personal 3D printer. The printer, shown in Figure 21 3D Printer used to generate cores was built from a collection of sourced hardware and premade components and is capable of maintaining print accuracy at a layer height of 0.010 inches. Thorough calibration and a number of printer modifications were required to successfully print thin walled cores with the necessary dimensional stability and surface finish.

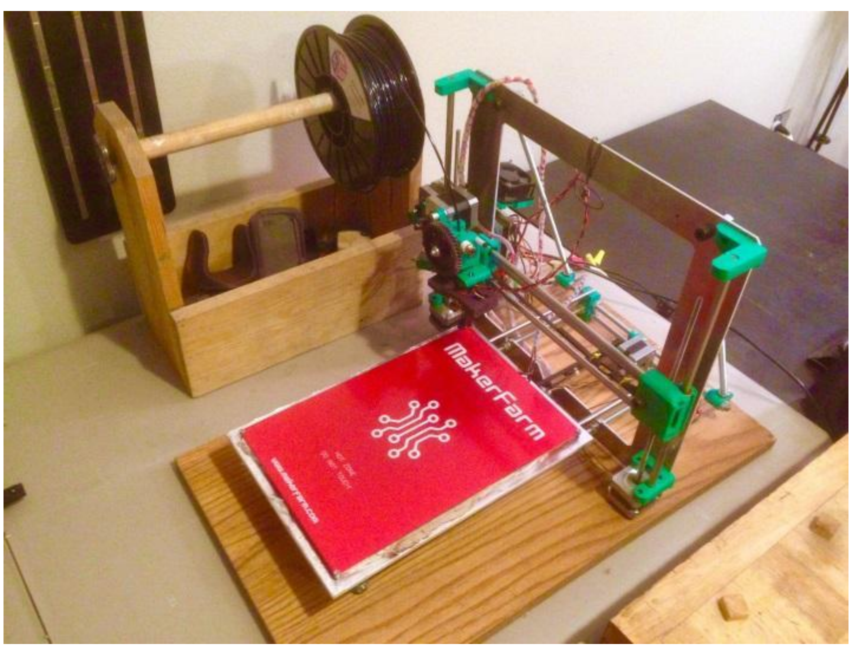


Figure 21 3D Printer used to generate cores

The cores were printed as four inch tall hollow cylinder sections and bonded together with cyanoacrylate (CA). Surface imperfections and discontinuities were smoothed with sand paper. To reduce the weight and material consumption of the core, a low wall thickness was desired. The cores used in fabrication of the test section were printed with 0.085 inch thick walls.

Core Preparation

Once all cores had been printed and the steel mating sections ground down to reduce the stress riser, cores were assembled and prepared for carbon application. In order to provide the strongest possible bond between the carbon fiber and steel, a layer of 3M DP420 bonding epoxy was applied underneath the first ply of carbon. The following steps were taken at all locations where steel met carbon fiber.

- Cut all carbon fiber plies to the required profile.
- Clean the surface using acetone and lint free rags.
- Rough the steel surface with 80 grit sandpaper until entire contact area has been abraded.
- Clean with acetone.
- Apply even coat of DP420 (Figure 22).
- Wet out carbon and apply to the surface (discussed in later steps).
- Vacuum bag (discussed in later steps) and allow a full cure. Use paper towels or similar to fill the ends of the tubes and keep the vacuum bag from being drawn inside.
- Sand off any carbon fiber wrinkles on the cured part.

Figure 22 Even coating of DP420 being applied to chain stay bracket

Figure 23 Chain stay bracket with bonding ply

With the bonding ply adhered to the steel (Figure 23), the fairing around the bottom bracket was created and cores assembled. Figure 24 illustrates the frame jig used to hold all cores in place during the application of the initial plies. A more dimensionally robust frame jig would be required in the production of a full bike. To fabricate the epoxy core around the bottom bracket:

- Adhere core endcap (flat ABS print of the outer cross sectional profile at end of chain stay bracket) to front of chain stay bracket with CA.
- Assemble all cores and tack in place with CA (Figure 24).
- Clean all surfaces with acetone.
- Thoroughly mix the ProGlas laminating resin and hardener in the appropriate 4:1 ratio by volume. Graduated pharmacy syringes work well.
- Mix in glass filler beads until the mixture reaches a consistency similar to peanut butter. Use respiratory protection.

Apply the epoxy mixture to the chain stay bracket, matching the necessary geometry of the upper core and core endcap. Spread mixture into the intersection between the bottom bracket and chain stay bracket and smooth to an even radius. Allow the epoxy to fully cure and sand the fairing down to the final shape as seen in Figure 25.

Figure 24 Cores assembled in the frame jig

Figure 25 Sanded bottom bracket fairing prepared for carbon application

Cutting Plies

The cutting of the carbon fiber plies is a critical step in any complex laminate. Profiles must be determined that will provide complete coverage while maintaining consistent fiber direction and eliminating excessive wrinkling or warping of the fabric. Additionally, the ply seam where edges of plies overlap form weak points in the laminate due to non-continuous fibers. These seams also create areas of extra thickness due to the overlapping material. For these reasons, each layer must take into consideration the location of ply seams in previous layers to disperse the weak areas and maintain a uniform thickness. To achieve this, four seam locations are defined and plies should be cut to rotate through the seam positions. These seam locations are illustrated in Figure 26 Seam locations of plies

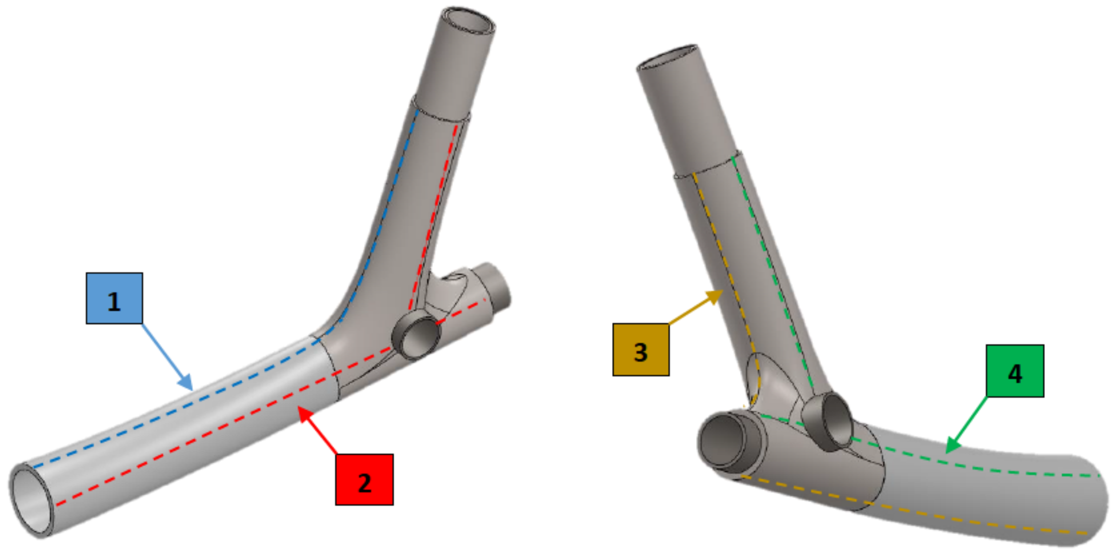


Figure 26 Seam locations of plies

Ply Book for Rear Boom Tube Joint				
Ply #	Orientation	Seat Tube Seam	BB Inclusion	Boom Tube Seam
0	0°	1	←	2
1	45°	3	→	1
2	0°	2	←	3
3	45°	1	→	4
4	0°	4	←	2
5	45°	2	→	1
6	0°	3	←	3
7	45°	4	→	2
8	0°	2	←	4
9	45°	1	→	3
10	0°	No Ply	→	1
11	45°	No Ply	→	2
12	0°	3	←	No Ply
13	0°	No Ply	→	3

Table 10 Carbon Fiber layup sequence and ply cutting guide

Table 10 details the order in which these seam locations were used. The form was also split into two sections, upper and lower, as a single ply could not reasonably be cut to cover all areas. This division formed an additional circumferential seam near the bottom bracket. To alternate the location of this seam and ensure equal load transfer from the bottom bracket to both of the connecting tubes, inclusion of the bottom bracket area alternated between the seat tube ply and the boom tube ply. The "BB (bottom bracket) Inclusion" column of Table 10 indicates whether the bottom bracket area was covered by the seat tube ply or the boom tube ply.

To determine the appropriate shape for each ply, the section to be covered is tightly wrapped in low adhesion painters tape. This skin of tape is then cut along the desired seam lines and the skin removed. Figure 27 shows the frame fully wrapped in painters tape and Figure 28 shows the tape template with seams cut and templates being removed from the frame.

Figure 27 Blue painters tape skin applied to frame

Figure 28 Tape template being removed from part

Darts (small slits perpendicular to the ply edge) are cut in the profile to allow the skin to lay flat. Ply profiles used multiple times are transferred to vacuum bag material as a more robust template. Care must be taken to avoid tight geometry as areas with many cuts are more likely to disintegrate during wet-out and ply application.

Figure 29 Boom Tube, seam location, 3 templates in vacuum bag material and tape

Templates are then oriented on the fabric (0° or 45° degrees) and used to cut out carbon fiber plies (Figure 30). Scissors work well in areas with tight radii and a utility knife easily makes long smooth cuts. Ensure that the work surface has been cleaned with acetone.

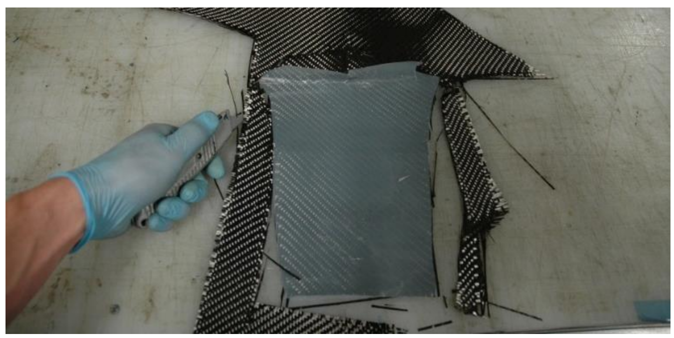


Figure 30 Seat tube ply, seam location 1 being cut out

Wetting Out Plies

Once all necessary plies have been cut, mix an appropriate amount of epoxy. A useful approximation for the necessary epoxy is 0.6 ml of resin and 0.15 ml of catalyst per gram of carbon fiber fabric (intended for 4:1 catalysts). This amount provides some excess epoxy to facilitate wet out and consistently produces a 65% fiber volume (Volume carbon/ Volume epoxy) after vacuum bagging and curing. Once the resin and catalyst have been combined the curing process begins and all layup steps should be completed within 45 minutes.

Figure 31 Measuring resin for wet-out

After thoroughly mixing the epoxy, pour a small puddle onto the carbon fiber ply and spread it with a rubber squeegee (Figure 32). Keeping the squeegee level and very clean avoids snagging on individual tows of carbon and spreading epoxy out from the middle of the ply helps to avoid warping the fabric. Wetting out the ply while it is lying on the template can also ensure that the fabric does not warp drastically. Leaving the carbon on the template also helps when lifting the ply off the table. Additional epoxy can be poured on to the fabric as needed but should not be applied in excess. Use only enough epoxy to evenly wet the fibers and carefully inspect each ply to ensure there are no dry spots.

Figure 32 Wetting out of a carbon fiber ply

Use acetone to clean the part and allow it to dry thoroughly before ply application if any surface contamination could have occurred. Once sufficiently impregnated with epoxy, transfer the ply onto the part and align it carefully. Press the ply onto the part surface and smooth the fabric until an even surface is achieved, fibers are properly oriented, and overlaps are in the desired locations. It is critical to ensure that all concave corners have been given enough material to avoid bridging. Bridging is described in more detail in the Defects section below and is a high risk around the interface corner between the bottom bracket shell and chain stay bracket.

Figure 33 Applying the wetted out ply to the sterile part

After smoothing the ply to the part, vacuum bagging begins by wrapping a layer of peel ply around the entire wetted area. It is important to completely cover all epoxied surfaces as breather material does not easily release from cured epoxy. Small strips of tape can be useful to tack the peel ply to the part but must be used sparingly as it can inhibit the flow of epoxy. As with all other steps, avoid wrinkles and vigilantly check for bridging.

Vacuum Bagging

Next, breather material is applied over the entire part. Wrinkles in this layer will cause ridges of epoxy buildup and any bridging is unacceptable. Once the part has been covered, an eight inch long and three inch thick strip of breather should be taped to the surface near the bottom bracket to provide an air channel from the laminate to the vacuum port.

Figure 34 Breather material applied and ready for the vacuum bag

Once all intermediate fabrics have been fitted and checked for bridging, the vacuum bag can be brought over the part and sealed. For the rear boom tube joint, a vacuum bag was built to go over the entire part including the rear triangle. The vacuum bag was made by sealing together three full widths of vacuum bag side by side and sealing the ends to create one long tube. The same bag was reused for all thirteen plies. It is recommended to construct the vacuum bag before wetting out the plies as it can be a time consuming process.

It is beneficial to create a vacuum bag significantly larger than the part as this provides more material to fit around contours and avoid bridging. Additionally, after each layer the bag must be opened to work on the part. This is done by cutting off the sealant tape from one end of the bag. After many plies this removal of material adds up and can make the bag too small for the final plies of the laminate. The decision to make a bag that fully engulfed the part was made in the wake of an unsuccessful attempt at sealing a vacuum bag directly to the surface of the part at the steel test fixture and around each of the rear triangle stays. This was extremely complicated and did not consistently provide an air tight seal.

One complication of bagging the entire part was the hollow area inside the rear triangle. This volume had to be filled with a foam blank to keep the bag from breaking as it stretched around the stays. Future vacuum bags could be made bigger to avoid this problem. Breather material should also be used to cover any sharp corners and fill the open ends of tubes. The blue foam and breather material plugging the hole on the top of the seat tube can be seen in Figure 35.

Figure 35 Blue foam filler material and cover on top of seat tube to protect the vacuum bag

Once the vacuum bag has been pulled over the part and sealant tape used to close the end, the vacuum hose can be connected to the vacuum port. As the bag is drawing down, vacuum bag material needs to be collected at areas at risk of bridging and wrinkles minimized along the part surface. The vacuum port also needs to be positioned in contact with the short tail of breather material and off the surface of the laminate.

Once the vacuum bag is fully sealed, a vacuum gauge should always be used to determine if there are any leaks in the bag. A vacuum pressure of 24 in-Hg is desired and when the vacuum hose is removed there should be no drop in vacuum pressure and if a leak is detected it must be located and sealed. A leak in the bag reduces the compaction of the plies and can result in interlaminar separation and insufficient epoxy removal. After ten hours under vacuum the epoxy should be sufficiently evacuated and application of the next lamina can begin.

