Madake Bambusero

The Design and Fabrication of a B amboo B icycle

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INTRODUCTION

The goal of this project was to design and build a bicycle from the ground up, using the methods explored in Single Track Vehicle Design. The project was open-ended, so long as the end product was indeed a single track vehicle. There was no requirement for uniqueness in terms of design, so long as our proposed handling charactaristics could be demonstrated with the analysis developed in the course.

I had the liberty of chosing myself as the target customer, and decided to build a racing bicycle to my own specifications. Designing and welding a steel frame was an option, but I chose not to pursue this due to the lack of avialability of shops and tools on campus. I have my own small shop in my yard, an 8' x 8' shed that holds a drill press, workbench, vice, and a few other tools; it was preferable to me to use my own setup for the fabrication phase, as I would need to be able to work at my own schedule.

Having heard of and seen bamboo bicycles in the past, I decided that this would be my material of choice. This project focused on methods of fabrication, but it also fulfilled the requirements of designing and justifying handling charactaristics using the Patterson Control Model (PCM) [1]. In addition, load handling capabilities were considered, and a qualitative analysis was done to guide the fabrication process.

This report gives a detailed synopsis of the process of designing and building a bamboo bicycle. The greatest amount of detail is given in the fabrication section, as this process was both extensive and somewhat unique. I have also included several appendices, which contain data and analyses used throughout the project. It is my hope that this report gives a complete and accurate description of my process and results, and can be used by others who wish to pursue a similar project.

Background

For several years, various builders have been constructing bicycles out of Bamboo. My introduction to the concept of a Bamboo Bicycle came in 2008 when I heard a talk by Craig Calfee in Santa Cruz. Calfee makes high end Bamboo bicycles, and claims that they are stiffer than many carbon frames, lightweight, crash-tolerant, and possess excellent vibration dampening[2].

Bamboo also has the advantage of being a sustainable building material. It is grown mostly in Asia, but can also be grown domestically. It takes only about three years for a bamboo shoot to reach full size. The energy input required for bamboo is significantly less than that for other common bicycle materials such as steel, aluminum, titanium, or carbon fiber. Additionally, the material is fully biodegradable should the bicycle become unusable.

Problem Statement

My goal for this project was to construct a fully functional road racing bicycle, with myself as the intended rider. I wanted a bicycle that was fast, lightweight, and responsive. The bicycle was to have good stiffness and vibration dampening, and would be able to accept a set of standard road components. My initial budget was $1000 for the whole project: $250 for frame materials, $500 for a component group, and $250 for any extra tools I would need for construction.

The initial hand sketch for the bicycle, showing a rough geometry layout and the concept for the joints, is shown in Figure 1 below.

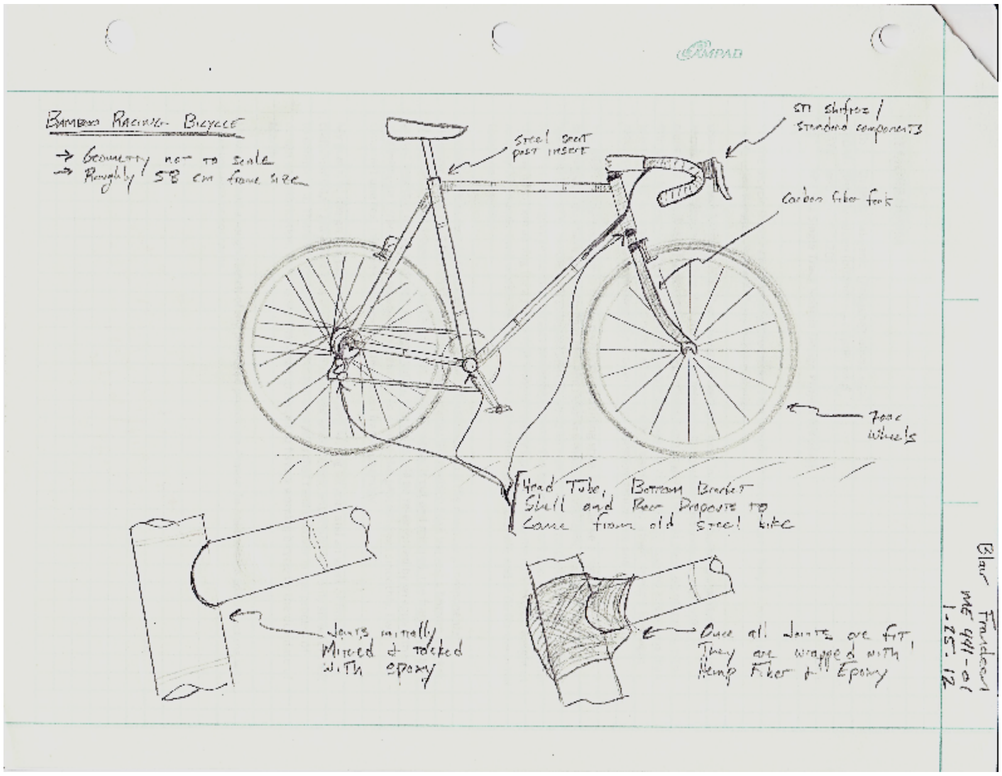

Figure 1. Initial sketch for a bamboo bicycle.

For the purpose of guiding the design and fabrication process, I created an extensive list of engineering targets, which is attached as Appendix A. Some of these targets were developed during the process. The targets provided me a clear means of evaluating the success of the project.

DESIGN

The concept for this project was that of a highly responsive racing bicycle. There was nothing particularly novel or unique about the geometry. Despite this, careful attention was paid to the handling considerations and geometric layout. Using both SolidWorks and a MATLAB code, I was able to carefully choose among different configurations for my final design.

Planning

I came up with the concept and began to plan on January 6th, 2012, giving me only two months until the March 7th completion date. Because of the length and intensity of the fabrication process, and the relatively short timeframe, it was imperative to stay on schedule. To keep myself on track, I created a Gantt chart with an outline of the expected tasks. This chart, and a revised edition taking into account previously unforseen requirements, is attached in Appendix B.

Handling Considerations

The Patterson Control Model (PCM)[1] was used to design the handling capabilities of the bicycle. Using a MATLAB code that compared different geometric configurations from an Excel sheet, I was able to carefully choose how the bicycle handled. In accordance with my problem statement and engineering targets, I designed the bicycle to have a high control sensitivity and responsiveness.

Ergonomic & Geometric Considerations

The bicycle was largely modeled after standard road racing geometry. Knowing my height of six feet, and my previous experience riding road bicycles, I knew my frame size to be roughly 58 cm, which is measured from the bottom bracket center to the center of the seat tube.

Aside from a measurement of my stand over height, I did not take any other measurements to determine my reach or knee-to-pedal alignment. If the bicycle did not end up fitting correctly in terms of either of the above requirements, it could be easily fixed by using a set-back seat post or a longer stem.

The final drawing that defines the frame geometry is shown in Figure 2 below. A full size version, along with drawings used in the fabrication process, is included in Appendix C.

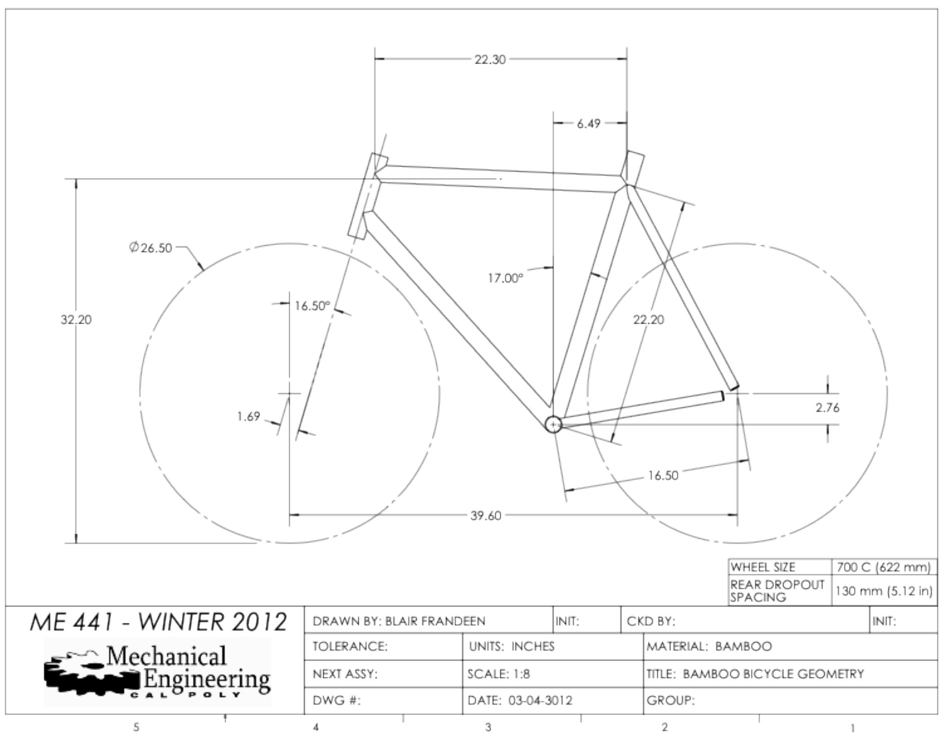

Figure 2. Engineering drawing defining final frame Geometry.

Load Handling Capabilities

In order to examine load handling capabilities, a representative model[1] of the bicycle was created in Structure, and subjected to various loading conditions. Structural analysis of Bamboo, an anisotropic material whose properties are not well known, was beyond the scope of both my knowledge and this project. However, the finite element analysis performed yielded important qualitative results, which helped to guide me in the fabrication process. From the finite element analysis, I came to the following conclusions:

[1] The geometry used in the FEA was not my final geometry, but the overall general layout was the same, and sufficient for the purpose of a qualitative analysis.