Figure 36 A vacuum gauge should be used to check the bag quality for every ply

Figure 37 Seat tube ply curing under vacuum

The Final Layer

The final layer is extremely important for the finished appearance of the bike and a few tricks can significantly improve its quality. After wetting out the carbon, it can be beneficial to allow the ply to partially cure before applying it to the part. This makes the carbon fabric less likely to fray at the edges and maintain a tight weave but comes at the cost of reduced epoxy removal. The epoxy should still be wet to the touch but highly viscous and two hours of cure time should be sufficient, depending on temperature.

When applying the semi-cured ply, align the seams in hidden locations and keep the edges from fraying. Edges can be carefully cleaned up with scissors immediately before application. For the final carbon layer only, release film should be used instead of peel ply to leave a smooth, resin rich surface. This allows more intensive sanding without damaging fibers. Figure 38 illustrates the application of release film for the final layer. Extensive darting was used to eliminate the risk of bridging and to provide a high quality final surface. All slits were covered with additional pieces of release film.

Figure 38 Release film being applied to the final lamination layer

The final surface is achieved by sanding the epoxy rich layer down to a smooth, even surface. Starting with 100 grit sand paper, knock off any large epoxy ridges and then progress through 150, 220, 340, 400, and 600 grit paper. Wet sanding keeps the sand paper from clogging and reduces the amount of carbon dust. It is important to avoid sanding through the epoxy layer into the carbon fiber as this reduces the strength of the laminate. Always use an appropriate vacuum system and personal protection when sanding or cutting carbon.

Figure 39 Resin rich final ply before sanding

The frame section turned out very well and met the requirement for a high quality finished surface. This test section was not finished with a final clear coat but was achieved with extensive sanding.

Figure 40 Full finished test section

Figure 41 Bottom bracket and boom tube details of finished test section

Defects

Wet layup is a complicated manufacturing method and defects do happen. Careful inspections of the part must be made at all stages of the process to avoid mistakes before they happen and to fix errors before it is too late.

Wrinkles in the cured fabric can be avoided with appropriate vacuum bagging practices but do occur. These carbon ridges need to be sanded off and brought back level with the surrounding surface. This is not preferable and sanding should be kept to a minimum to maintain maximum fiber length and ply integrity.

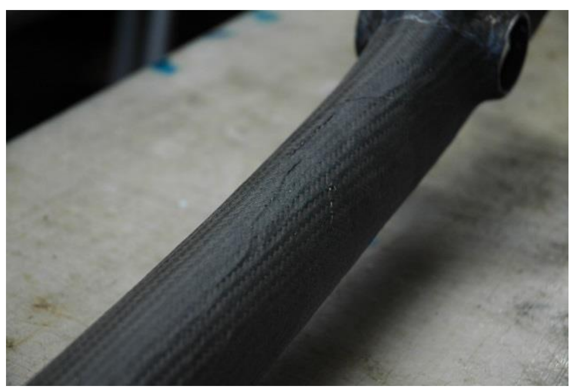


Figure 42 Wrinkles do happen and should be gently sanded off

Figure 43 details a section of the cured laminate that has dry fibers on the surface. This was either the result of insufficient epoxy application during wet out or a poor vacuum bag that did not provide full compression of the ply. In this case epoxy was re-applied directly to the area before adding the next layer.

Figure 43 A matrix starved section of carbon fiber

Bridging is another major concern and can occur as a result of improper placement of plies or careless vacuum bagging. In this case, illustrated in Figure 44, insufficient vacuum bag material was placed in the concave corner and the carbon fiber was not compressed. The bottom bracket area is highly susceptible to bridging as the vacuum bag can be pulled inside the bottom bracket shell under vacuum which pulls the material away from the concave corner. The uncompressed laminate in this area was completely sanded off and a repair layer applied.

Figure 44 Evidence of bridging around the bottom bracket shell

Testing

To evaluate the structural integrity and stiffness of the frame, physical tests simulating high load cases and typical riding were completed based on validation tests used in industry. The two stiffness modes that are most important for the rear triangle are torsional and vertical stiffness as described in the stiffness section of the design requirements above. Additionally, the frame was tested to failure in a vertical loading scenario to simulate excessive loads or a vertical drop. Milo Clausen and the Oregon State University Wood Science Lab graciously permitted and facilitated the use of testing fixtures and an instrumented hydraulic press.

Figure 45 Loading cylinder lowering into position for the torsion test

Torsional Stiffness Test

The torsion test was performed by securing the steel test fixture bonded to the frame and applying the load to a moment arm fixed through the bottom bracket shell. The rear axle was also supported at the frame centerline to limit vertical deflection and simulate the constraint of a rear wheel. The displacement and applied load from the press were recorded by the onboard load cell and control system. Dial indicators were also used to validate the recorded displacement as well as displacement of the frame at the centerline above the bottom bracket to distinguish torsional deflection from vertical deflection. The test setup can be seen in and Figure 46 below.

Figure 46 Dial indicators being set up for torsion test

With the frame in the fixture, load was applied 8.35 inches from the centerline in ten pound increments up to a maximum of 250 pounds. The frame deflected a total of 0.15 inches at the moment arm, equivalent to .87 degrees of rotation about the centerline when normalized for vertical deflection.

Vertical Stiffness and Maximum Load Test

After completing the torsion test, the frame was re-fixtured on the loading table to restrain the bonded test fixture and secure the rear axle to the loading cylinder. Dial indicators were once again used to validate the cylinder displacement and measure deflection of the test fixture at two locations. The test set up can be seen in Figure 47 below.

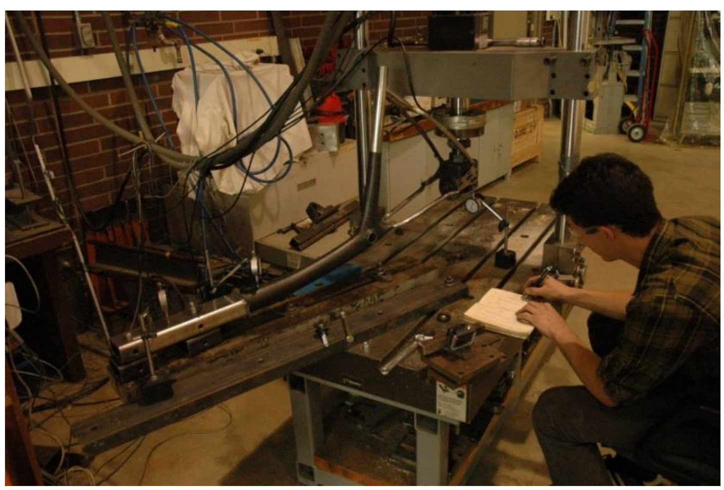


Figure 47 Dial indicator values being recorded during vertical loading test

The load was applied at the rear axle in increments of 20 pounds up to a maximum of 1205 pounds before failing. The frame experienced 2.4 inches of deflection, normalized for fixture deformation. The load had to be applied in three different stages due to a washer yielding in the test fixture and a repositioning of the loading cylinder after exceeding the maximum travel.

Results

Torsional Stiffness

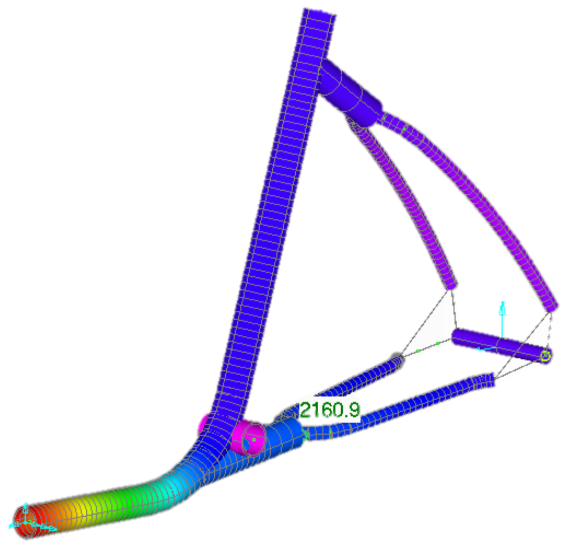


Figure 48 Finite Element Model of the vertical stiffness test

Using load and displacement measurements from the loading cylinder and normalizing for bending deflection of the moment arm and vertical deflection at the centerline, the carbon fiber test section exhibited a torsional stiffness of 217.8 ft-lbf/degree. A representative finite element model indicates that the equivalent steel section has a torsional stiffness of 212.3 ft-lb/deg. This represents a 2% increase in torsional stiffness. This does not meet the desired 10% increase but demonstrates that adequate rigidity can be accomplished in future designs. It is possible that the data collected underestimates the actual torsional stiffness as there was some rotational compliance in the test fixture that was not accounted for. Including this deflection would increase the measured stiffness of the carbon fiber frame.

Vertical Stiffness

With a vertical load applied at the rear axle and deflection of the test fixture accounted for, at load levels below 800 pounds, the carbon fiber frame displayed a linear stiffness relationship of 375.0 lbf/in of deflection. Compared to a finite element model of the equivalent steel tubing used on The Standard, this represents an 18% increase in stiffness, exceeding the design goal of a 10% increase. The base line of vertical stiffness was also determined using a finite element model (Figure 49 Finite Element Model to establish base line for the vertical stiffness test. This beam element model was given a fixed constraint at the front cut away and a load was applied to the center of the rear axle.

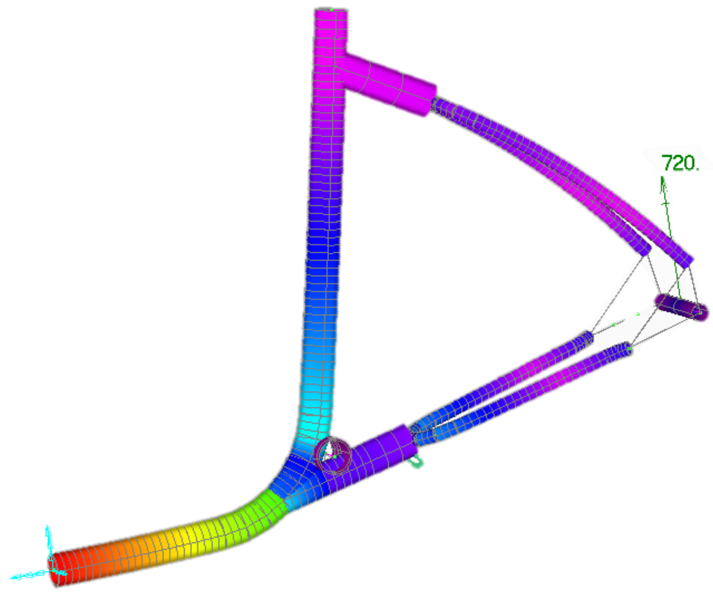


Figure 49 Finite Element Model to establish base line for the vertical stiffness test

Breaking Strength

The frame was taken to failure in the vertical loading case and broke at the upper surface of the boom tube near the test fixture. The carbon fiber frame supported 1205 lbf at the rear axle before failing. The location of the failure indicates that the carbon fiber failed in compression at the stress riser where the steel tube of the test fixture ends and the ABS plastic begins. This was the expected failure mode but occurred at a higher load than expected. This represents a 475% increase in failure strength over the steel boom tube subjected to a similar loading condition. It is possible that this is an overestimate of the actual force required to fail the material as internal ply failure could have occurred at lower loads but gone unnoticed.

Cost and Weight Analysis

Based on material usage during fabrication of the test section and properties of the specified materials, a cost and weight estimate has been established. Table 11 provides a summary of the specified tubes intended to replace each section of the steel frame. An expanded version of this table including normalized bending stiffness is included in Appendix C-3.

	Part No.	Weight (lb)	Cost
Boom Tube	35043-A	1.1	$ 123
Staples	35051	0.6	$ 82
Steering Tube	35051	0.4	$ 60
Top Tube	45244	0.3	$ 37
Head Tube	45202	0.2	$ 22
Front Arm	35043-A	0.8	$ 84
Middle Connection	Wet Layup	2.0	$ 186
Front Connector	Wet Layup	1.7	$ 156
Front Elbow	Wet Layup	0.5	$ 45
Rear Boom Joint	Wet Layup	2.2	$ 181
Carbon T Joints	Wet Layup	1.0	$ 110
Rear Triangle	Steel	4.9	$ 300
TOTAL		**15.58**	**$ 1,390**

Table 11 Review of selected carbon fiber tubes and joints

This estimate only accounts for the raw material costs and does not include the cost of labor, tools, or additional fabrication steps such as paint.

For reference, Table 12 has been created to help estimate cost and material usage for a typical twelve inch long, two inch diameter, thirteen ply tube of carbon fiber completed with wet layup around a 3D printed core.

Material used for 12 inch long, 2" diameter, 13 ply tube				
Cost of Wet Layup	Consumed Material	Scrap	Cost per unit	Cost
Carbon (yd)	0.54	0.15	$58.75	$36.77
Resin + Catalyst (gal)	0.08	0.00	$185.96	$15.74
Peel Ply (yd)	0.37	0.10	$16.82	$6.78
Breather (in^2)	0.28	0.05	$4.43	$1.32
Vacuum bag (in^2)	0.70	0.10	$4.59	$3.55
Sealant Tape (in)	0.65	0.00	$9.16	$5.98
Core (g)	127.20	0.00	$0.10	$12.72
Total				**$82.86**

Table 12 Material consumption for 1 foot length of 2" diameter, 13 ply tube

Conclusion

The intent of this thesis was to develop a preliminary design of a carbon fiber cargo bike frame for Metrofiets Cargo Bikes. The requirements for the design include a wide range of factors affecting the marketability of a bicycle. A market study exploring other available cargo bikes was performed and information about the current state of Metrofiets was gathered to establish a baseline for the design. A manufacturing method was selected based on cost and feasibility and materials have been recommended that fulfill the necessary structural requirements. Material testing of the purchased composite materials was then performed.

A detailed design of the rear boom tube joint was developed and a representative test piece manufactured. This test piece was subjected to physical testing exploring the stiffness and failure strength and results were compared to finite element models of the original steel frame.