1. The load causing the largest normal stresses in the members is a front impact load. This represents the bicycle's front wheel hitting a curb or sharp bump head-on. If we model this as a static load of 500 lbf with a safety factor of 2.0, both the seat tube and the down tube must sustain 1175 lbf of tensile load, while the top tube and seat stays experience 1056 lbf 500 lbf of compressive loads, respectively. (Figure 46)

2. The load causing the largest bending stresses is a front brake load, which can also model the bicycle hitting a wall head-on. These stresses occur at the intersection of the down tube and head tube, and similar but smaller stresses occur at the head tube to top tube intersection. (Figure 47)

3. A pedaling load, which models the full force of the rider on one pedal, produces a significant bending stress where the seat tube and the bottom bracket shell intersect. (Figure 48)

4. The combined loading case of the front impact plus a handlebar load produces lower stresses than the front impact on its own. This result indicates that the isolated, worst-case-scenario load cases may not be realistic, and that combined stresses may work to counteract one another. (Figure 49)

To summarize, the strongest members of the bicycle must be the seat tube and down tube, while the strongest joints must be around the head tube and bottom bracket shell.

FABRICATION

The process I used can be largely credited to the "Building a Bamboo Bicycle" Wordpress blog[3]. From this site I did much of my research on joint fabrication, material selection, and heat treatment.

Building a bamboo bicycle took more time than I ever thought it would. Roughly five weeks passed between the cutting of the bamboo poles from their grove to completion of the bicycle, and few days passed when work was not done on the frame. I did not keep track of my hours, but I would estimate roughly 200 working hours for the entire project.

Material Selection & Acquisition

Bamboo

There are several types of Bamboo which are appropriate for bicycle building. These include Tonkin Cane, Moso, Old Hamii and Black Bamboo[4]. Of these, Tonkin Cane seems to be the material of choice. Tonkin is strong, straight, and has large spacing between nodes. It is also used for making high-quality Bamboo fly fishing rods.

There are several suppliers of Tonkin Cane Bamboo[5], [6], but finding one who was willing to ship me just enough poles to build a bicycle proved impossible. Most suppliers required purchase of an entire bale, roughly 10 times the amount I required, with shipping charges exceeding the cost of the Bamboo.

To remain within my budget and sanity level, I was forced to purchase what was available. I located some Black Bamboo poles locally at Bamboo Batu in San Luis Obispo[7], but selection was too limited for this project. Finally I visited Paso Bamboo Nursery[8] just north of Paso Robles (Figure

3), where I was able to hand pick several poles of *Phyllostachys Bambusoides*, commonly known as Madake (Figure 4).

Figure 3. Gavino Villa, owner of Paso Bamboo Nursery, with a grove of *Phyllostachys Bambusoides*.

Figure 4. Madake Bamboo poles as I purchased them. This stack of bamboo would turn into a bicycle in the following month.

Hemp Fiber and Epoxy Resin

The hemp fiber and epoxy resin combination would be used to join the members of the frame such that they could handle the required loads. I used the Super Sap CLR Epoxy from Entropy Resins[9], which has been proven to work for bamboo bicycles[3], [10]. I chose a slow hardener so I would have time to wet and shape the joints.

Hemp fiber was purchased from Hemp Traders[11], and a 1 kg bale proved to be enough for a complete bicycle. I considered using hemp webbing or rope, for a higher tensile strength, but I was not sure that this was necessary. Another option for wrapping the joints was to use carbon fiber, but this has been shown to present long-term problems; in short, the carbon and bamboo have dissimilar coefficients of thermal expansion, which can lead to separation of the joints over time[2], [12].

Metal Pieces

Not every piece of the frame can easily be made from bamboo. Most bottom brackets require a piece with special threading, and headsets need a tight press fit into a head tube. The frame must have dropouts that will accompany a rear wheel, as well as a means of clamping the seat post. While these things may technically be feasible with bamboo, it is far easier and safer to use steel or aluminum.

I ordered a 1-1/8” (36 mm outer diameter) chromoly head tube from Nova Cycles[13], as well as a seat tube. Unfortunately the seat tube was too small to be fit inside the bamboo, and I ended up using an aluminum shim cut on a lathe.

I found a chromoly mountain bike that had already been chopped up, and with the help of a hacksaw and a grinder acquired a bottom bracket shell (Figure 5) and a set of rear dropouts (Figure 6).

Figure 5. Bottom bracket shell after removal from a chromoly mountain bike frame.

Figure 6. Rear dropouts from the same chromoly frame.

Component Selection

One of the primary design criteria was for the bicycle to accept standard road components. Prior to the start of the project I had a set of racing wheels (Chris King hubs with Mavic Open Pro rims) and a set of Shimano 105 9 speed STI shifters. All components were selected to be compatible with these. I chose a Reynolds carbon fiber fork with a 1-1/8" threadless steering tube from eBay to complete the frame.

The remaining components were purchased from eBay, craigslist, the SLO bike kitchen, and local shops. A complete list of components used, and their masses, is included in Appendix F. The total cost of components I purchased was $520.99. The detailed cost analysis is included in Appendix G.

Bamboo Preparation and Heat Treatment

It is of critical importance to properly prepare bamboo before constructing a bicycle. The proper way to dry bamboo is to harvest in fall or winter, and to let it stand vertically for at least three months. Given the time constraint of this project, I did not have time to let the bamboo dry correctly. Additionally, bamboo should be heat treated with a flame torch to increase hardness and kill pests [14].

Upon acquiring the Bamboo, I began to experiment with heat treatment methods. My goals for heat treatment were as follows:

- Reduce mass by evaporating any water content in the bamboo.
- Shrink bamboo to reduce diameter. Any shrinking that occurs after assembly risks separation of the joints.
- Kill any pests to preserve bamboo over time.
- Increase hardness and strength.

I purchased a propane torch and used this to treat the bamboo. I would subject the bamboo to flame at a distance of 3" to 6", for times ranging from 3 to 10 minutes depending on the size of the bamboo. Additionally, I placed samples in my gas oven and examined the effects. I found that heat treating with a propane torch followed by placing the bamboo in an oven to be effective in reducing mass and diameter. I was able to locate one study of bamboo heat treatment [15], which helped to guide the process and give some insight as to its effects.

The gas oven was too small to accommodate the tubing I needed to use for the frame, but I was allowed to use the autoclave in the Cal Poly composites lab for this purpose (Figure 8). After treating with a propane torch, the tubing was placed in the autoclave at atmospheric pressure, and heated to 300 ˚F in a timespan of roughly 1 hour, and allowed to cool.

Figure 7. Bamboo poles prior to heat treatment, cut to approximate length. Extra poles were cut to ensure there would be enough usable material for one bicycle.

Figure 8. Bamboo poles in autoclave prior to final heat treatment.

One smaller piece of bamboo exploded while under the flame torch (ideal gas law, I know), but no other damage occurred during heat treatment. Overall, the mass was reduced by an average of 32.1%, and the diameters were reduced by an average of 4.2% as a result of heat treatment, the details of which are recorded in Appendix E.

Joint Assembly

Before beginning construction of the bicycle, I tested the method for which I would join the bamboo tubing. The method was largely developed from the "Building a Bamboo Bike" WordPress blog[3].

Mitering

To ensure a strong fit, the two pieces of Bamboo must have as much surface area contact as possible, and for this purpose the joints were carefully mitered. I used the Tube Notcher Plus software from Cobra Torch[16] (Figure 9) to get the approximate profile of the miters, and a Dremel rotary tool with a sanding attachment to come to the final shape (Figure 10).

Figure 9. Tube mitering software used to transfer mitering profile onto Bamboo.


Figure 10. Using a Dremel rotary tool with a sanding attachment to bring miter to final shape.

Once the miter had a reasonably snug fit, the two pieces were tacked together with epoxy resin and allowed to cure overnight. The tack was not expected to add significant structural strength, but enough to wrap the hemp fiber without any trouble.

Hemp Fiber Reinforcement

The hemp fiber was prepared, and in most cases wrapped around the dry joint one or more times to practice how the wrap would work. For the test joints, I coated the area to be wrapped with epoxy resin before applying the hemp fiber (Figure 11). After wrapping the hemp fiber, I applied additional epoxy to the outside (Figure 12), and used perforated electrical tape to apply pressure and squeeze out any excess resin as shown in Figure 13.


Figure 11. Applying epoxy resin to a pre-tacked joint.


Figure 12. Hemp fiber wrapped around a joint and saturated with epoxy resin.


Figure 13. Perforated electrical tape is wrapped around joint to apply pressure, and to squeeze out excess epoxy resin.

Later on in the assembly process, I noticed that the hemp fiber was not saturated well enough using the method described above, and decided instead to pre-saturate the hemp fiber before wrapping. To do this, I laid the hemp fiber on a sheet of plastic, and poured the mixed epoxy resin over the fiber (Figure 14). Using a second sheet of plastic and a squeegee, I was able to push the resin in between the fibers as shown in Figure 15. This seemed to have beneficial effects in both in terms of strength and ease of finishing.

Figure 14. Pre-mixed epoxy resin is poured over the hemp fiber.

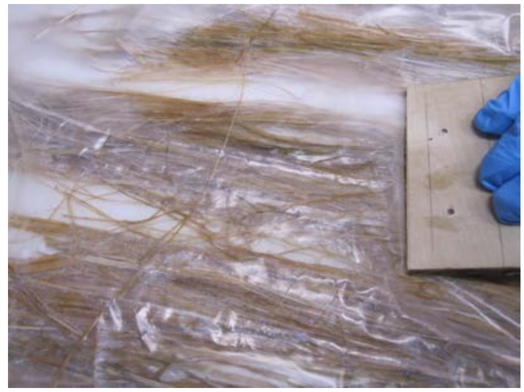

Figure 15. A wooden squeegee is used to push the resin through the fibers, ensuring they are fully saturated.

Frame Assembly

Front Triangle

Once the final geometry had been determined, it was drawn to scale on a piece of MDF, and checked carefully using over-dimensioned engineering drawings. These planning layouts are included in Appendix C.

The bottom bracket shell was mitered and tacked into the seat tube, with a small amount of the original seat tube plus a bamboo sleeve to ensure a tight fit as shown in Figure 16 below. I used the cups from the original bottom bracket shell in order to bolt the bottom bracket-seat tube assembly to the MDF jig (Figure 17).

Figure 16. Bottom bracket shell to seat tube assembly, showing miter and sleeve to ensure a tight fit.

Figure 17. Bottom bracket and set tube held securely to MDF jig.

Next the head tube was cut to length and clamped down to the MDF. This was done very carefully to ensure a correct head tube angle and frame geometry. I used a carpenter's square with lines on the MDF to measure horizontal position (Figure 18), and a set of dial calipers to ensure the center of the head tube was on a level with the center of the bottom bracket shell.

The down tube and top tube were both cut and mitered to fit in this assembly, and the front triangle was tacked together with epoxy (Figure 19).

Figure 18. Using a carpenter's square and carefully marked lines on the MDF to position the head tube.

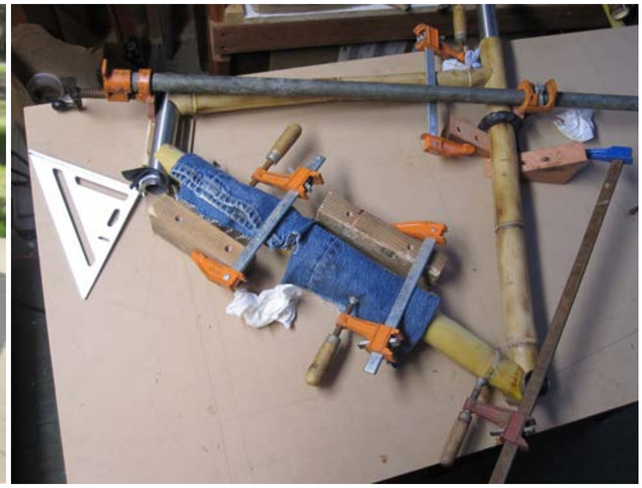

Figure 19. The front triangle as it was glued and clamped together.

Rear Triangle

Fabricating and installing the rear triangle was far more challenging than the front triangle. My first problem was that the dropouts I had acquired (Figure 6) did not fit inside my bamboo stays, and the old frame had had a different geometry and thus a different angle between the seat stays and the chain stays.

I first cut the dropout tubes in half along their length, so they became half cylinders which cupped around the bamboo stays. Using a long pipe, a propane torch, and a small vice, I heated and then bent the dropouts to the correct angle, as demonstrated in Figure 20 below. Along with the Madake bamboo I used for most of the frame, I had purchased some Mexican Weeping Bamboo, which has a solid core. I used this solid bamboo to make plugs that fit snugly inside my stays, increasing their compressive strength (Figure 21).

Figure 20. Using a lever arm and a vice to bend dropouts to the correct angle.

Figure 21. Rear dropout to seat stay assembly shows halved chromoly tubing, bamboo stay, and solid bamboo plug.

The two rear stay assemblies were glued together separately, with the ends of the stays that could attach to the front triangle left long enough to miter.

Attachment of the rear triangle to the frame proved to be the one of the most challenging and difficult tasks in the entire project. I only had the time and resources to do it once, and failure meant that the rear wheel would never align correctly. I ended up using the back wheel in the jig to correctly miter and position the rear stays, as shown in Figure 22. Using dial calipers, I checked that the center of the rear wheel would line up with the centers of both the center of the bottom bracket and head tube.

The miter joints of the chain stays to the bottom bracket proved to be very difficult to shape. There was little contact area in the initial tacking (Figure 23), and after the clamps were removed one of the stays came loose but did not completely detach. The stays were carefully held in place until the first layers of hemp fiber and epoxy resin had set.

Figure 22. Using the back wheel in the MDF jig to correctly align and attach the rear stays.

Figure 23. Junction between rear stays and bottom bracket shell shows poor contact in miter joints.

Cross Braces

I used the solid bamboo to construct two cross braces for the rear triangle. These improve stability, and the upper brace is used to mount the rear brake caliper. These were mitered with a dremel and installed once the rear triangle was securely in place (Figure 24).

Both braces proved to be problematic due to some poor planning and execution on my part. The upper cross brace was positioned too close to the wheel, and there was no clearance between it and the rear tire as shown in Figure 25. I was forced to remove this cross brace and re-do it, costing me valuable time. However, it was relatively simple to cut out the old brace (Figure 26) and grind the seatstays smooth again using the Dremel tool.

The lower brace also presented problems. It was also too close to the rear wheel (Figure 27), making it very difficult to install or remove the rear wheel. Currently one must either deflate the tire, remove the rear derailleur, or remove the quick-release skewer when changing the wheel. A somewhat embarassing mistake, but it will be rarely noticed. The second problem the lower brace presented was that it left a hole between itself and the bottom bracket shell of roughly ½” diameter.

It was difficult if not impossible to wrap and apply pressure to the hemp fiber in this area, much less sand it. If I were to re-do this piece, I would place it directly against the bottom bracket shell, and drill a small hole later on to accommodate the front derailleur cable.

Figure 24. Initial mitering of upper cross brace.

Figure 25. First iteration of upper cross brace was too close to the rear tire.

Figure 26. Removal (or amputation) of cross brace.

Figure 27. Lower cross brace, after some material removed to accommodate for the rear tire clearance. Material was also removed from the right side of this joint to give clearing for the small chainring.

Hemp Fiber and Epoxy Reinforcement

Hemp fiber and epoxy resin were used to reinforce all the joints on the frame, using the method described in the Joint Assembly section above. This was done in several phases or layers, with smaller wraps done first and larger wraps done towards the end. In wrapping the initial layers, the direction of the hemp fibers was carefully chosen such that there would be fibers going in every direction once all reinforcement had been completed.

The layers of hemp fiber and epoxy resin were sanded in-between wrappings with Dremel tool, a balloon sander attachment for a power drill, and by hand. This helped to remove excess hemp fiber that had not properly been saturated, and to create a smooth surface for the next layer to adhere to. Representative photos of this process are shown in Figure 28 through Figure 33 below.


Figure 28. First wrapping of upper seat-tube junction, after sanding.


Figure 29. First wrapping of dropout connections, before sanding.

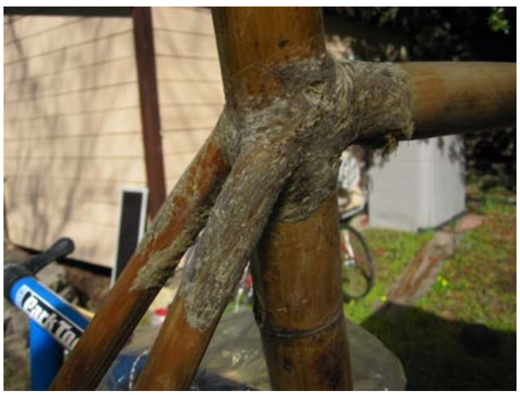
Figure 30. Second wrapping of upper seat-tube joint, after sanding.


Figure 31. Second wrapping of head tube junctions, with fibers positioned to give tensile strength in the directions of the tubing.


Figure 32. Head tube junction after 3 or 4 wrappings. The epoxy had not completely saturated the hemp fiber, leaving a lot of dry material in the joint that had to be sanded out and re-done.


Figure 33. Final wrapping of bottom-bracket junction, after sanding. The geometry here made this quite challenging to sand and wrap correctly.

Seat Tube Shim

Using a lathe and mill at the hangar, I machined a seat tube shim out of 6061 aluminum. The outside was turned down to fit snugly inside my bamboo seat tube (Figure 34). This diameter happened to be equal to that my seat post clamp. A boring bar was used to machine the inside of the shim to fit my seat post, and an endmill was used to create a short slot so that the aluminum could be clamped. Because of the solid bamboo node just below the junction of the seat tube and the top tube, the seat post is limited in how far it can go down. The seat post had to be cut short in order to accommodate a rider with regularly sized legs.

The shim was pressed into the frame (Figure 35) using a long bar clamp and epoxy resin, and holds the seat post very tightly.

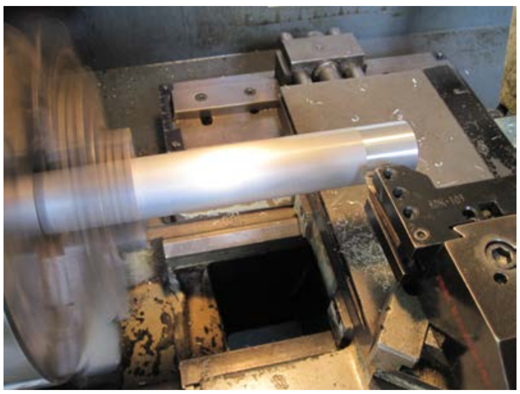

Figure 34. Turning the seat tube shim to fit snugly inside the bamboo.

Figure 35. Seat post shim and clamp installed in bamboo frame.

Front Derailleur Hanger

The seat tube was a much larger diameter than any available clamp-on derailleur, so a braze-on style mount had to be fabricated. I used a piece of U-channel aluminum, and after a few hours of cutting, pounding, heating, and grinding, had something on which to mount a front derailleur (Figure 36). I used a spring clamp to hold the derailleur hanger against the frame while I adjusted its position with the drive train installed (Figure 37). Once the derailleur was in a satisfactory position, I glued the hanger in place, and wrapped it with a layer of hemp fiber and epoxy resin.

Figure 36. Shaping the front derailleur hanger to fit on the seat tube.

Figure 37. Adjusting the derailleur hanger while to ensure that shifting can occur on the front chain rings.

Cable Routing

Figure 38. Positioning barrel adjusters to be glued to the frame for cable routing.

Some used barrel adjuster parts were glued to the frame and wrapped with the hemp fiber and epoxy resin (Figure 38). This gives a nice effect of the cables being seamlessly integrated into the frame.