The design goals and outcomes were:

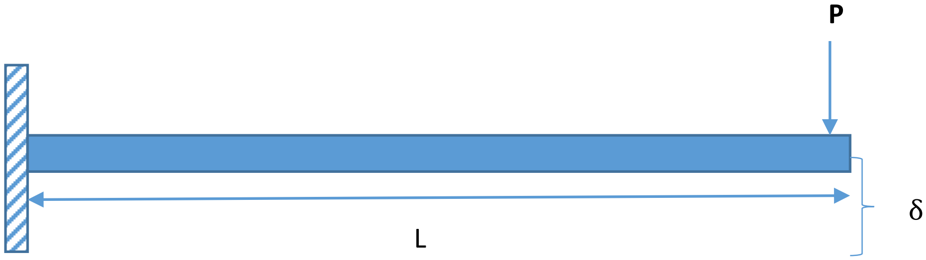
- Strength goal: 400 pound carrying capacity of rider and cargo and equal or greater strength than the steel frame
  - Test section exhibited a 475% increase in failure load
- Stiffness goal: 10% increase in frame stiffness
  - Achieved 18% increase in vertical stiffness
  - Achieved 2% increase in torsional stiffness
  - Analysis of specified tubing indicates improved stiffness in all locations
- Weight goal: 30% Reduction in Frame Weight
  - A 42% decrease in frame weight is estimated based on the specified materials and weight of the manufactured test section.
- Marketing goal: Maintain the Metrofiets Aesthetic
  - A visually pleasing form was achieved and the overall structure of The Standard was maintained. The fabricated test section had an extremely high quality surface indicating the manufacturing method can be used to produce a marketable frame.

Apart from a very small deficiency in Torsional Stiffness, the frame design meets or exceeds all design goals for an estimated material cost of $1,390. Further design and testing of other sections of the bike need to be completed before the design can be considered finalized, however, it is my opinion that this manufacturing method could be used to produce a high quality carbon fiber cargo bike.

Figure 50 Proud of a successful design and execution

Equations

Bending Stiffness:



For a cantilever beam with one fixed end and a point load applied at the free end, the standard beam deflection equation states:

$$\delta = \frac{PL^3}{3EI} \tag{0.1}$$

Where:

δ = Deflection at load application point
P = Applied load
L = Beam length
E = Young's modulus of elasticity
I =Area moment of Inertia

This can be generalized for k number of beams with the equation:

$$\delta_{jj} = \frac{PL^3}{3\sum_{n=1}^{k} E_n I_{ii,n}} \tag{0.2}$$

Equation (0.2) can be solved to represent the stiffness of the beam in terms of applied load versus deflection (lbf/in) at the load application point:

$$\frac{P_j}{\delta_j} = \frac{3\sum_{n=1}^{k} E_n I_{ii,n}}{L^3} \tag{0.3}$$

This expression allows a stiffness comparison between beams of different geometries and materials assuming they are of equal length.

The bending stiffness of the beams is most easily compared when displayed as a ratio:

$$\text{Ratio of Bending Stiffness} = \left(\frac{P_j}{\delta_j}\right)_{\text{Tube 1}} \Big/ \left(\frac{P_j}{\delta_j}\right)_{\text{Tube 2}} \tag{0.4}$$

Combining (0.3) and (0.4) reveals that the same stiffness comparison can be made using only the material modulus of elasticity and the area moment of inertia.

$$\text{Ratio of Bending Stiffness} = \left(\sum_{n=1}^{k} EI\right)_{\text{Tube 1}} \Big/ \left(\sum_{n=1}^{k} EI\right)_{\text{Tube 2}} \tag{0.5}$$

Torsional Stiffness:

The basic torsional deflection equation states:

$$\gamma = \frac{LT}{JG} \tag{1.1}$$

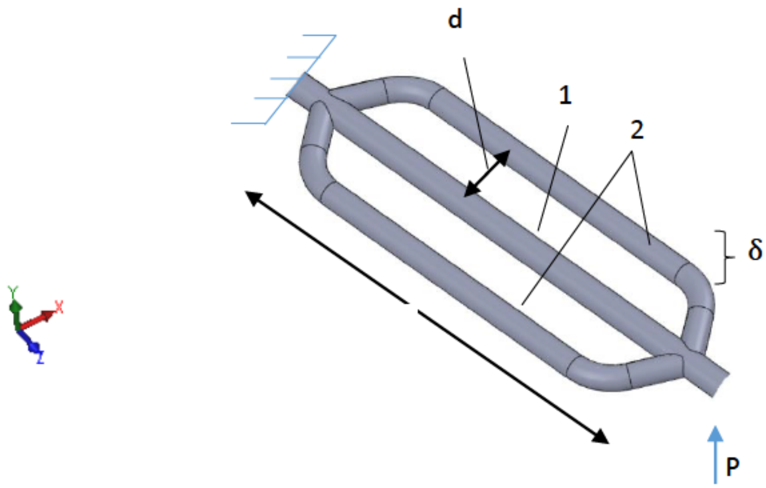
Where:

γ = Angular deflection
L = Beam length
T = Applied torsion
J = Polar moment of inertia
G = Shear Modulus

Using the same process applied to the bending stiffness equation above, the torsional stiffness can also be reduced to a simple relationship between the polar moment of area and the shear modulus of elasticity:

$$\text{Ratio of Torsional Stiffness} = \left(\sum_{n=1}^{k} JG\right)_{\text{Tube 1}} \Big/ \left(\sum_{n=1}^{k} JG\right)_{\text{Tube 2}} \tag{1.2}$$

Boom Tube Stiffness:



Bending Stiffness Comparison:

Assuming a three tube structure used for the front boom tube area, equation (0.5) for establishing the stiffness value of a beam assembly can be represented as:

$$\text{Stiffness}_{ii,combined} = E_1 I_{ii,1} + 2E_2 I_{ii,2} \tag{2.1}$$

This equation is applicable to vertical bending as well as horizontal bending as long as the appropriate area moment of inertia is used. For irregular cross sections, SolidWorks was used to determine the area moment of inertia. For a circular tube:

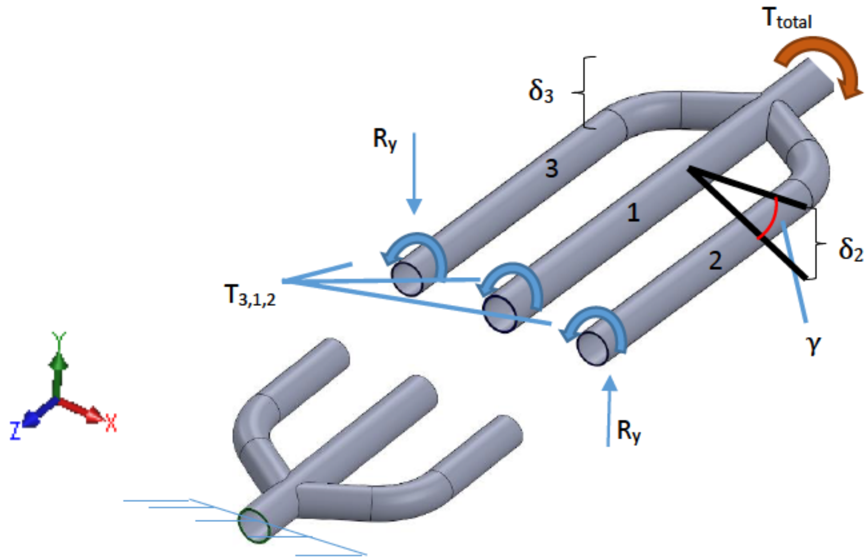
$$I_{ii} = \frac{\pi(d_{o,n}^4 - d_{i,n}^4)}{64} \tag{2.2}$$

To determine the area moment of inertia for the tubes offset from the assembly's centroid, the parallel axis theorem must be applied:

$$I_{ii'} = I_{ii'} + Ad_i^2 \tag{2.3}$$

Where:

d_i= Distance from the assembly center to the tube center in the direction of bending
A= Cross sectional area of the tube



Assuming static equilibrium, reaction forces of each beam can be determined with the help of the free body diagram:

$$\sum M_z = 0 \tag{3.1}$$

$$T_{total} = T_1 + (T_2 + R_2 d) + (T_3 + R_3 d) \tag{3.2}$$

In this assembly all tubes rotate together forcing equal angular deflection:

$$\gamma_1 = \gamma_2 = \gamma_3 \tag{3.3}$$

Using the equation for torsional deflection of a beam, the angular deflection can be related to the applied torque on each tube:

$$\gamma_n = \frac{T_n L_n}{G_n J_n} \tag{3.4}$$

To estimate the applied bending moment, vertical deflection (δ) of the outer tubes can be related to the angular deflection:

$$\delta_n = d_x \sin\gamma \tag{3.5}$$

A small angle approximation can be used due to the low deflections of the assembly:

$$\sin\lambda = \lambda \tag{3.6}$$

Equation (3.5) becomes:

$$\delta_n = d_x\lambda \tag{3.7}$$

The force required to vertically deflect the outer tubes can be determined with the beam bending equation. Reaction force R has replaced P from equation (0.1):

$$R_n = \frac{\delta_n 3E_n I_n}{L_n^3} \tag{3.8}$$

Combining the deflection equations and the force balance equation (3.2) produces:

$$\frac{T_{total}}{\gamma} = \sum_{n=1}^{3}\frac{J_n G_n}{L} + d\sum_{n=1}^{3}\frac{3E_n I_{ii,n}}{L^3} \tag{3.9}$$

Material Failure Analysis

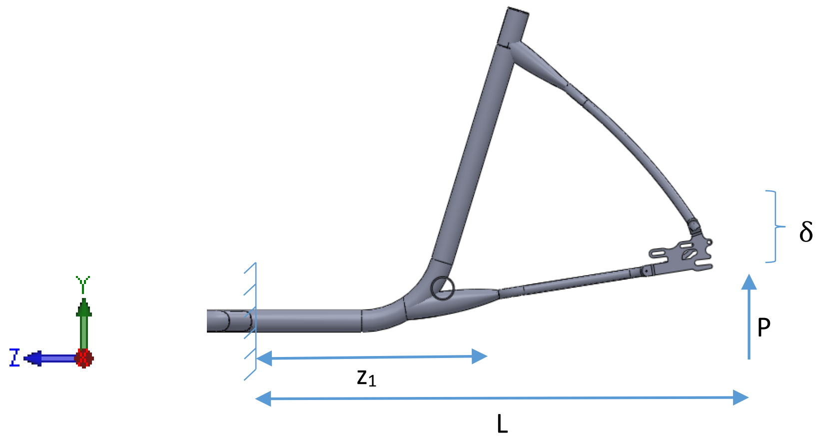


Figure 51 Vertical Deflection Free Body Diagram

Steel:

To find the stress in a beam subjected to a bending moment:

$$\sigma = \frac{My}{I} \tag{4.1}$$

The yield stress of steel can be used to solve for the maximum moment

$$M_{\max} = \frac{\sigma_{yield} I}{y_{\max}} \tag{4.2}$$

Composite Failure Analysis:

To establish strength equivalency to the steel frame, the maximum loading case is assumed to be the failure point of the steel tubing. The maximum stress in a carbon fiber frame can be determined for this loading scenario and failure indices applied.

To find the maximum stress in the carbon fiber section in the maximum bending load case:

$$\sigma_{max,carbon} = \frac{M_{max,Steel} y_{carbon}}{I_{Carbon}} \tag{4.3}$$

A similar procedure can be applied to evaluate the torsional shear strength of the beam. To find the maximum shear stress in a carbon fiber beam with a circular cross section under torsion:

$$\tau_{\max,carbon} = \frac{T_{Yield,\text{steel}} r_{carbon}}{J_{carbon}} \tag{4.4}$$

Where:

r= radius of the outer wall

To find the max shear in a thin walled non-circular object, equation 6.66 from Boresi, Schmidt [23] can be applied. This equation assumes equal shear flow around the entire perimeter of the tube and an even stress through the thickness:

$$\tau = \frac{T}{2A_{effective}h} \tag{4.5}$$

Where:

$A_{effective}$= the area enclosed by the mean perimeter of the cross section
h= wall thickness at the point of interest

The maximum shear and normal stresses can be converted to shear and normal forces per unit length with equation 7.82 from Daniel, Ishai [19]. The force per unit length is a commonly used value in composites analysis and is the required input for the ESP Composites failure indices.

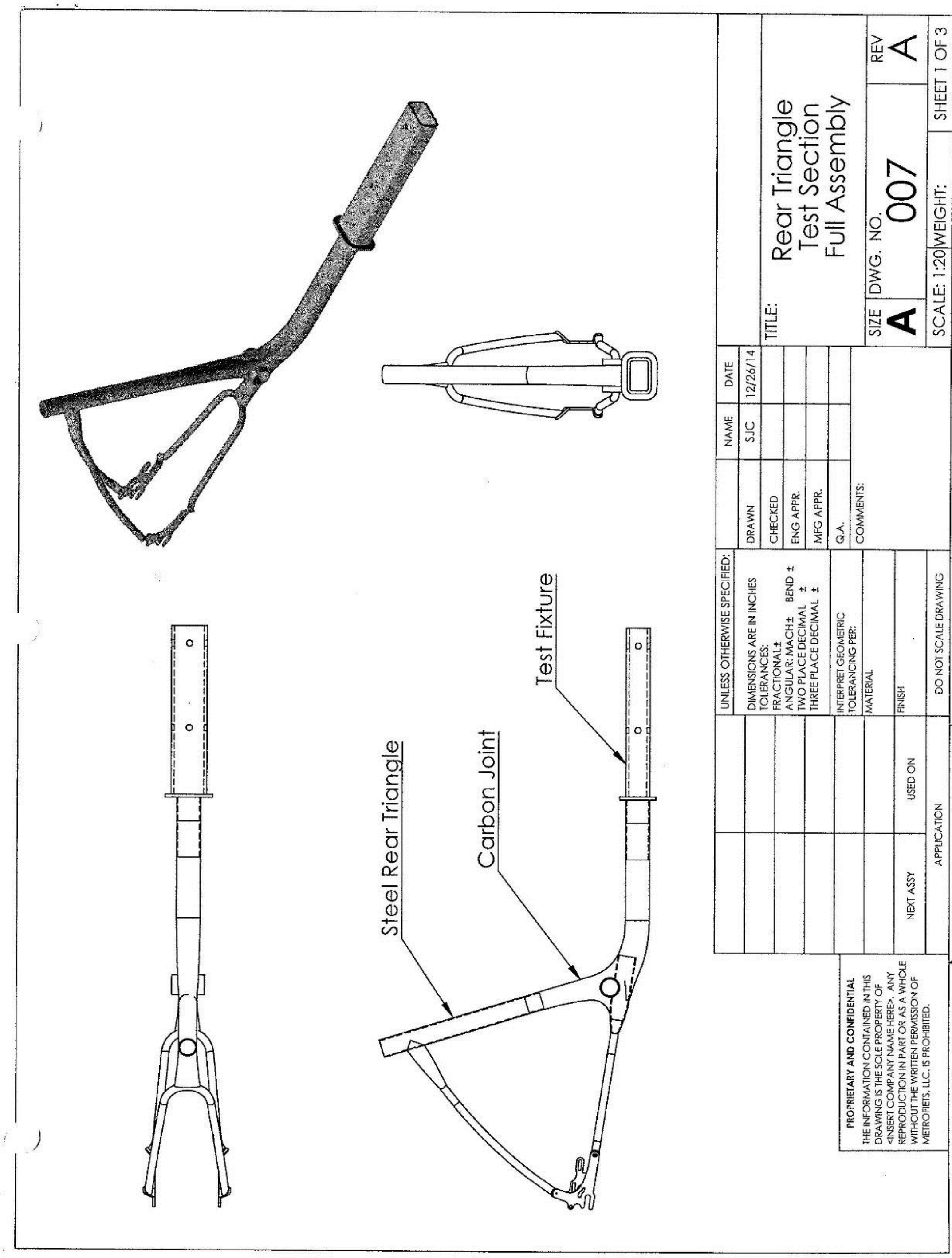
$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} = \frac{1}{h} \begin{bmatrix} N_x \\ N_y \\ N_{xy} \end{bmatrix} \tag{4.6}$$

Shear and normal forces per unit length can be input to ESP composites to calculate the safety factor with the Max Stress, Max Strain, and Tsai-Wu failure criteria.