Reaming and Facing, Installation of Headset

The frame was taken to the SLO bike kitchen to use specialized tools on the headset and bottom bracket assemblies. The bottom bracket threads were chased (Figure 39) to ensure easy installation. The head tube was reamed and faced (Figure 40) to accommodate a standard headset. Also used were the star-nut setting tool and headset press to install the bearing cups. The fork was installed temporarily as shown in Figure 41, but removed again so that the frame could be finished. The headset cups were left in, and protected with electrical tape and masking tape while I did the final hemp-fiber wrappings and sanding on the head tube.

Figure 39. Chasing the threads of the bottom bracket shell.

Figure 40. Simultaneously reaming and facing the head tube to accommodate a standard headset.

Figure 41. Headset, Fork, Stem, and Handlebars installed. All but the headset cups, which were press-fit into the frame, were removed before finishing.

Finishing

After seemingly endless amounts of sanding, the frame was finished with a clear coat of epoxy resin. This gave an overall nice finish, but there were several flaws due to the hemp fiber wrappings not being completely flat. A proper finish would require more clear coats and/or more sanding and shaping of the joints. Time did not allow for this, but I can hope that the single clear coat that was applied is enough to seal and protect the bamboo for a long time to come.

Testing and Final Results

Upon assembly of all components, the bicycle was ridden for the first time at midnight under a full moon. Overall the handling qualities are superb, and the geometry very closely matches the design specifications. I am very pleased with this bicycle, and am proud of my work.

Figure 42. Pride. They tell me it's a sin but god damn it feels good!

Handling Characteristics

The bicycle geometry was measured, as was the weight distribution and the mass moment of inertia. This was used in the PCM to analyze the handling characteristics as compared to the initial design. For reference, I also compared the designed and actual characteristics to one of my other bicycles, a SOMA Double Cross, which is a more stable and heavier touring bike. The control spring constant, control sensitivity, fork flop, roll authority and yaw authority are compared in Figure 43 below.

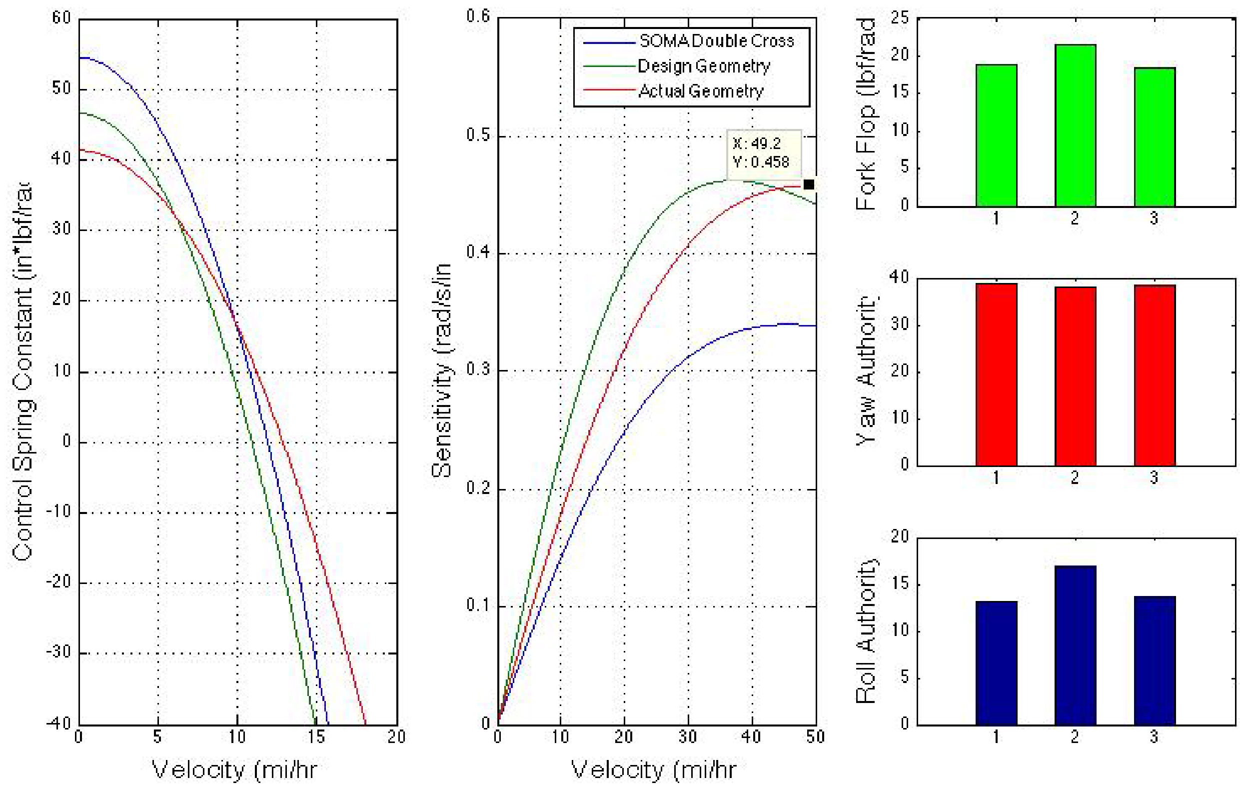

Figure 43. Handling characteristics for SOMA Double Cross, Design Geometry and Actual Geometry compared using the Patterson Control Model.

The height of the mass center measured was six inches greater than the height designed for, leading to differences in the plots above. This discrepancy could be an error in the design, in that I did not have a clear way to design for or predict where the mass center would be located. It could also be an error in measurement, as I had nobody to help me position the bicycle on the scales while measuring. As determined earlier in the quarter, the uncertainty in the height of the mass center is ±1.75 in, which could also have contributed to this discrepancy.

Ergonomics & Geometry

Overall the bicycle fits me very well, although I have not ridden it extensively. Nearly all the dimensional engineering targets listed in Appendix A were met, with the notable exceptions of the mass center height and stand over height.

Rideability

As expected, the vibration dampening of bamboo gives for an exceptionally smooth ride. The bicycle is responsive, but also comfortable to ride at high speeds.

The frame is not as stiff as I would have liked it to be. A force applied to either pedal produces a significant deflection of the bottom bracket, and I am afraid that this reduces the power transfer capabilities of the bicycle. Additionally, I worry that the bottom bracket shell may eventually break loose due to fatigue, but time will tell.

I believe the reason for the lack of stiffness has to do with the rear stays being slightly undersized. It could also be a result of the poor miter job of the chainstays to the bottom bracket shell, and the extreme difficulty of effectively wrapping that joint.

Cost Analysis

I kept careful track of all expenses related to this project. My total cost for the project was $1,253.23, an overrun of 19.4% from my initial estimate of $1050. I made a few mistakes in purchasing components, such as a seat tube, front derailleur, and seat post clamp that I did not need. Additionally, I ended up using roughly only half of the epoxy resin and hemp fiber that I purchased. However, it is always better to have too much than too little when it comes to materials.

I feel that the tools I purchased for this project, namely the Dremel rotary tool, large clamps, measuring tools, and propane torch were good investments, and I expect to use them again in the future.

The complete cost analysis is included for reference in Appendix G.

DISCUSSION

In the process of building this bicycle, I learned several things about the feasibility and characteristics of bamboo bicycles. Additionally, I gained several insights into the design process, and saw the results of careful planning and goal setting. Finally, I have identified a few specific areas for continued research and development of bamboo bicycles.

Practicality and Utility of Bamboo Bicycle Concept

Bamboo has several attractive attributes for building bicycles, but also some difficulties. The material has proven to be strong, lightweight, and seems to possess excellent vibration dampening qualities. Additionally, it is a sustainable and organic material, requiring far less energy to produce than steel. The bamboo itself can be grown quite inexpensively, and the tools used to shape the bamboo are less costly than tools used for metal.

There are also a few disadvantages to bamboo bicycles. First, and most noticeable to myself, is the intense amount of labor required to complete a frame. I did not track my hours, but I would estimate I've spent over 200 hours for the entire project. Calfee claims each of his frames requires 40 man-hours of work [2], which seems reasonable for an operation that is already set up with tools, material, and experience which I did not have. One specific complication is that a naturally grown material will never be perfectly straight or round. Thus, mass-production of bamboo bicycles is inherently labor-intensive

Another issue is that the mechanical properties of bamboo are not very well known. I was able to locate little information on tensile strength or Young's modulus, and finding information that pertained to my particular material was impossible. The mechanical properties of bamboo are surely influenced by where it was grown, how and when it was harvested, and how it has been dried and treated.

Insights into the Design and Fabrication Process

This project has turned out to be largely successful, and I would attribute this to two tangible things which can be found in this report. The first is the use of careful scheduling shown in the Gantt charts (Appendix B). Regularly checking this schedule helped to keep the project on schedule. I found that it was easiest to plan by working backwards: How many days do I want for testing? How long will it take to assemble components? How long to finish the frame? and so forth. It may also be of interest to attempt to predict and keep track of hours for each specific task.

Setting clear and specific engineering targets was also a strong point in this project. In addition to guiding the fabrication and design process, these engineering targets give tangible criteria for success or failure of a project. I can say with confidence that this project is successful, based on the large number of targets in Appendix A which were met. Some important targets, such as frame stiffness and overall life of the machine, were not considered, but would also have been useful.

Questions for Further Study

While my bicycle seems to have turned out well, and seems to be strong enough for normal use, there are several aspects of my prototype which I do not understand. Additionally, the project opened up several questions regarding fabrication methods and processes for bamboo bicycles. The following are open ended problems that could be taken up for further study.

Mechanical Properties of Bamboo and Joining Methods

A detailed analysis taking into account the anisotropic nature of both the bamboo and the hemp fiber-epoxy joints was far beyond the scope of this project and my current knowledge. Determining the properties of bamboo analytically is difficult for reasons described above, and mechanical testing of a specific material is likely more feasible. The properties of the nodes in the bamboo are also of interest. One study that I read[15] performed tension testing on rectangular samples, but I am curious as to the properties of an un-modified stalk.

The hemp fiber-epoxy joints should also be subjected to mechanical testing, particularly cantilever bending, tension, and fatigue. The forming method of these joints can also be explored, as well as the possibility of using a pre-wound hemp cord or webbing, rather than the loose fiber used for this prototype.

Methods of Heat Treatment

Heat treatment of bamboo is certainly essential to creating a strong and long-lasting machine. In this project, a rather unique situation was encountered, in that the bamboo I had was green and needed to be dried very quickly. As of this writing it appears as if I was successful, but there is the very real possibility that the bamboo has not finished curing, and may indeed split in the next months. There are very small cracks at the nodes in some of the main tubes, and I will monitor these throughout the life of the bicycle.

While the heat treatment methods I experimented with seemed to be effective, they could certainly be refined for a specific species of bamboo and application.

Use of Bamboo for Other Components

In this project bamboo is used as the primary frame material, but every other component and some parts of the frame are still made of standard bicycle metals. According to Appendix F, the 'bamboo bicycle' is only 25% bamboo by mass. I am curious as to the feasibility of expanding the use of bamboo to other parts of the bicycle, such as the seat post, stem and handlebars, or front fork.

There is also the possibility of using bamboo or other naturally based composites to make other components, and the research and development required for this could be *very* extensive.

Scalability and Sustainability

As mentioned above, bamboo bicycles require a large amount of labor in their production. Additionally, the joining methods used produced a significant amount of landfill waste, almost certainly exceeding the mass of the bicycle. This included used nitrile gloves, plastic sheets, electrical tape, sandpaper, and cleaning supplies. If bamboo bicycles are to be honestly marketed as 'sustainable', the process of manufacturing should reflect that.

CONCLUSION

This project saw the conception, design, and fabrication of a very unique but very useful machine from start to finish. I built this bicycle out of passion and determination, with little concern for what grade I would receive or how others would react to it. As of this writing the bicycle is still perfectly functional. However, if it were to have broken the first time I sat down on it, I would have said the same thing I'm saying now: It was worth it for the journey. The experiences and lessons learned are of far greater worth than any machine.

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Appendix A: Engineering Targets

The following list of engineering targets was used to guide the design process, and as a means to evaluate the final results. There was no practical way to evaluate the load handling capabilities, so these are left as unknown.

Table A-1. Engineering targets.

DIMENSIONS

SPECIFICATION	DESCRIPTION	TARGET	TOLERANCE	FINAL RESULT	TARGET MET?
Bottom Bracket Drop	Height of BB Center from Ground	2.76 in	± 0.25 in	2.6875	Yes
BB Shell Width	Should Accept Standard Bottom Brackets	68 mm	± 1 mm		Yes
BB Threading	Standard Threading	1.37 x 24 tpi		Fits Standard Bottom Bracket	Yes
COM Height	Height of Mass Center	39.14 in	± 2 in	46.78 in	No
COM X-Pos	X Location of Mass Center (from rear wheel)	17.42 in	± 1 in	16.71 in	Yes
Front Wheel-Downtube Clearance	Shortest Distance from Front Wheel to Downtube	2 in	± 0.5 in	1.5 in	Yes
Front Wheel-Pedaling Clearance	Front Wheel Should Never Hit Feet, Even in Sharp Turn	0.25 in	- 0.125 in	0.375 in	Yes
Head Tube Angle	Determines Trail & Handling Characteristics	16.5˚	± 0.5˚	16˚	Yes
Headtube Size	Should Accept a 1-1/8" threadless headset	1-1/8"	± 0.01 in	Fits Standard Headset	Yes
Rear Dropout Spacing	Should Accept Modern Road Wheels	130 mm	± 1 mm	130 mm	Yes
Rear Wheel-Brake Clearance	Distance Between Bottom of Brake Caliper and Tire	0.25 in	- 0.125 in	0.25 in	Yes
Rear Wheel-Seat Tube Clearance	Shortest Distance from Seat Tube to Rear Wheel with 700x25C Tire	1 in	± 0.5 in	0.75 in	Yes
Seatpost Size	Should Accept a standard seatpost	31.6 mm	± 0.1 mm	Seatpost fits perfectly	Yes
Small Chainring Clearance	Shortest Distance Between Small Chainring and Right	0.25 in	± 0.125 in	0.125 in	Barely

	Chainstay				
Standover Height	Ground to Center of Top-Tube	32.2 in	± 0.5 in	33.25 in	No
Trail	Intersection of Ground and Steering Axis	2.16 in	± 0.25 in	2.04 in	Yes
Wheel Size	Should Work with 700x25C tires	700c (622 mm)	± 4 mm	Untested with 700 x 25C, 700 x 23 a very tight fit	Unknown
Wheelbase	Distance Between Contact Points for Straight ahead riding	39.6 in	± 0.5 in	40.0 in	Yes

WEIGHT

SPECIFICATION	DESCRIPTION	TARGET	TOLERANCE	FINAL RESULT	TARGET MET?
Frame Weight	Before any components are installed	6 lbf	± 1 lbf	5.0 lbf	Yes
Total Weight	With all Components Installed	20 lbf	± 2 lbf	21.17 lbf	Yes

HANDLING CAPABILITIES

SPECIFICATION	DESCRIPTION	TARGET	TOLERANCE	FINAL RESULT	TARGET MET?
Critical Speed	Where Control Spring = 0	10.9 mph	± 2 mph	12.9	Yes
K1 Constant	Determines Handling at Low Speed	46.6	± 5	41.3	Almost
Roll Authority	Determines Response to Roll Input	16.9	± 2	13.7	No
Top Speed	Where Control Sensitivity is a Maximum	35 mph	± 5 mph	49	No
Yaw Authority	Determines Response to Yaw Input	38	± 2	38.5	Yes

COST

SPECIFICATION	DESCRIPTION	TARGET	TOLERANCE	FINAL RESULT	TARGET MET?
Component Group	Derailleurs, Cables, Fork, Crankset, Brakes, Stem, BB, Headset, Etc.	$500	± 20	$520.99	Almost

Disposables	Gloves, Acetone, Tape, Sandpaper, Things that Cannot be Reused	$50	± 10	$94.71	No
Frame Materials	Bamboo, Epoxy, Metal Bits, Etc.	$250	± $20	$300.29	No
Tools	Dremel, Torch, Clamps, Anything that can be used again for other projects	$250	± 20	$269.24	Yes

LOAD HANDLING CAPABILITIES

LOAD	DESCRIPTION	TYPE	MAGNITUDE (lbf)	SAFETY FACTOR	
Bump	Rider Hits Bump at Speed	Force / Impact	500	2	Unknown
Handlebar	Rider Leans forward on Bars	Force / Static	100	1.5	Unknown
Pedal Stand	Rider Standing on Pedals, Coasting	Force / Static	200	1.5	Unknown
Pedal Stroke	Rider Pedaling Full Force	Force-Moment / Dynamic	200	2	Unknown
Seat	Rider sitting on ass	Force / Static	200	1.5	Unknown

QUALITY TARGETS

(things that cannot easily be quantified)

NAME	DESCRIPTION	FINAL RESULT	TARGET MET?
Joy of Riding	Bicycle is fun and pleasurable to ride. You don't want to get off, just keep pedaling. Fuck you, give it back, it's my turn now!	Nearly everyone (30+ people) who rode the bike at the Parade (March 7th, 2012) enjoyed it and had good things to say. I must say I quite like it myself.	Yes
Comfort	Bicycle fits me well, and I do not have to strain to stay in a strong riding position. I can ride for long periods of time (1+ hours) without back, knee or butt pain.	Great fit. Have not ridden for more than half an hour, and have not ridden without a backpack as of this writing, but overall it seems to fit perfectly. Small adjustments to the saddle position and stem angle can be made with no cost if need be.	Yes

Vibration Dampening	Bicycle should respond well to small bumps, manhole covers, potholes, and dead squirrels encountered while riding. Minimal force should be transferred to riders hands/hips.	Handles bumps incredibly well. Frame is almost not stiff enough, but in terms of comfort on the road it does very well.	Yes
Aesthetics	Bike Should Look Fucking Badass. It's made of fucking bamboo, holy shit! The Joints are clean and smooth. The shape of the frame comes naturally from the curves and unevenness of the bamboo. The color is uniform and cohesive. No loose ends. Transition from bamboo to metal is seamless. No drippy glue joints. No major scratches / flaws of craftsmanship. If it rides like crap at least it should look pretty.	Overall bicycle is very aesthetically pleasing. I've spend hours staring at it, and have several good photographs. The final sanding on the joints could have been better, as well as the finish coat, as there are several noticeable imperfections here.	Yes

Appendix B: Gantt Chart

The following two Gantt charts were used for planning purposes, and assisted in keeping the project on schedule. The initial Gantt chart is displayed in Figure 44 below. Once the project was halfway completed, a revised Gantt chart, Figure 45 on the following page, was made to accommodate for the epoxy cure time and other previously unforeseen considerations.

These Gantt charts ended up being a very useful guide, and the actual design and construction schedule is reflected very closely.