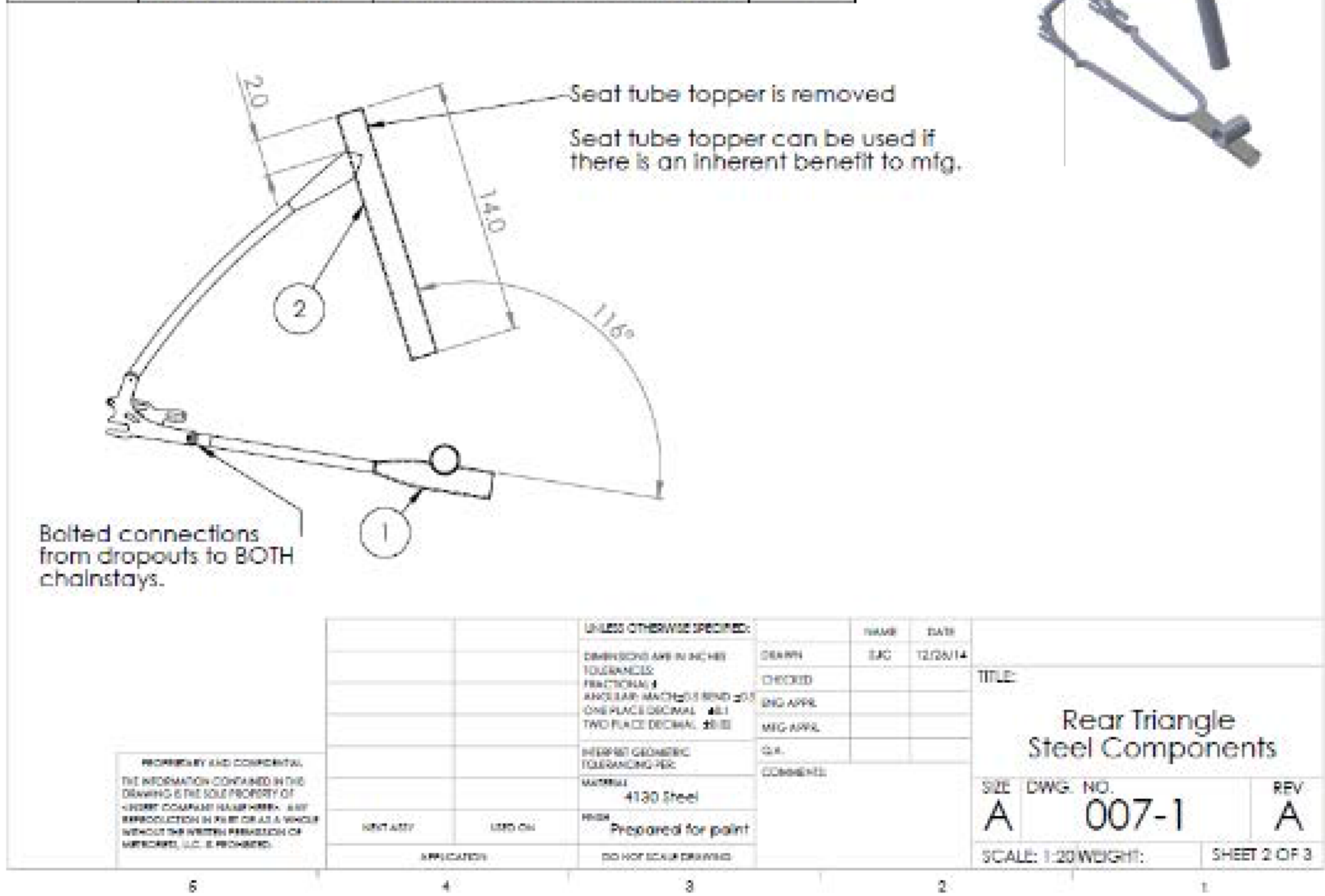
Appendix A – Part Drawings

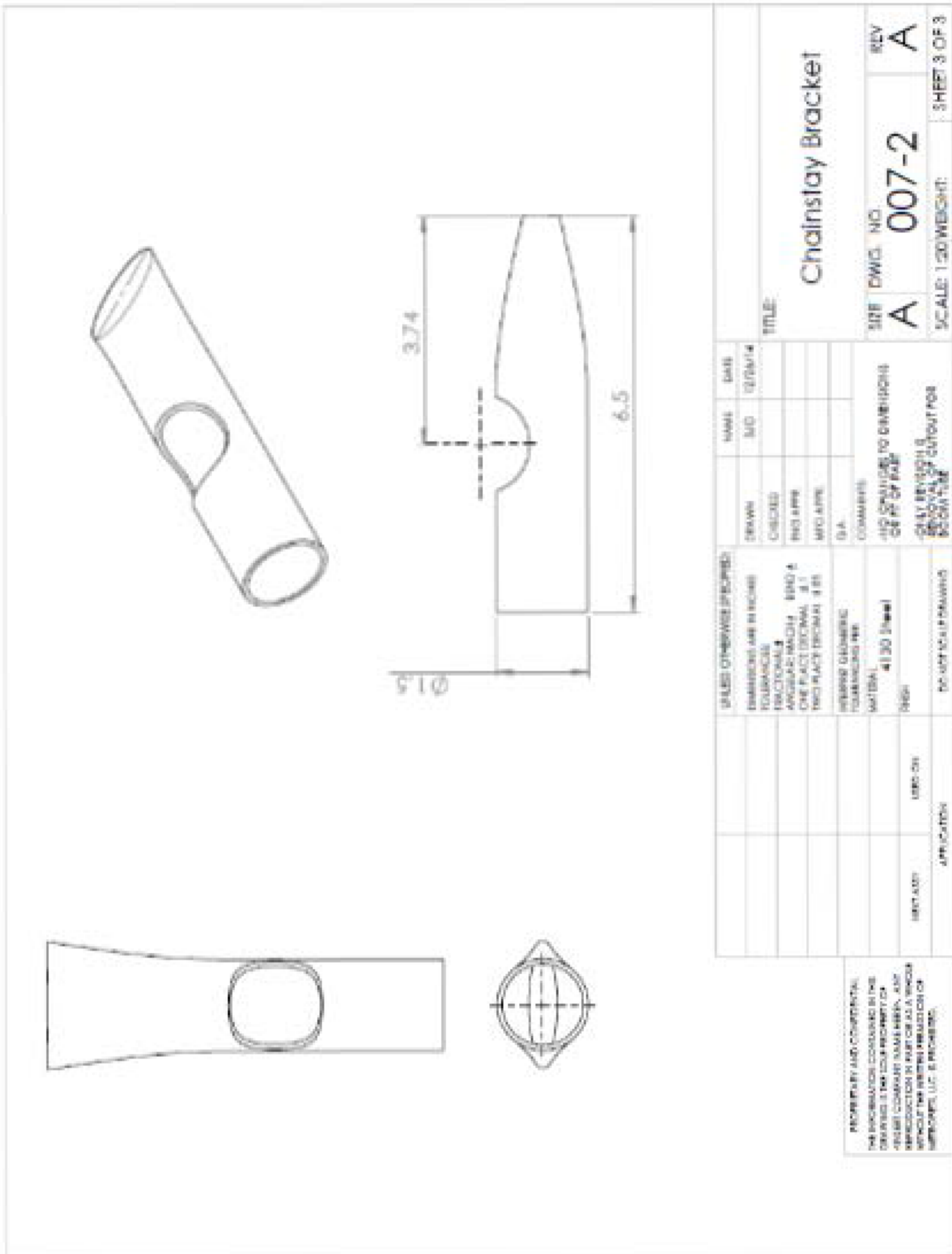
Solid models were completed in DS SolidWorks

A – 1 Rear Triangle Manufacturing Drawings

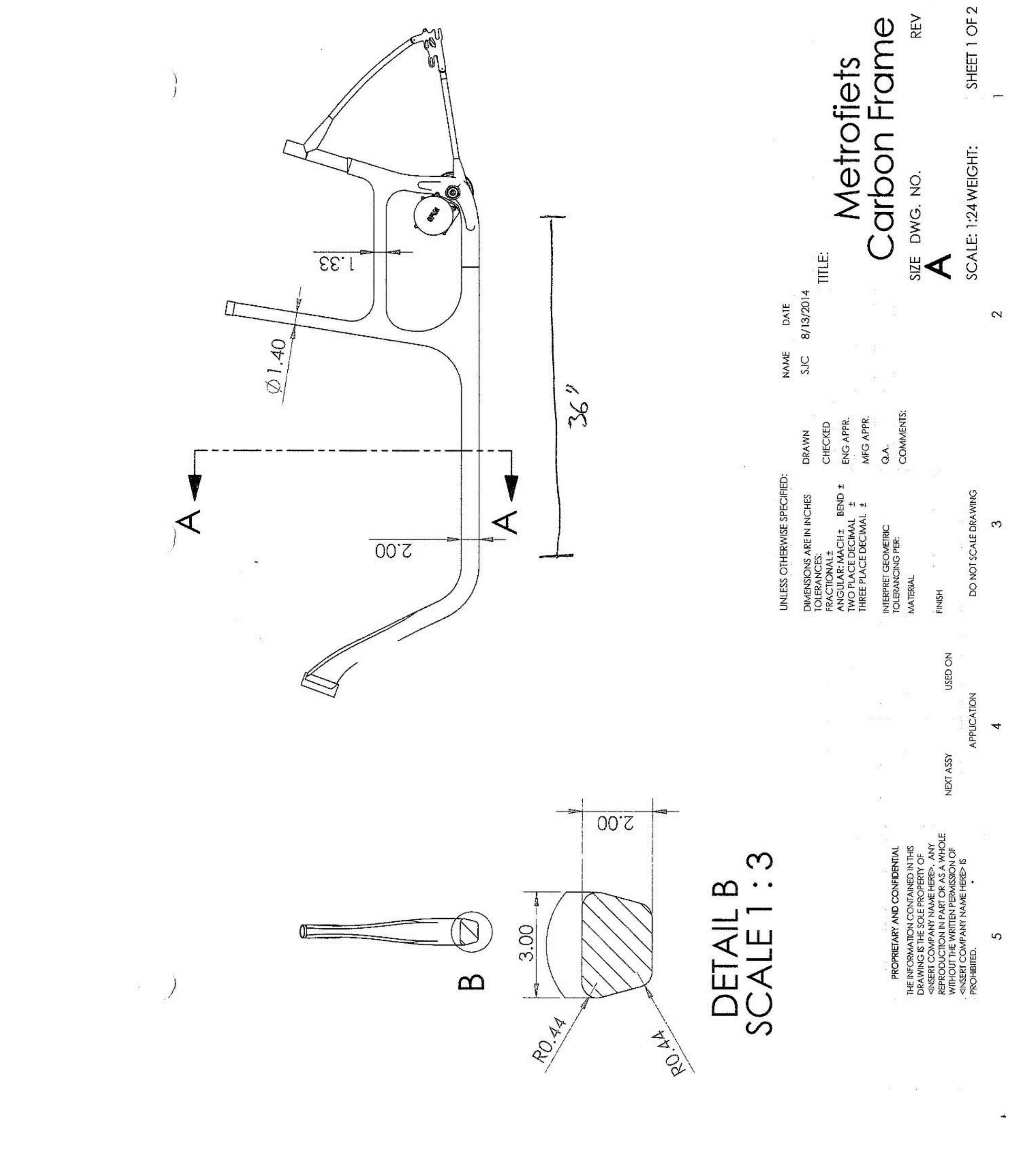


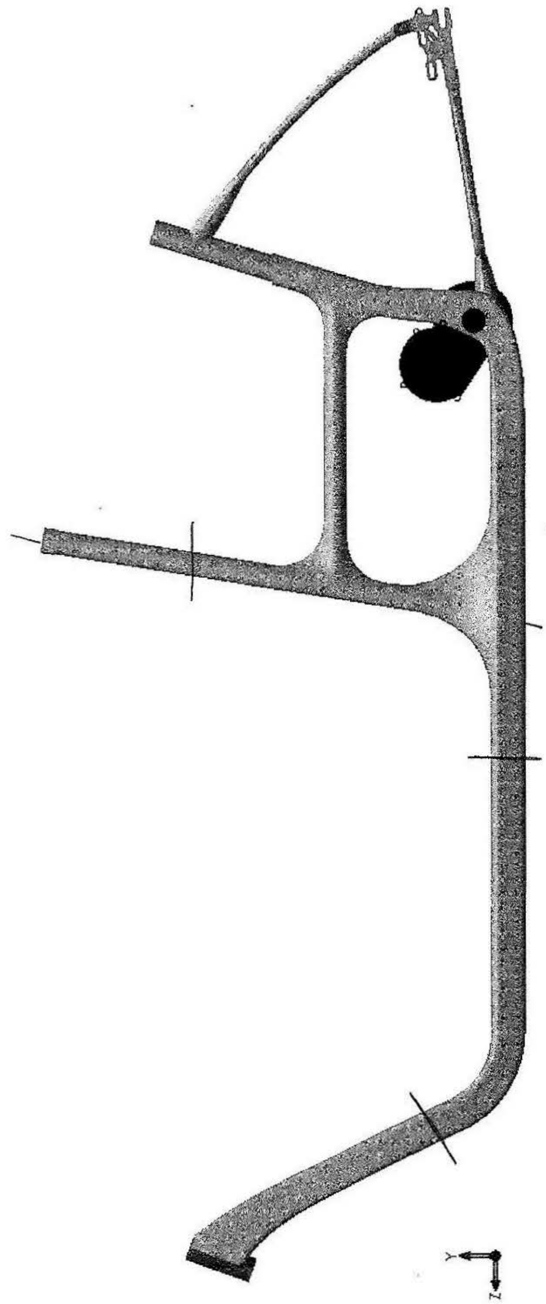
ITEM NO.	TITLE	DESCRIPTION	QTY.
1	Chainstay Bracket Revised	Standard Bracket without cutout for boom tube	1
2	Seat Tube Revised	1.50 X 0.083 4130 Steel Tubing	1



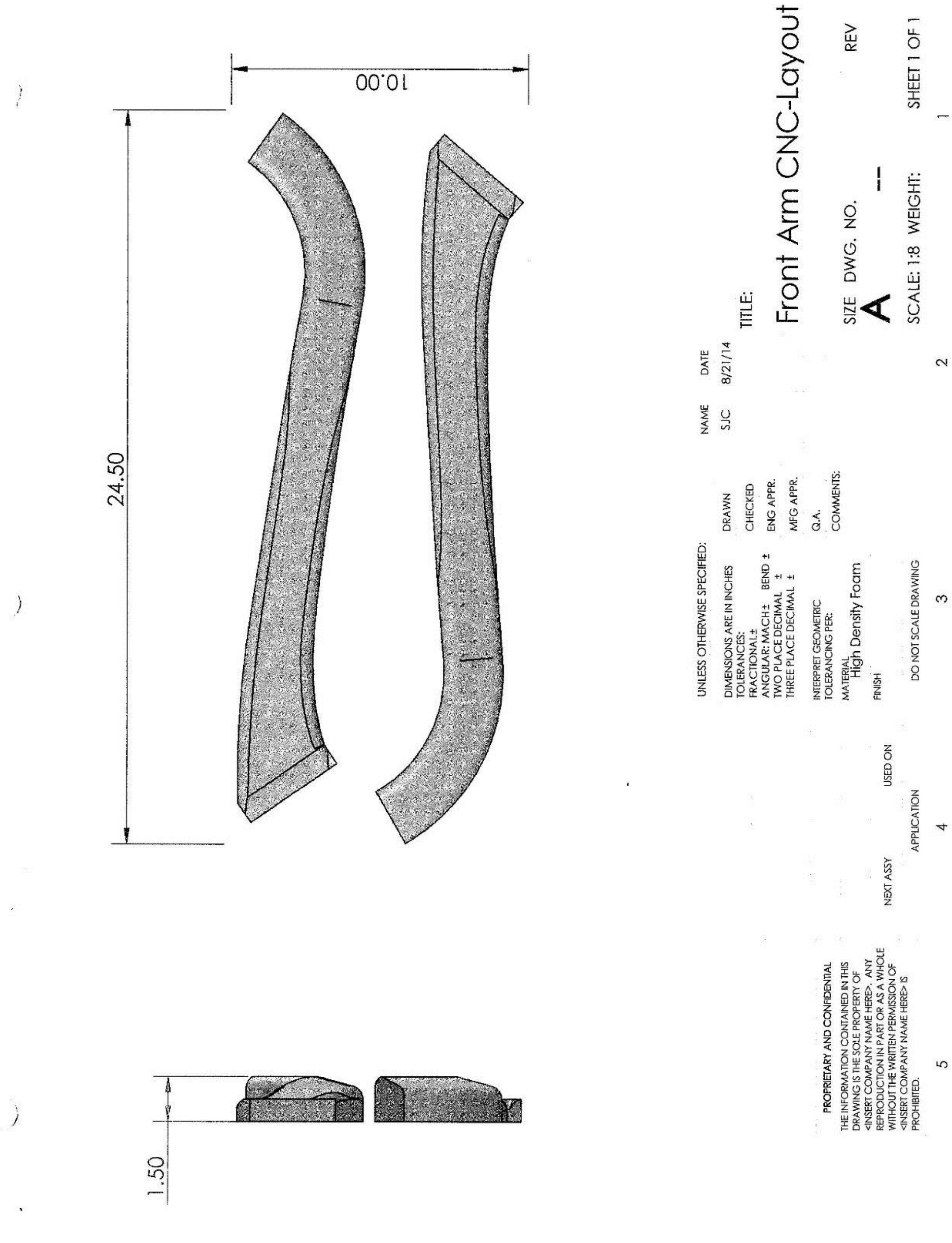

3.74
6.5
Ø1.5
4130 Steel
TITLE:
Chainstay Bracket
SIZE
A
DWG. NO.
007-2
REV
A
SCALE: 1:20 WEIGHT:
SHEET 3 OF 3

A – 2 Full Wet Layup Concept Drawings




Y
Z

A – 3 Front Arm CNC Layout for Foam Cores



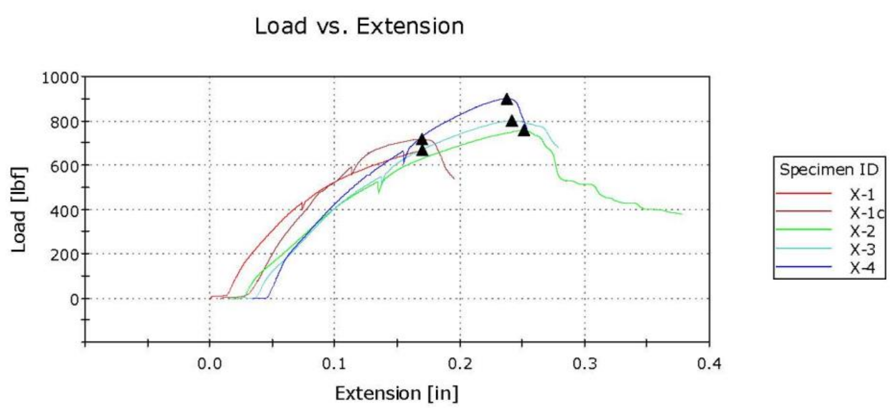
Appendix B – Material Testing Data

Bluehill 3 was used to control an Instron tensile test machine

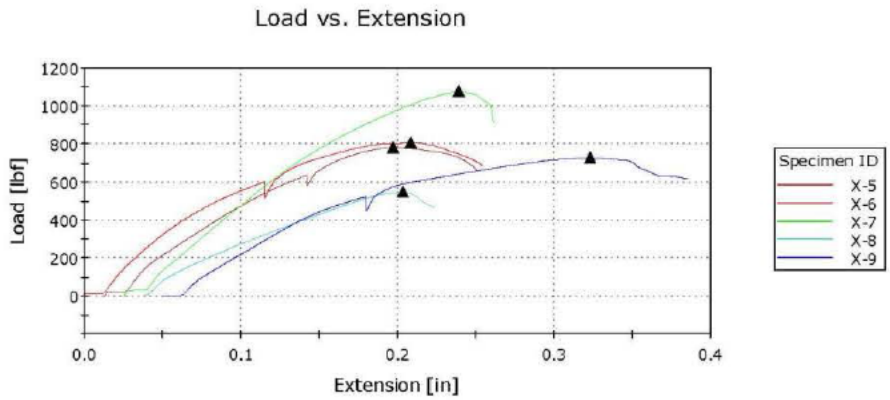
B – 1 Testing data from 45°off axis tensile test

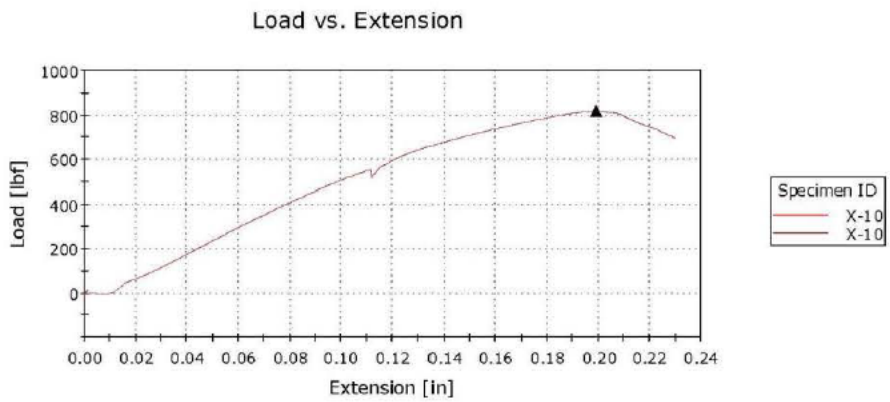
1in Straight Coupon

This method was developed for Metrofiets LLC. by Sam Conklin to test composite samples



Page 1 of 3





	Specimen ID (GFR20XX.T.XX.XX)	Thickness [in]	Width [in]	Maximum Load [lbf]
1	X-1	0.05900	0.97900	668
2	X-1c	0.05900	0.97900	718
3	X-2	0.05900	0.99000	759
4	X-3	0.05800	0.98600	801
5	X-4	0.05900	0.99300	899
6	X-5	0.06100	0.99000	808
7	X-6	0.06400	0.98700	783
8	X-7	0.05900	0.98600	1078
9	X-8	0.06200	0.97900	549
10	X-9	0.06000	0.97300	729
11	X-10	0.06100	0.98900	-----
12	X-10	0.06100	0.98900	817

	Tensile strain (Strain 1) gauge length [in]	Tensile stress at Maximum Load [psi]	Extension at Maximum Load [in]
1	1.00000	11560.36272	0.17
2	1.00000	12427.52504	0.16
3	1.00000	12988.45517	0.23

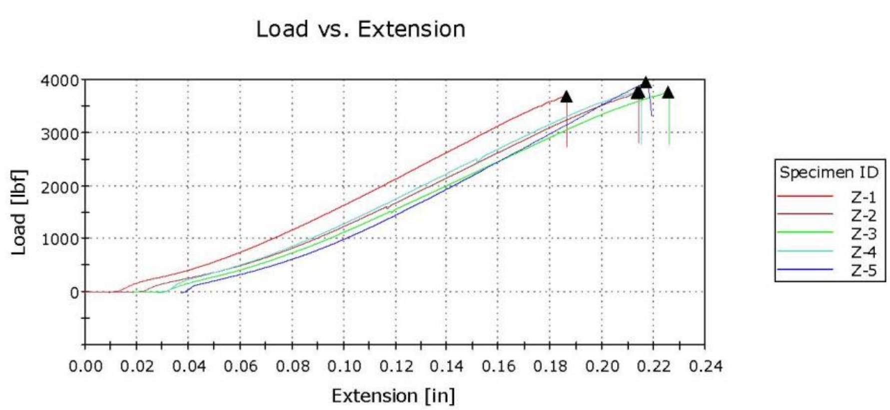
Page 2 of 3

	Tensile strain (Strain 1) gauge length [in]	Tensile stress at Maximum Load [psi]	Extension at Maximum Load [in]
4	1.00000	14000.72602	0.22
5	1.00000	15339.66373	0.20
6	1.00000	13377.79590	0.21
7	1.00000	12397.50102	0.18
8	1.00000	18529.08062	0.21
9	1.00000	9049.40043	0.17
10	1.00000	12485.49056	0.27
11	1.00000	-----	-----
12	1.00000	13545.85872	0.20

B – 2 Testing data from 0° tensile test

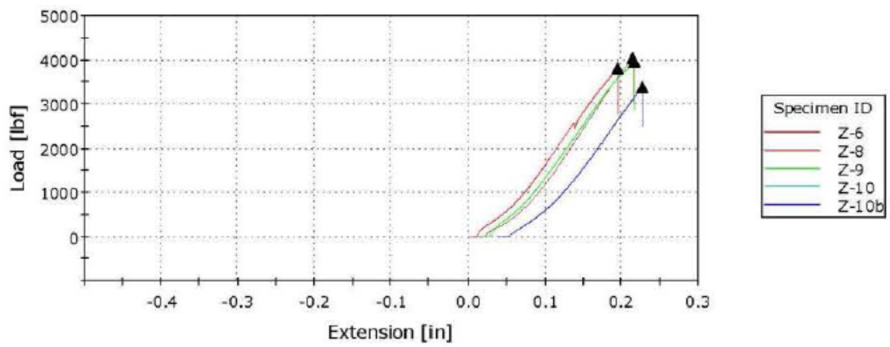
1in Straight Coupon

This method was developed for Metrofiets LLC. by Sam Conklin to test composite samples



Page 1 of 2

Load vs. Extension



	Specimen ID (GFR20XX.T.XX.XX)	Thickness [in]	Width [in]	Maximum Load [lbf]
1	Z-1	0.04100	1.01700	3678
2	Z-2	0.04000	1.01700	3745
3	Z-3	0.04100	1.01900	3759
4	Z-4	0.04300	1.01900	3769
5	Z-5	0.04000	1.01500	3942
6	Z-6	0.04200	1.01900	3807
7	Z-8	0.04100	1.01600	4035
8	Z-9	0.04200	1.01900	3961
9	Z-10	0.04100	0.99500	-----
10	Z-10b	0.04100	0.99500	3387

	Tensile strain (Strain 1) gauge length [in]	Tensile stress at Maximum Load [psi]	Extension at Maximum Load [in]
1	1.00000	88205.13873	0.19
2	1.00000	92067.13111	0.20
3	1.00000	89980.34596	0.21
4	1.00000	86027.66959	0.19
5	1.00000	97086.38892	0.18
6	1.00000	88941.78236	0.19
7	1.00000	96856.65143	0.20
8	1.00000	92551.00331	0.20
9	1.00000	-----	-----
10	1.00000	83034.23931	0.19

B – 3 Comparison of Material Properties

	Carbon Fiber Tow		Epoxy			Laminate			Steel
	My Fibers Orca 6K 33	AS-4 Carbon (book)	Epoxy ProGlas 4:1	3501-6 (book)	Epoxy 977-3 (book)	Laminate (from testing)	Book Laminate (AS-4 3K 5H/3501-6S)	Std CF Fabric	4130
E1, Msi (GPa)	33 5 (231)	34 (235)	0 526 (3.6)	.62 (4.3)	0.54 (3.7)	10.0 (68.9)	11.2 (77)	10.2 (70)	29.7 (205)
E2 Msi (Gpa)	-	2.2 (15)	0 526 (3.6)	.62 (4.3)	0.54 (3.7)	10.0 (68.9)	10.9 (75)	10.2 (70)	29.7 (205)
G12 Msi (Gpa)	-	4.0 (27)	-	.24 (1.60)	0.2 (1 26)	?	0.94 (6.5)	0.73 (5)	11.6 (80)
v12	-	0.20	-	0.35	0.35	?	0.06	0.10	0.30
Ft, ksi (MPa)	640 (4,410)	535 (3,700)	11.9476 (82.3)	10 (69)	13 (90)	89.7 (618)	140 (963)	87.02 (600)	63.1 (435)
Fs, ksi (Mpa)	-	-	-	15 (100)	7.5 (52)	6.36 (43.9)	10.3 (71)	13.1 (90)	47 3 (326)
Max Tensile Strain (%)	1.70%	1.70%	-	2-5%	-	0.90%	1.30%	0.85%	0.21%
Max Shear Strain (%)						0.87%	1.10%	1.79%	0.41%
Fiber Volume	N/A	N/A	N/A	N/A	N/A	0.65	0.62	0.50	N/A