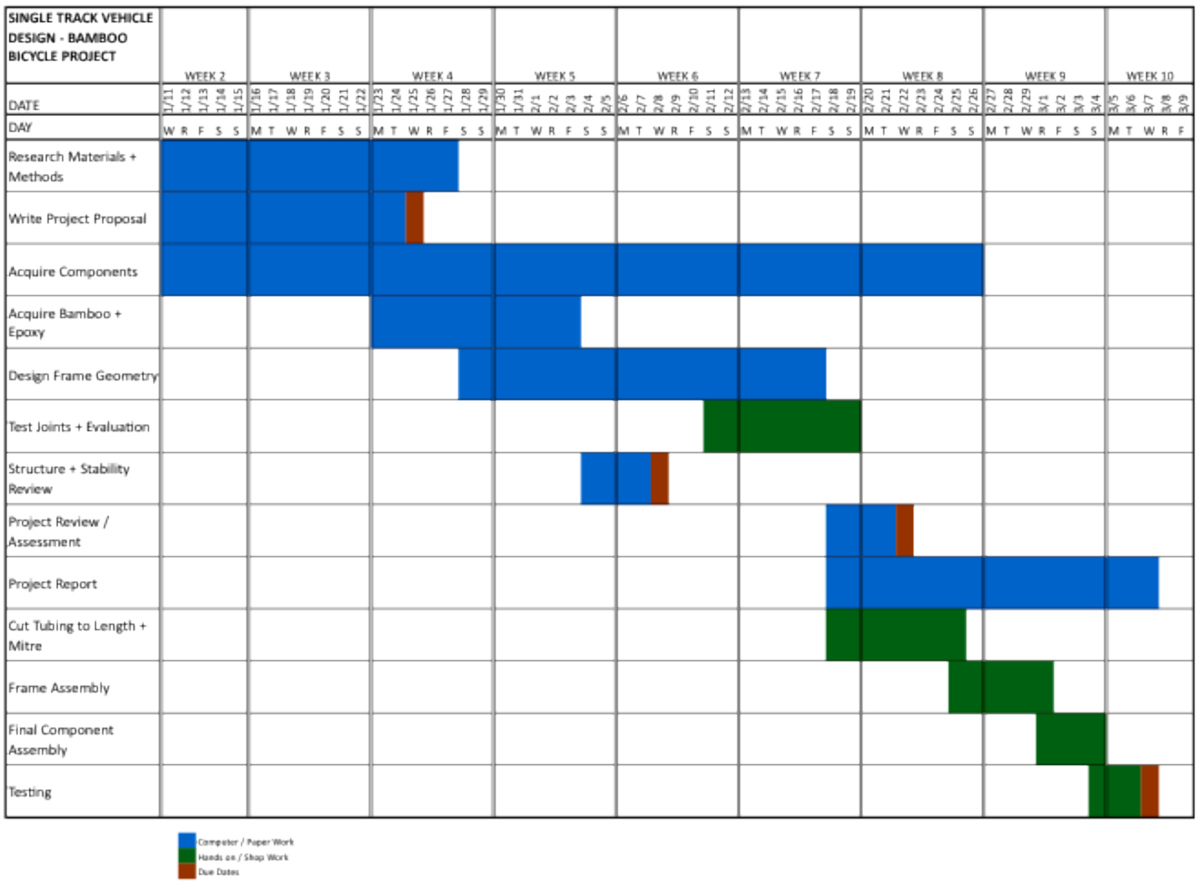


Figure 44. Initial Gantt chart used for planning purposes.

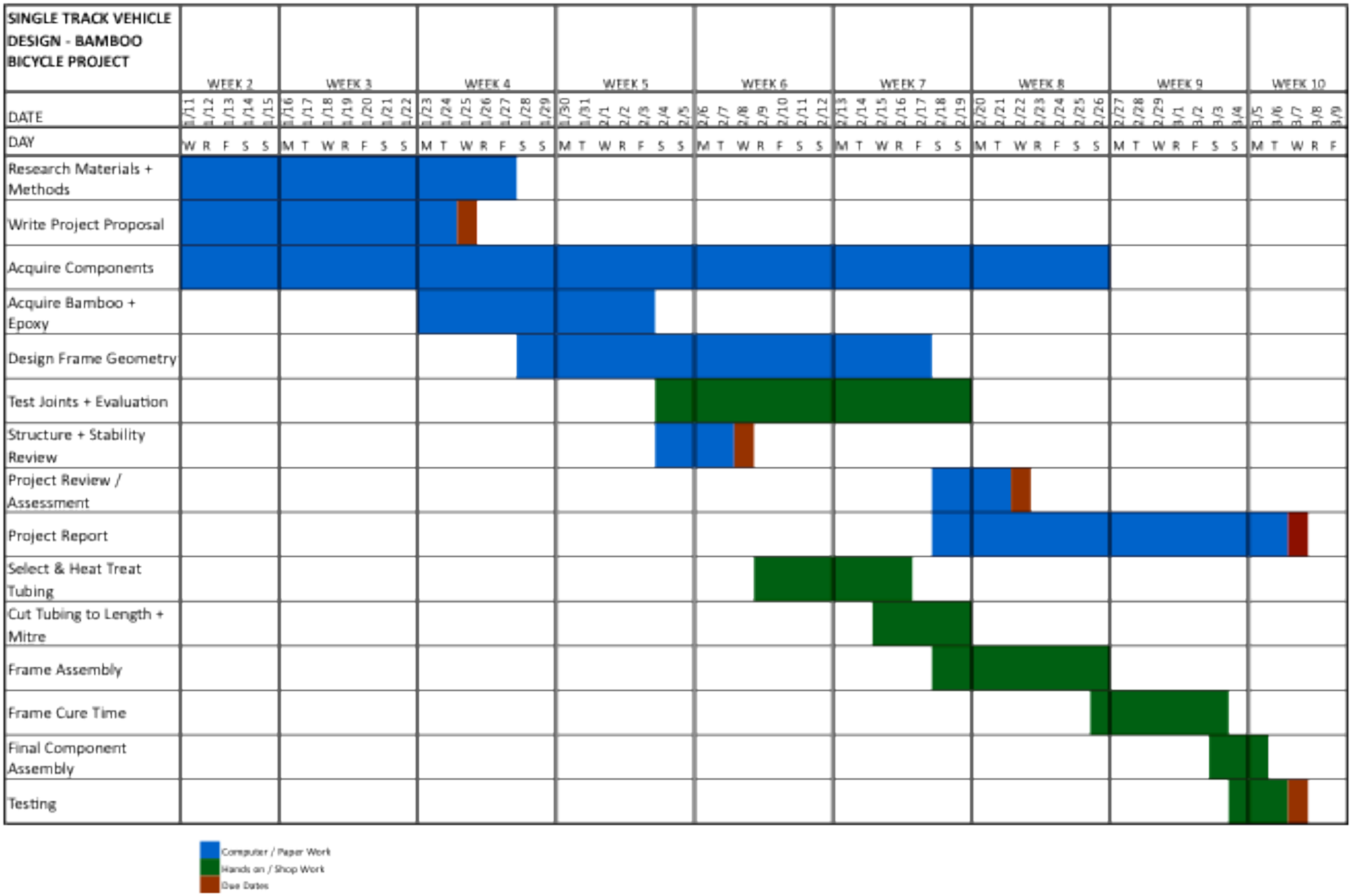


Figure 45. Revised Gantt chart used for planning purposes. This table accounts for the epoxy cure time and other considerations that had not been forseen earlier.

Appendix C: Engineering Drawings

The attached engineering drawings were used in the design and fabrication of this bicycle.

Frame Geometry

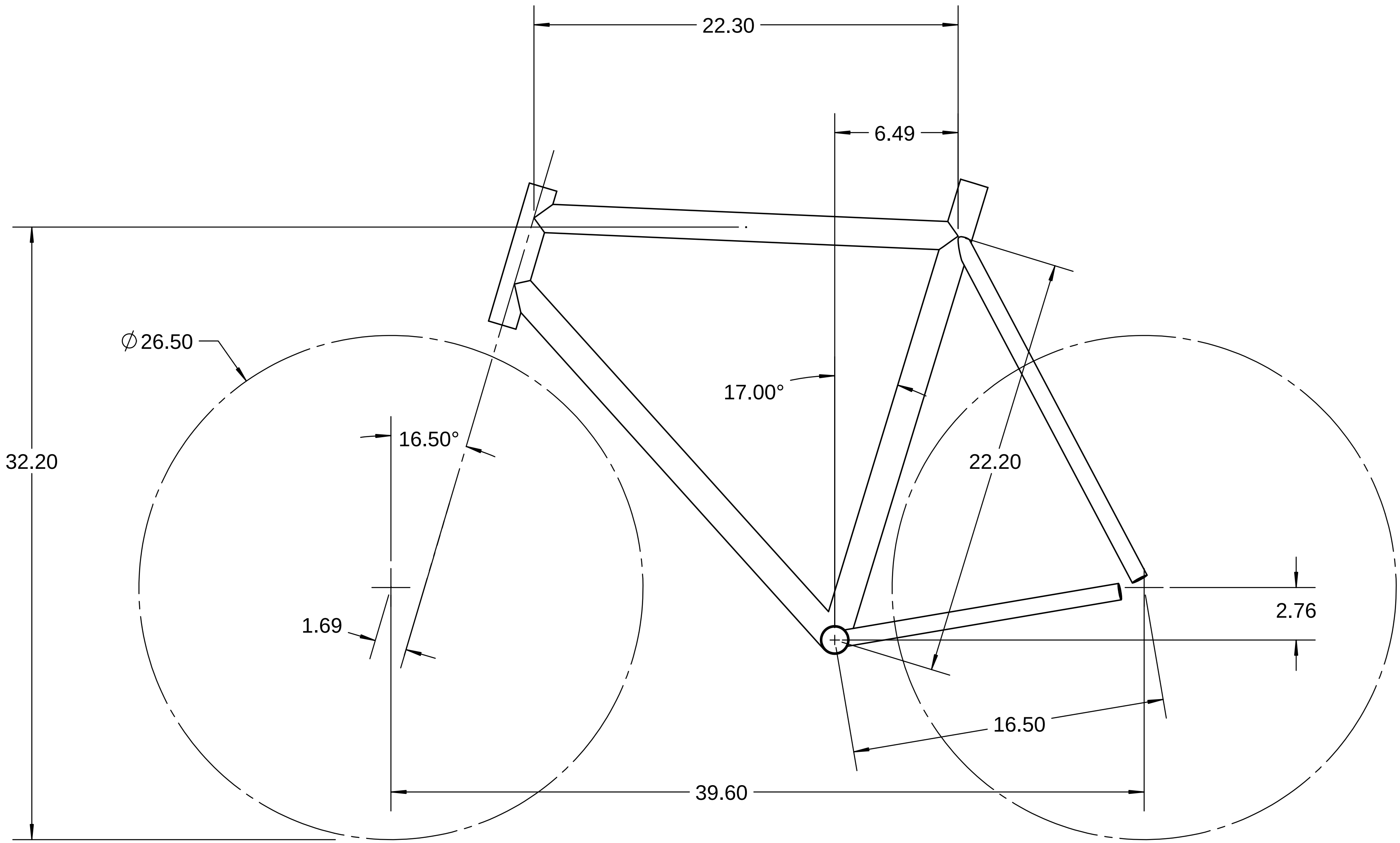
Page C-2. Shows all relevant geometric dimensions to completely define the frame.