Appendix C – Tube Stiffness Comparison Data

Properties of tubes and rear cross sections used in stiffness comparisons

C – 1 Stiffness comparison values of rear boom tube joint

	Ixx (in^4)	Iyy(in^4)	J (in^4)	EIxx	EIyy	JG
Steel (base line)	0.093	0.093	0.19	2.77E+06	2.77E+06	2.16E+06
Front (circle)	0.74	0.74	1.48	5.25E+06	5.25E+06	3.86E+06
Rear (oval)	0.62	0.43	1.02	4.40E+06	3.05E+06	2.66E+06

C – 2 Enclosed area of rear cross section from rear boom tube joint

	J (in^4)	Enclosed Area (in^2)	Radius of Max Shear Stress (in)
Carbon- oval	1.02	2.88	0.91

C – 3 Review of purchased tubes

	Part No.	Normalized Torsional Stiffness	Normalized Bending Stiffness	Length	Linear density (lb/ft)	Weight (lb)	Cost
Boom Tube	35043-A	1.40	1.62	24.68	0.55	1.1	$123
Staples	35051	1.40	1.62	35.46	0.20	0.6	$83
Steering Tube	35051	0.52	2.49	25.88	0.20	0.4	$60
Top Tube	45244	1.15	2.05	17.75	0.18	0.3	$38
Head Tube	45202	no data	no data	4.00	0.49	0.2	$22
Front Arm	35043-A	1.40	1.62	16.89	0.55	0.8	$84
Middle Connection	Wet Layup	1.78	1.89	24.90	0.96	2.0	$172
Front Connector	Wet Layup	1.78	1.89	20.90	0.96	1.7	$144
Front Elbow	Wet Layup	1.78	1.89	6.02	0.96	0.5	$42
Rear Boom Tube Joint	Wet Layup	0.94	1.35	24.20	0.96	2.2	$167
Carbon T Joints	Wet Layup	1.78	1.89	18.00	0.68	1.0	$105
Rear Triangle	Steel	1	1	-	-	4.9	$300
		TOTAL				**15.6**	**$1,341**

Appendix D – ESP Composites

ESP Composites was used for stress analysis of the composites

D – 1 Material Properties used in ESP Composites for Wet Layup Carbon Fiber

ESP Composites

Lamina Orthotropic Properties

	Material 1	Material 2	Material 3	Material 4
Reference Info	Example Carbon Fiber Epoxy Hot/Wet			
E_1 [psi]	10,000,000			
E_2 [psi]	10,000,000			
ν_{12} [in/in]	0.100			
G_{12} [psi]	730,000			
t_{ply} [in]	0.0150			
α_1 [in/in/F]				
α_2 [in/in/F]				
β_1 [in/in]				
β_2 [in/in]				

Strain Based Lamina Allowalbes or Design Cutoffs

	Material 1	Material 2	Material 3	Material 4
ε_{1t} [in/in]	0.00897			
ε_{1c} [in/in]	-0.00800			
ε_{2t} [in/in]	0.00897			
ε_{2c} [in/in]	-0.00800			
γ_{6s} [in/in]	0.00870			

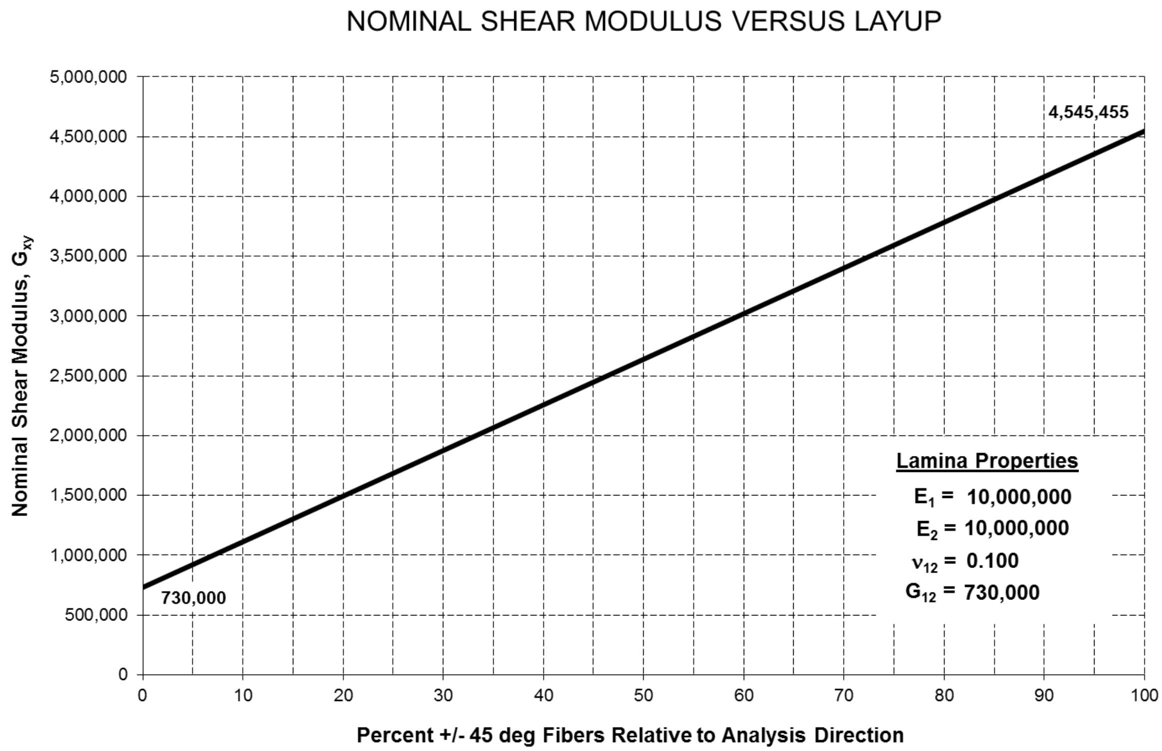
Stress Based Allowables

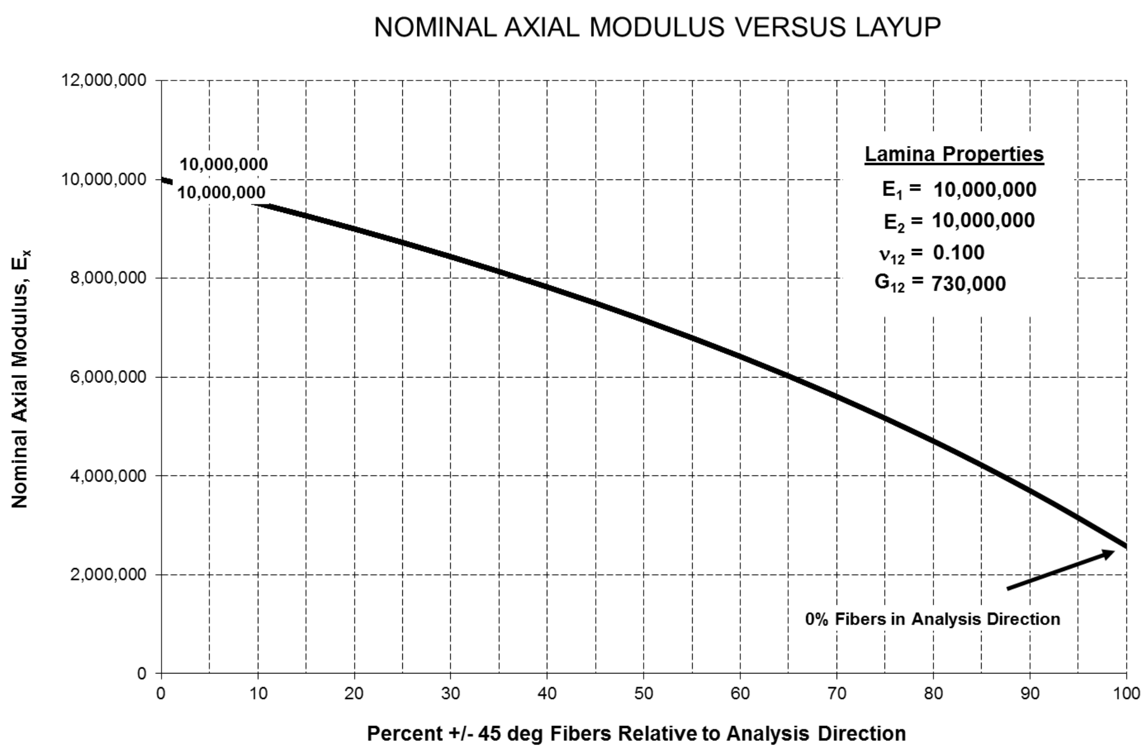
	Material 1	Material 2	Material 3	Material 4
F_{1t} [psi]	89,700	0	0	0
F_{1c} [psi]	-80,000	0	0	0
F_{2t} [psi]	89,700	0	0	0
F_{2c} [psi]	-80,000	0	0	0
F_6 [psi]	6,351	0	0	0

APPLY SYMMETRY (EVEN PLY COUNT) | APPLY SYMMETRY (ODD PLY COUNT)

				Lamina Mid-Ply Strains Global X,Y System			Lamina Mid-Ply Strains Local 1,2 System			Lamina Mid-Ply Stresses Global X,Y System			Lamina Mid-Ply Stesses Local 1,2 System		
Ply	Mat ID	θ [deg]	z mid [in]	ε_x	ε_y	γ_{xy}	ε_1	ε_2	γ_{12}	σ_x	σ_y	σ_{xy}	σ_1	σ_2	σ_{12}
1	1	45	-0.0825	0.000024	0.000047	0.000000	0.000035	0.000035	0.000024	376	411	0	394	394	17
2	1	0	-0.0675	0.000082	0.000030	0.000000	0.000082	0.000030	0.000000	863	387	0	863	387	0
3	1	45	-0.0525	0.000141	0.000013	0.000000	0.000077	0.000077	-0.000128	950	763	0	856	856	-94
4	1	0	-0.0375	0.000200	-0.000004	0.000000	0.000200	-0.000004	0.000000	2,016	160	0	2,016	160	0
5	1	45	-0.0225	0.000259	-0.000021	0.000000	0.000119	0.000119	-0.000280	1,524	1,115	0	1,319	1,319	-204
6	1	0	-0.0075	0.000318	-0.000038	0.000000	0.000318	-0.000038	0.000000	3,168	-67	0	3,168	-67	0
7	1	45	0.0075	0.000376	-0.000055	0.000000	0.000160	0.000160	-0.000432	2,098	1,467	0	1,782	1,782	-315
8	1	0	0.0225	0.000435	-0.000073	0.000000	0.000435	-0.000073	0.000000	4,321	-294	0	4,321	-294	0
9	1	45	0.0375	0.000494	-0.000090	0.000000	0.000202	0.000202	-0.000584	2,671	1,819	0	2,245	2,245	-426
10	1	0	0.0525	0.000553	-0.000107	0.000000	0.000553	-0.000107	0.000000	5,474	-520	0	5,474	-520	0
11	1	45	0.0675	0.000611	-0.000124	0.000000	0.000244	0.000244	-0.000735	3,245	2,172	0	2,708	2,708	-537
12	1	0	0.0825	0.000670	-0.000141	0.000000	0.000670	-0.000141	0.000000	6,627	-747	0	6,627	-747	0

D – 2 Carpet plots of wet layup carbon fiber





D – 3 Safety Factor Analysis, Torsion, Front Cross Section

Applied Loads	
N_x [lb/in]	0.0
N_y [lb/in]	0.0
N_{xy} [lb/in]	1143.2
M_x [in-lb/in]	0.0
M_y [in-lb/in]	0.0
M_{xy} [in-lb/in]	0.0
Temp Δ [deg F]	0.0
Moisture Δ [%]	0.000
total thickness [in]	0.1800

Laminate Mid-Plane Strains/Curvatures	
ε_x^0 [in/in]	0.000000
ε_y^0 [in/in]	0.000000
γ_{xy}^0 [in/in]	0.002434
κ_x [rad/in]	0.0000
κ_y [rad/in]	0.0000
κ_{xy} [rad/in]	0.0049

Margin of Safety (First Ply Failure if Lamina Allowables are Used)

	Max Strain	Max Stress	Tsai-Hill	Max Fiber Strain	Custom
M.S.	**2.07**	**2.07**	**2.07**	**5.49**	
ply no.	12	12	12	11	
ε_1	0.000000	0.000000	0.000000	0.001382	
ε_2	0.000000	0.000000	0.000000	-0.001382	
γ_{12}	0.002838	0.002838	0.002838	0.000000	

D – 4 Safety Factor Analysis, Torsion, Rear Cross Section

Applied Loads	
N_x [lb/in]	0.0
N_y [lb/in]	0.0
N_{xy} [lb/in]	2034.0
M_x [in-lb/in]	0.0
M_y [in-lb/in]	0.0
M_{xy} [in-lb/in]	0.0
Temp Δ [deg F]	0.0
Moisture Δ [%]	0.000
total thickness [in]	0.1800

Laminate Mid-Plane Strains/Curvatures	
ε_x^0 [in/in]	0.000000
ε_y^0 [in/in]	0.000000
γ_{xy}^0 [in/in]	0.004331
κ_x [rad/in]	0.0000
κ_y [rad/in]	0.0000
κ_{xy} [rad/in]	0.0087

Margin of Safety (First Ply Failure if Lamina Allowables are Used)

	Max Strain	Max Stress	Tsai-Hill	Max Fiber Strain	Custom
M.S.	**0.72**	**0.72**	**0.72**	**2.65**	
ply no.	12	12	12	11	
ε_1	0.000000	0.000000	0.000000	0.002459	
ε_2	0.000000	0.000000	0.000000	-0.002459	
γ_{12}	0.005049	0.005049	0.005049	0.000000	

Appendix E – Material Data Sheets

Relevant Material Data Sheets from the various suppliers

E – 1 Carbon Fiber Fabric Data Sheet

17210550 - ORCA 6K 10.9 OZ Carbon Fiber 2X2 TWILL

Orca Composites

6K Carbon Fiber
10.9OZ 2X2 TWILL

PRODUCT #: 17210550		**US SYSTEM**	
Type of Yarns:	Warp Yarn:	6K Carbon, 33MSI	
	Fill Yarn:	6K Carbon, 33MSI	
Fabric Weight, Dry:		10.9 oz/yd^2	370 g/m^2
Weave Style:	2X2 TWILL		

CONSTRUCTION

Nominal Construction:	Warp Count:	High Strength 6K
	Fill Count:	High Strength 6K
Fabric Thickness:		Verify

IMPORTANT

All information is believed to be accurate but is given without acceptance of liability. All values have been generated from limited data. The values listed for weight, thickness and breaking strengths are typical greige values, unless otherwise noted. Users should make their own assessment of the suitability of any product for the purpose required. All sales are made subject to our standard terms of sales which include limitations on liability and other important terms. The fabric style listed may not be available from inventory and minimum order quantities may apply.