Front Triangle Layout

Page C-3. Over-dimensioned drawing used for transferring front triangle geometry SolidWorks model to MDF.

Rear Triangle Layout

Page C-4. Over-dimensioned drawing used for transferring rear triangle geometry from SolidWorks to MDF, and for forming rear stays.



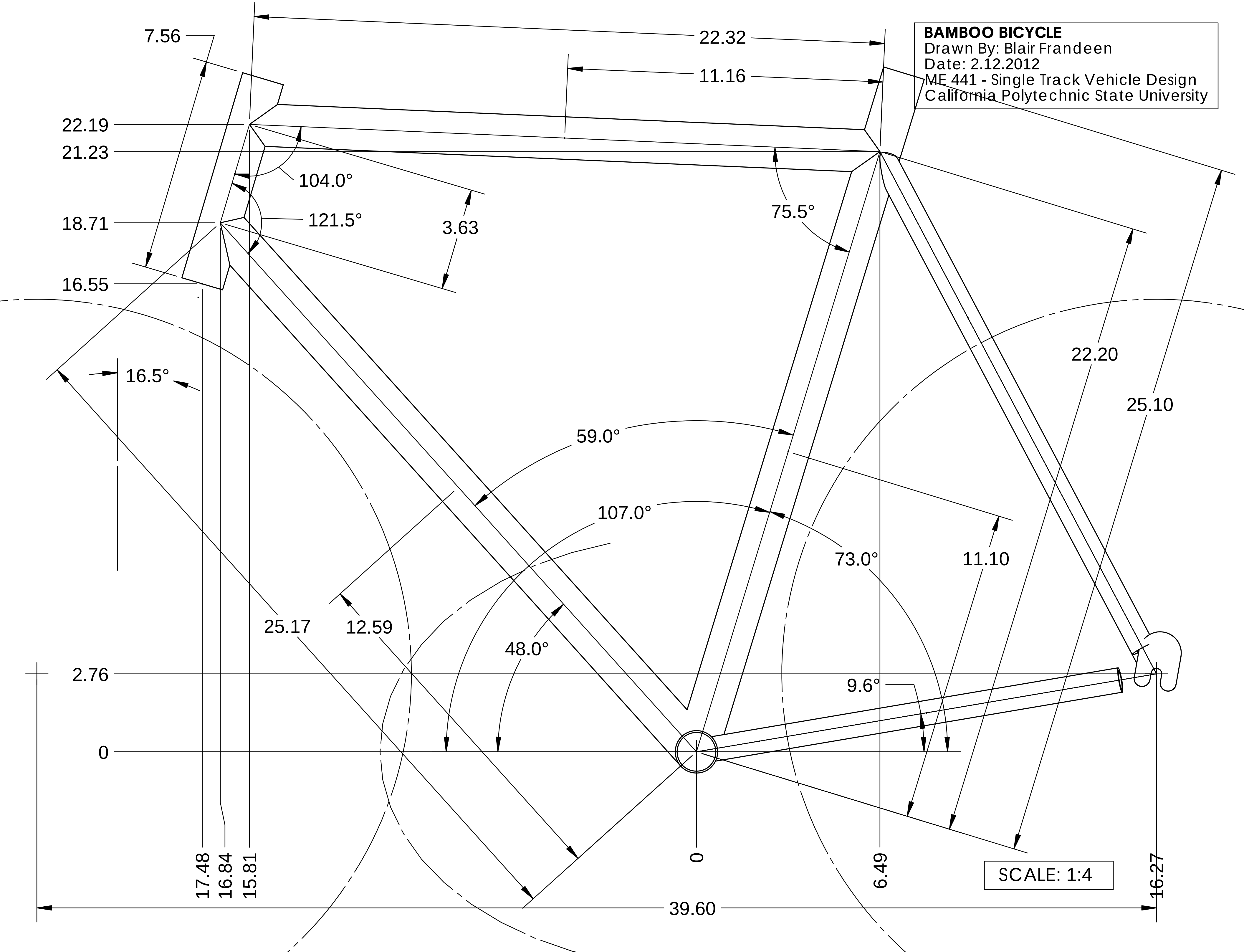
WHEEL SIZE	700 C (622 mm)
REAR DROPOUT SPACING	130 mm (5.12 in)

ME 441 - WINTER 2012

Mechanical Engineering
CAL POLY

DRAWN BY: BLAIR FRANDEEN	INIT:	CKD BY:	INIT:
TOLERANCE:	UNITS: INCHES	MATERIAL: BAMBOO	
NEXT ASSY:	SCALE: 1:8	TITLE: BAMBOO BICYCLE GEOMETRY	
DWG #:	DATE: 03-04-3012	GROUP:	

5 4 3 2 1


BAMBOO BICYCLE
Drawn By: Blair Frandeen
Date: 2.12.2012
ME 441 - Single Track Vehicle Design
California Polytechnic State University
7.56
22.32
11.16
22.19
21.23
104.0°
121.5°
3.63
18.71
75.5°
16.55
22.20
25.10
16.5°
59.0°
107.0°
73.0°
11.10
25.17
12.59
48.0°
2.76
9.6°
0
SCALE: 1:4
17.48
16.84
15.81
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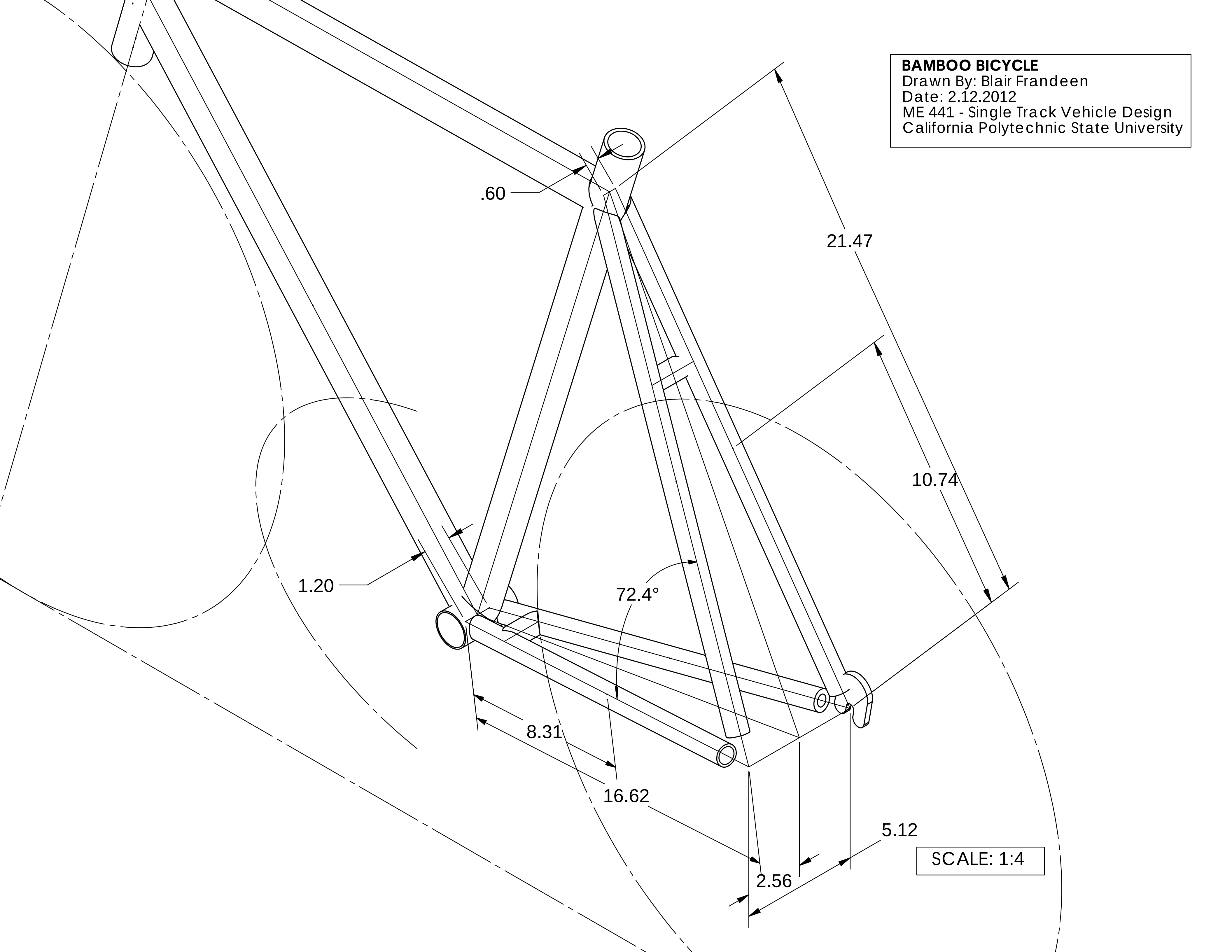
6.49
16.27
39.60


BAMBOO BICYCLE
Drawn By: Blair Frandeen
Date: 2.12.2012
ME 441 - Single Track Vehicle Design
California Polytechnic State University
.60
21.47
10.74
1.20
72.4°
8.31
16.62
2.56
5.12
SCALE: 1:4

Appendix D: Load Handling Analysis

The following analyses were performed using Structure. While they are not representative of actual stresses in the bamboo (due to its structural complexity), they offer qualitative results that helped to guide me in the relative size of the members.