FOR MORE INFORMATION

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E – 2 Carbon Fiber Filament Material Properties

Typical Fiber Properties	U.S. Units	SI Units
Tensile Strength 3K 6K 12K	 670 ksi 640 ksi 640 ksi	 4,620 MPa 4,410 MPa 4,410 MPa
Tensile Modulus (Chord 6000-1000)	33.5 Msi	231 GPa
Ultimate Elongation at Failure 3K 6K 12K	 1.8% 1.7% 1.7%	 1.8% 1.7% 1.7%
Density	0.0647 lb/in^3	1.79 g/cm^3
Weight/Length 3K 6K 12K	 11.8×10^{-6} lb/in 23.9×10^{-6} lb/in 48.0×10^{-6} lb/in	 0.210 g/m 0.427 g/m 0.858 g/m
Approximate Yield 3K 6K 12K	 7,086 ft/lb 3,485 ft/lb 1,734 ft/lb	 4.76 m/g 2.34 m/g 1.17 m/g
Tow Cross-Sectional Area 3K 6K 12K	 1.82×10^{-4} in^2 3.70×10^{-4} in^2 7.43×10^{-4} in^2	 0.12 mm^2 0.24 mm^2 0.48 mm^2
Filament Diameter	0.280 mil	7.1 microns
Carbon Content	94.0%	94.0%
Twist	Never Twisted	Never Twisted

ProGlas 4:1 Slow Curing Agent

PRO GLAS
PREMIUM EPOXY RESIN SYSTEMS

4:1 Slow
CURING AGENT

Description:

ProGlas 4:1 Slow is a modified aliphatic amine, light colored, low viscosity epoxy curing agent. Use with ProGlas 1300 series Epoxy Resin systems.

Features:

- Reduced vapor pressure
- Low mixed viscosity
- Low shrinkage
- Good Chemical resistance
- High clarity

Uses:

- Yacht/Boat Construction
- High Performance manufactured parts
- RTM/VARTM/Vacuum bagging
- Hand Lay-up application (fast wet out)
- Electrical Potting
- Tooling compounds
- Metal and plastics adhesive

TYPICAL PROPERTIES 25:100 weight

Uncured Curing Agent

Flash Point, ASTM D-3278, °F	>200
Mix ratio, ProGlas 1300 series	25:100
Gel Time 77° F	30-35 minutes (ProGlas 1300)

Handling Properties at 77 °F

Initial Viscosity	495 cps (ProGlas 1300)
Pot Life at 77° F	30-35 minutes (ProGlas 1300)

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ProGlas 4:1 Slow Curing Agent

Cured Resin[1]

Test	PROGLAS 1300 Value
Heat deflection temperature, °F	143.1
Tensile strength, psi	11947.6
Flexural strength, psi	19912.7
Flexural modulus, psi	526263.7
Barcol Hardnes (934-1)	41

Handling & Storage

All epoxy Resin/ Curing Agents, should be kept in tightly closed containers in a cool, dry place. Product will absorb moisture and carbon dioxide which may affect viscosity or create foaming when reacted with Resin/Curing Agents. This product will have a minimum shelf life of one year if properly stored in unopened containers.

ProGlas 4:1 Slow Curing Agent is available in 55-Gallon metal drums.

To ensure maximum stability and maintain optimum resin properties, resins should be stored in closed containers at temperatures below 75°F and away from heat sources and sunlight. All storage areas and containers should conform to local fire and building codes. Inventory levels should be kept to a reasonable min with first-in, first-out stock rotation.

Safety

Read and understand the Material Safety Data Sheet before working with this product

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E – 4 3M DP420 Bonding Epoxy Data Sheet

Typical Adhesive Performance Characteristics

Note: The following technical information and data should be considered representative or typical only and should not be used for specification purposes.

Substrates and Testing

A. Overlap Shear (ASTM D 1002-72)

Overlap shear (OLS) strengths were measured on 1 in. wide 1/2 in. overlap specimens. These bonds were made individually using 1 in. x 4 in. pieces of substrate except for aluminum. Two panels 0.063 in. thick, 4 in. x 7 in. of 2024T-3 clad aluminum were bonded and cut into 1 in. wide samples after 24 hours. The thickness of the bondline was 0.005-0.008 in. All strengths were measured at 73°F (23°C) except where noted.

The separation rate of the testing jaws was 0.1 in. per minute for metals, 2 in. per minute for plastics and 20 in. per minute for rubbers. The thickness of the substrates were: steel, 0.060 in.; other metals, 0.05-0.064 in.; rubbers, 0.125 in.; plastics, 0.125 in.

B. T-peel (ASTM D 1876-61T)

T-peel strengths were measured on 1 in. wide bonds at 73°F (23°C). The testing jaw separation rate was 20 inches per minute. The substrates were 0.032 in. thick.

C. Bell Peel (ASTM D 3167)

Bell peel strengths were measured on 1/2 in. wide bonds at the temperatures noted. The testing jaw separation rate was 6 in. per minute. The bonds are made with 0.064 in. bonded to 0.025 in. thick adherends.

D. Cure Cycle

With the exception of Rate of Strength Build-Up Tests, all bonds, were cured 7 days at 73°F (23°C) at 50% RH before testing or subjected to further conditioning or environmental aging.

Aluminum, Overlap Shear, at Temperature (PSI)

	3M™ Scotch-Weld™ Epoxy Adhesive DP420 Black	3M™ Scotch-Weld™ Epoxy Adhesive DP420 Off-White
-67°F (-55°C)	4500	4500
73°F (23°C)	4500	4500
180°F (82°C) (15 min.)[1]	1260	450
(30 min.)[1]	2250	700
(60 min.)[1]	2980	750
(4 hr.)[1]	2690	2500
250°F (121°C) (15 min.)[1]	570	200

[1]Represents time in test chamber oven before test.

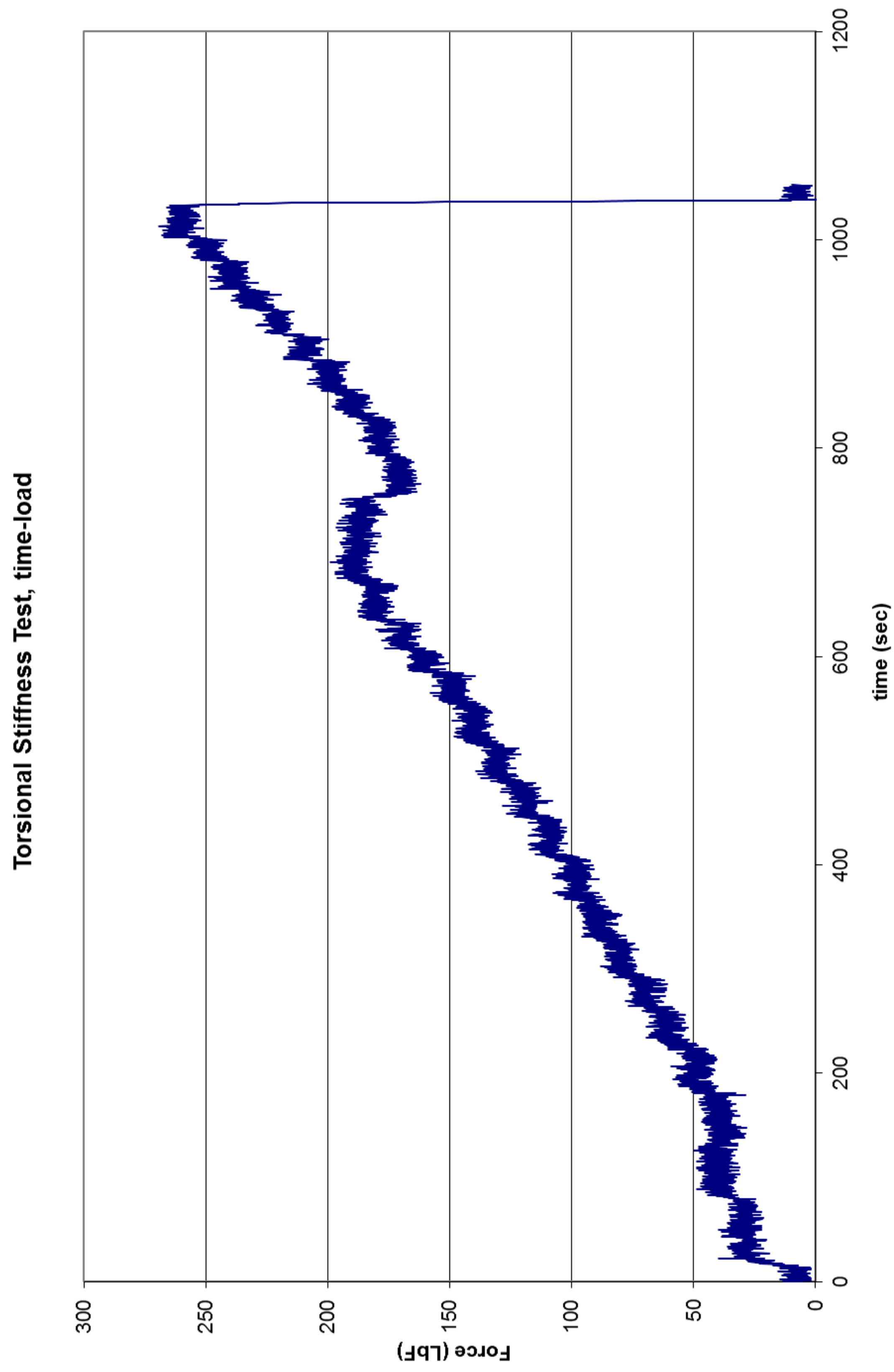
Metals, Overlap Shear, Tested @ 73°F (23°C) (PSI)

		Scotch-Weld Epoxy Adhesive DP420 Black	Scotch-Weld Epoxy Adhesive DP420 Off-White
Aluminum-	Etched	4500	4500
	Oakite degrease	4000	3500
	MEK/abrade/MEK	2500	3500
Cold Rolled Steel-	Oakite degrease	—	4000
	MEK/abrade/MEK	2200	2700
Copper-	MEK/abrade/MEK	5000	4000
Brass-	MEK/abrade/MEK	2800	4100
Stainless Steel-	MEK/abrade/MEK	1800	1700
Galvanized Steel-	Hot dipped	2900	2000
	Electrodeposited	3000	2100

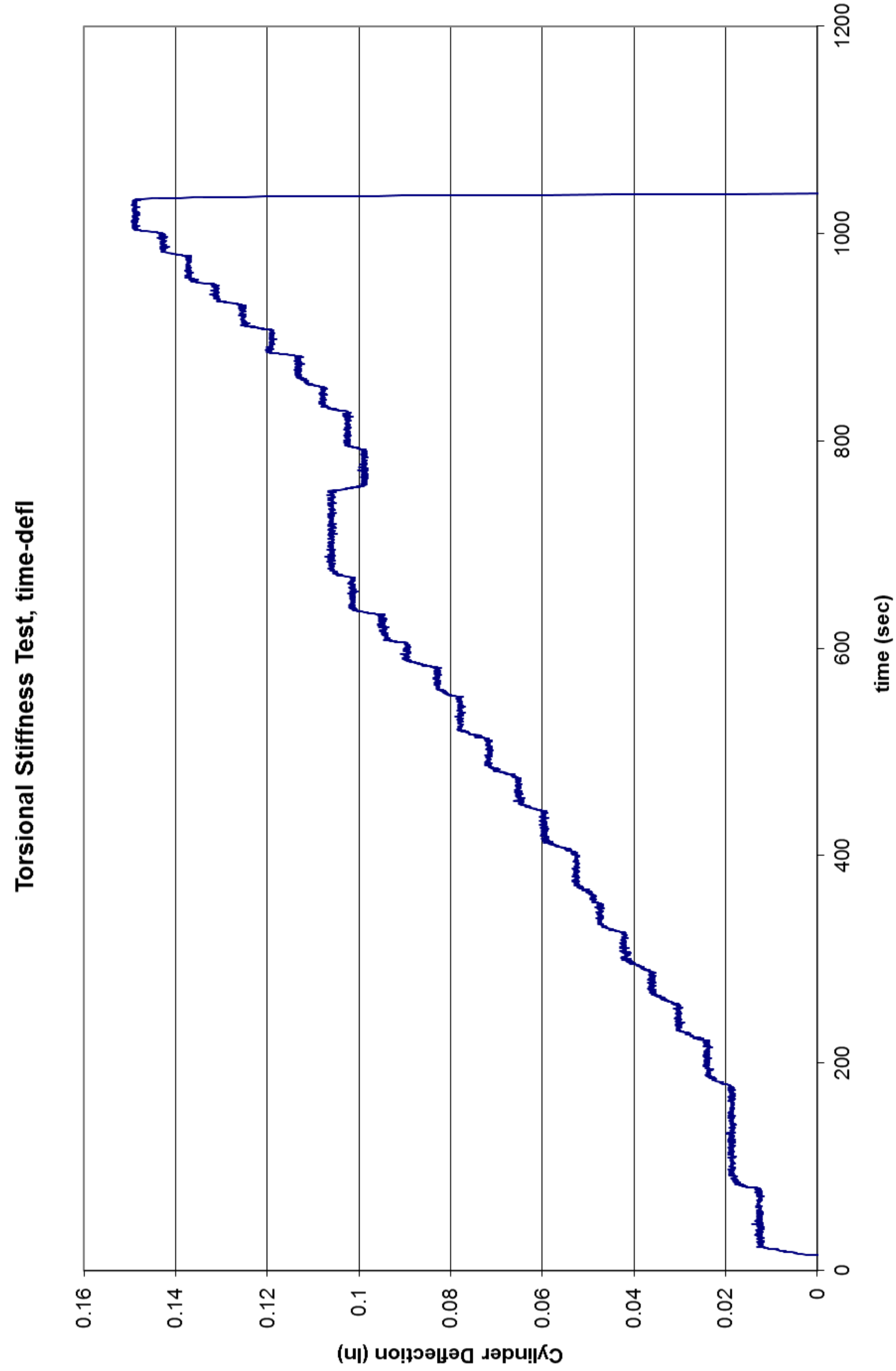
Appendix F – Torsion Testing Results

Direct data from the load cell and press

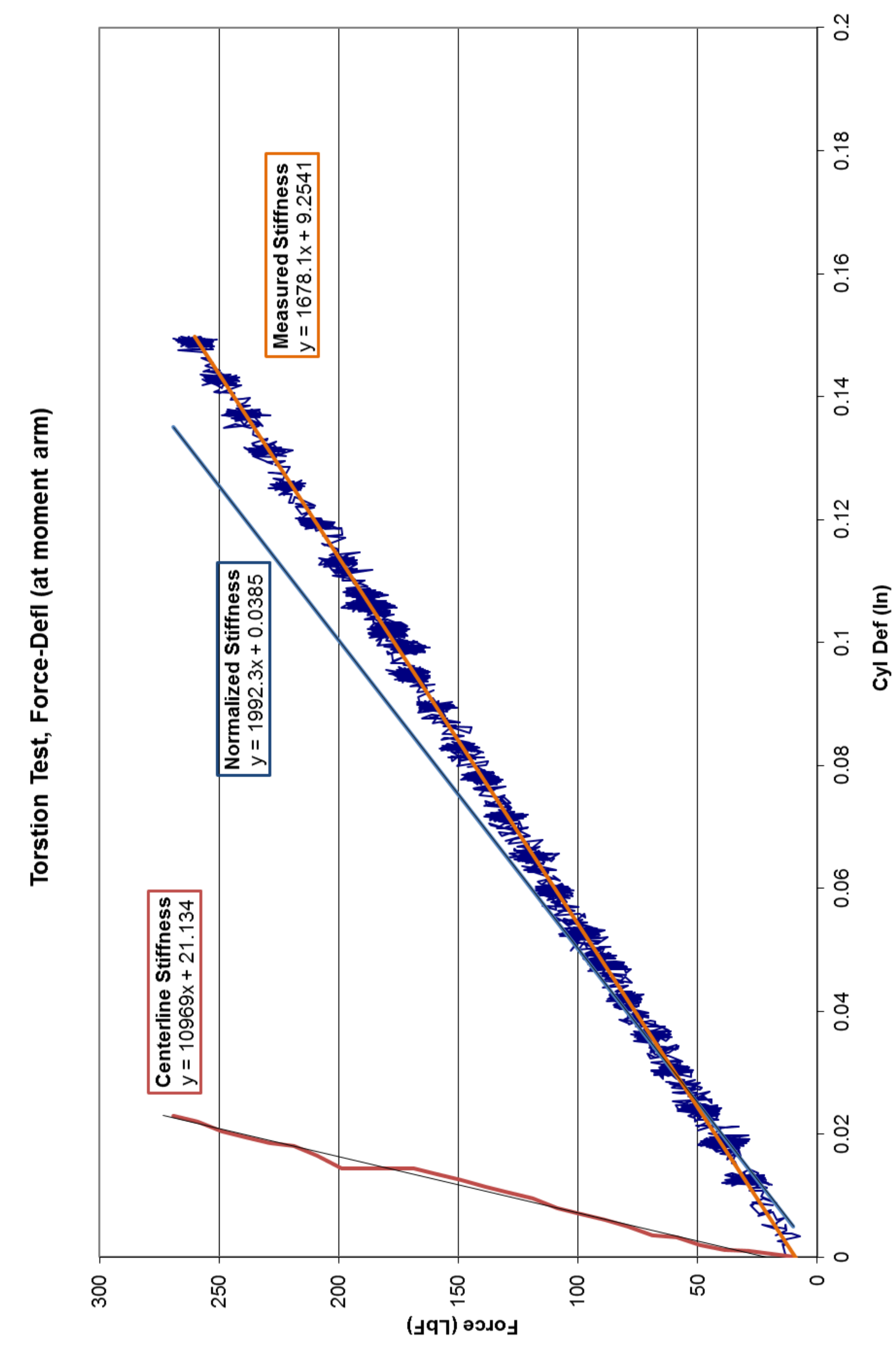
F – 1 Torsion Test, Load vs. Time



F – 2 Torsion Test, Deflection vs. Time



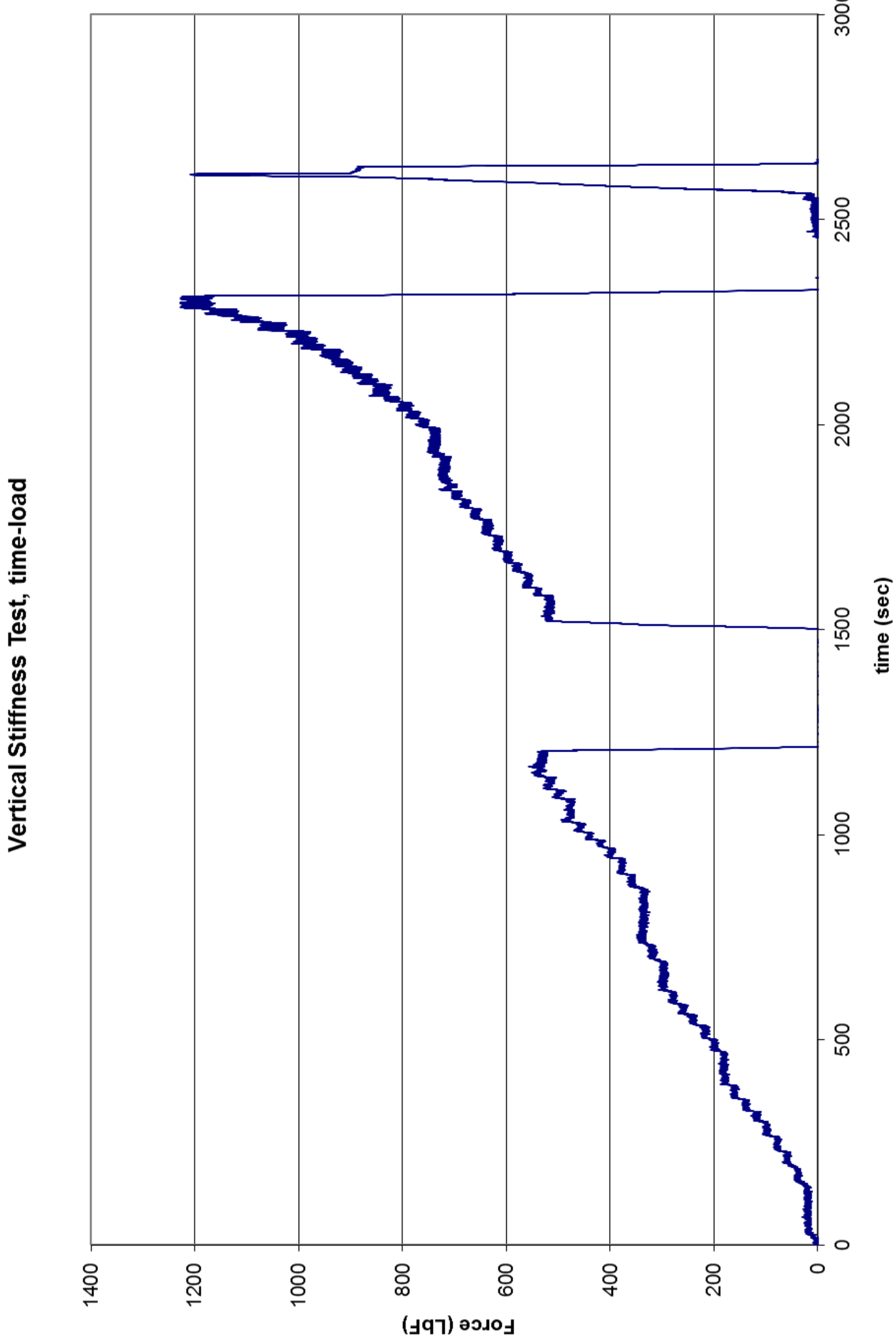
F – 3 Torsion Test, Load vs. Deflection



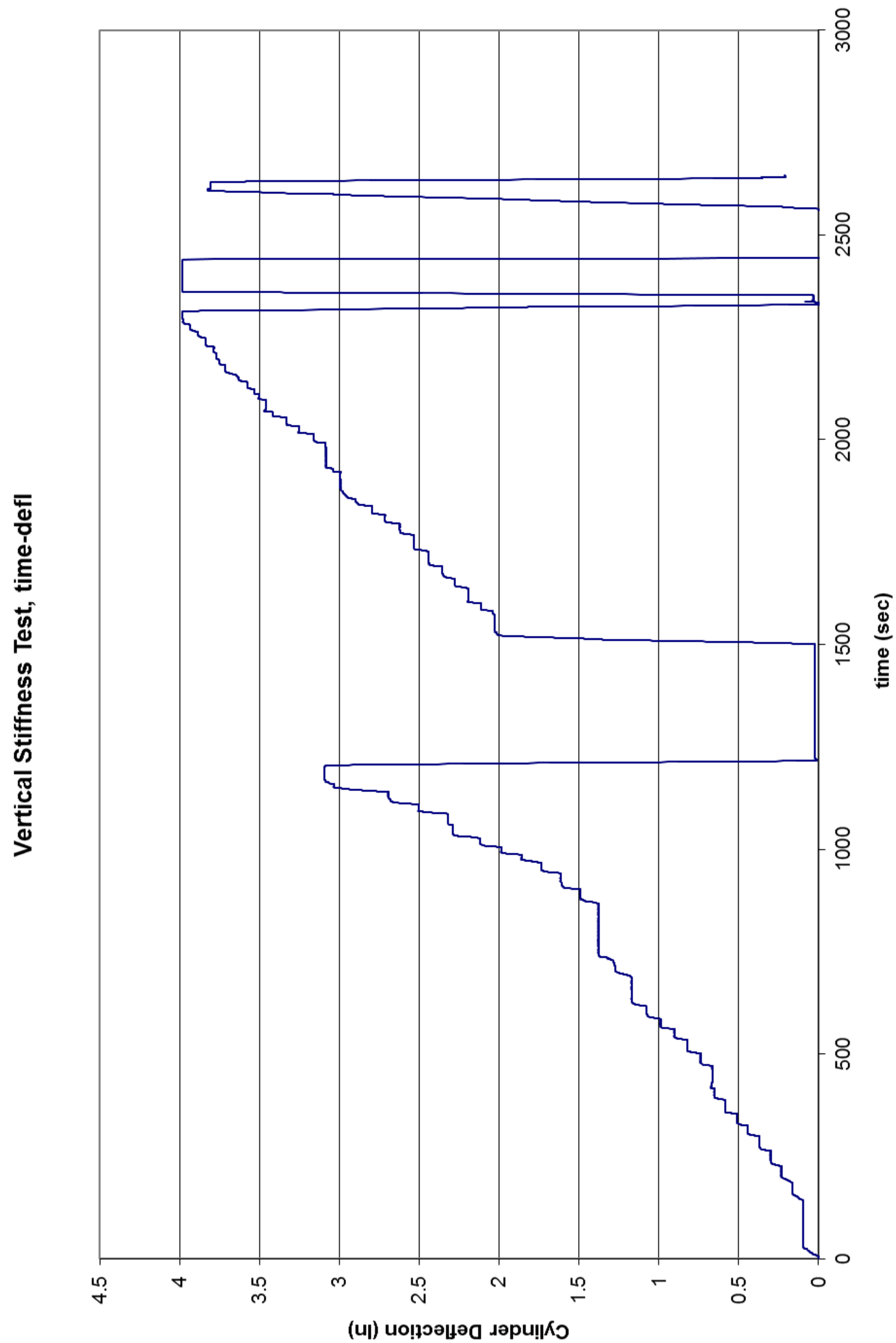
Appendix G – Vertical Deflection Testing Results

Direct data from the load cell and press

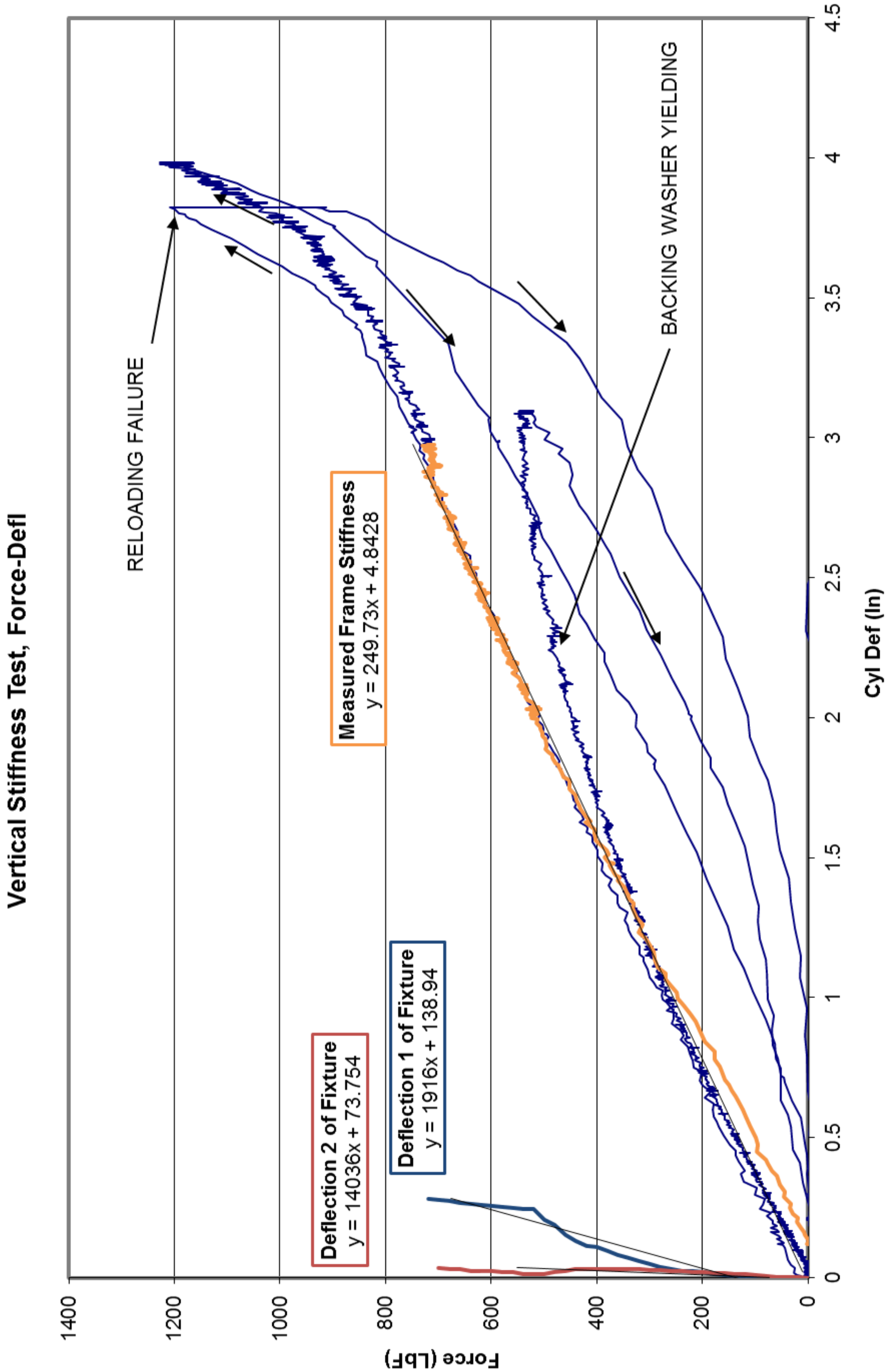
G – 1 Vertical Deflection Test, Load vs. Time



G – 2 Vertical Deflection Test, Deflection vs. Time



G – 3 Vertical Deflection Test, Load vs. Deflection



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