Graphical Results of Loading Conditions

The results below, (Figure 46 through Figure 49) show the resultant loads and the total bending stresses for selected loading conditions.

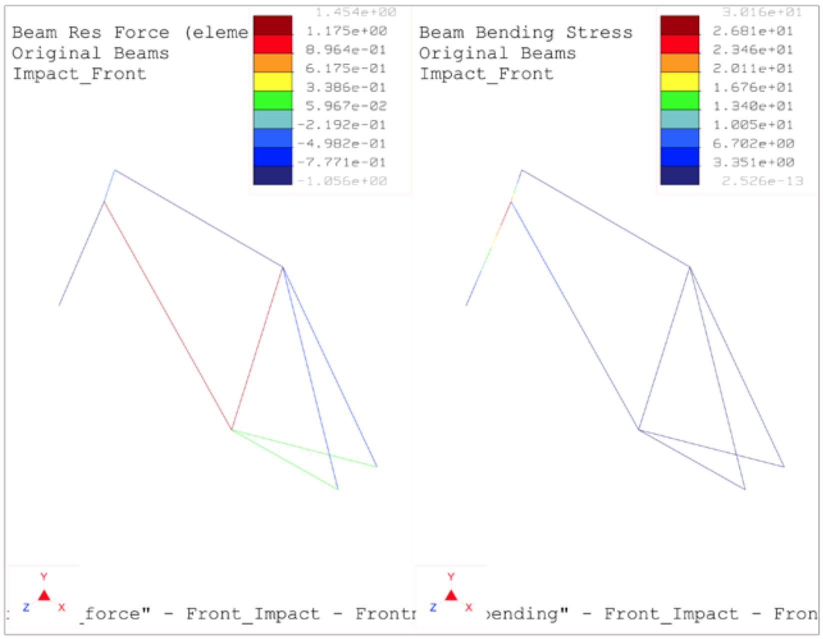


Figure 46. Front impact load on bicycle shows highest stress in down tube and seat tube.

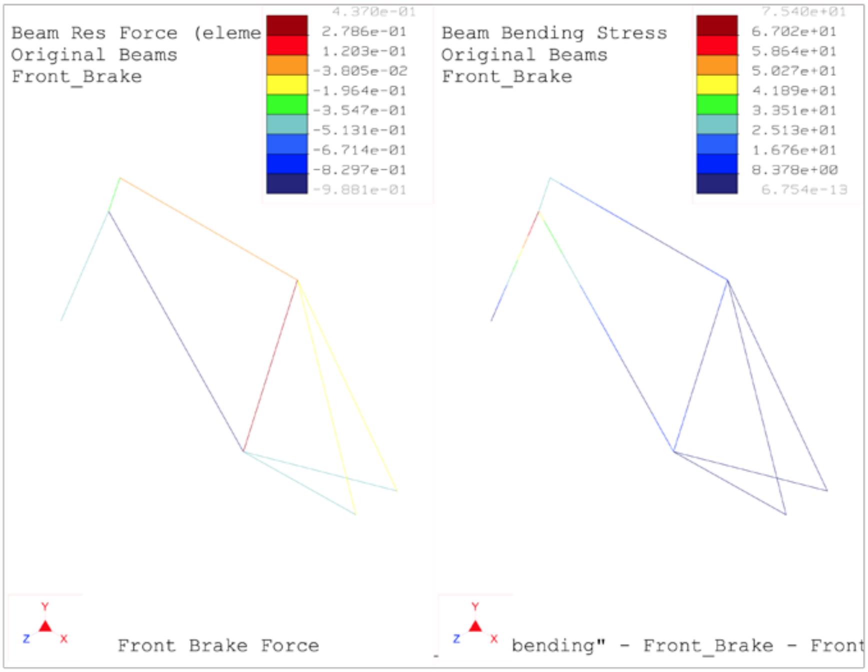


Figure 47. A front brake force, which can also model a head-on collision, produces high bending stresses in the intersections of the down tube and head tube, as well as the top tube and head tube.

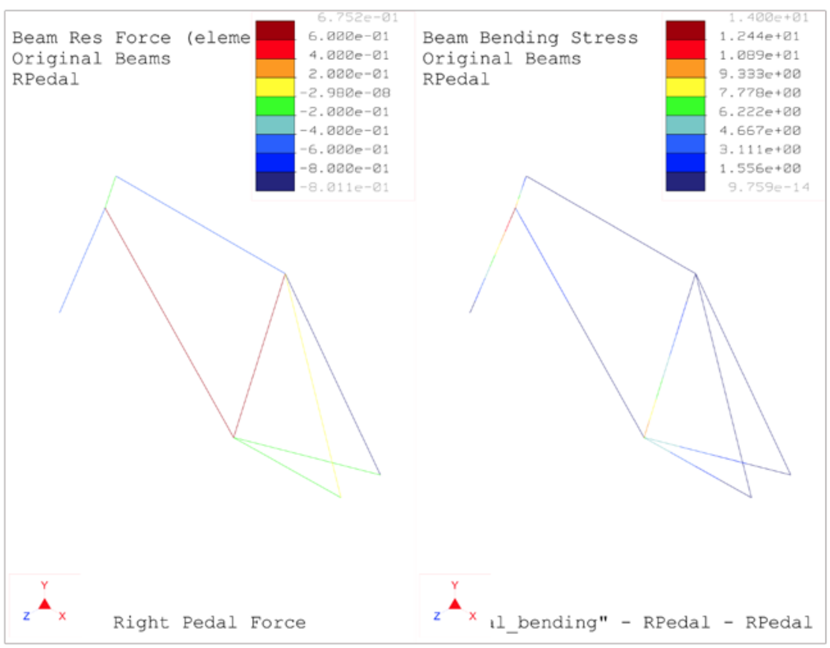


Figure 48. Pedaling load gives a high bending stress where the seat tube and the bottom bracket shell intersect.

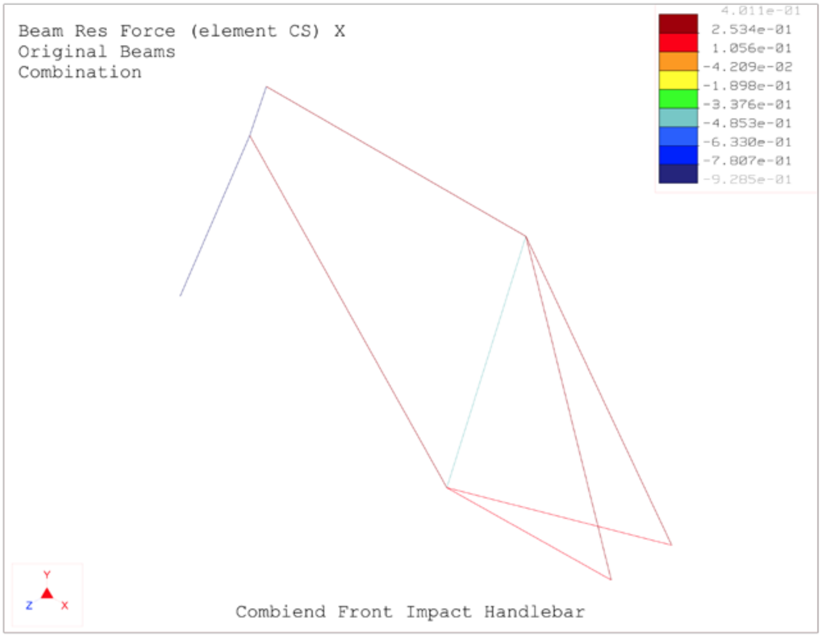


Figure 49. A combined loading case of a front impact plus a handlebar load produces lesser resultant forces than the case of a front impact load.

Analysis of Loading Conditions

All loading conditions were generated with a unit load. Table D-1 on the following page shows the resultant loads in each member given estimated loading magnitudes and factors of safety. Highlighted cells denote the maximum load in each member.

Table D-1. Analysis of expected loading conditions. The table shows maximum tensile and compressive forces in each member for the given loads and proposed factors of safety.

Load Condition	Magnitude (lbf)	Safety Factor	Seat Tube Unit	Seat Tube Total	Down Tube Unit	Down Tube Total	Top Tube Unit	Top Tube Total	Head Tube Unit	Head Tube Total
Seat Force	200	1.5	-0.307	-92	0.280	84.0	-0.223	-67.0	-0.139	-42
Coasting Pedal Force	200	1.5	0.496	149	0.496	148.8	-0.328	-98.4	-0.093	-28
Left Pedal Force	200	1.5	0.600	180	0.600	180.0	-0.600	-180.0	-0.200	-60
Right Pedal Force	200	1.5	0.600	180	0.600	180.0	-0.600	-180.0	-0.200	-60
Handlebar	150	2	-0.500	-150	0.290	87.0	0.298	89.3	-0.667	-200
Front Brake	300	2	0.279	167	-0.830	-497.8	-0.039	-23.1	-0.355	-213
Front Impact	500	2	1.175	1175	1.175	1175.0	-1.056	-1056.0	-0.498	-498
Rear Impact	500	2	0.859	859	0.859	858.5	-0.771	-770.7	-0.363	-363
Combined Brake + Handlebar	200	2	-0.200	-80	-0.600	-240.0	0.200	80.0	-1.360	-544
Combined Front Impact + Handlebar	500	2	-0.458	-458	0.253	253.4	0.253	253.4	-0.633	-633
MAX TENSION				1175		1175		253		-28
MAX COMPRESSION				-458		-498		-1056		-633

Load Condition	Magnitude (lbf)	Safety Factor	Chainstays Left Unit	Chainstays Left Total	Chainstays Right Unit	Chainstays Right Total	Seatstays Left Unit	Seatstays Left Total	Seatstays Right Unit	Seatstays Right Total
Seat Force	200	1.5	0.112	33.6	0.112	33.6	-0.307	-92.2	-0.307	-92.2
Coasting Pedal Force	200	1.5	0.025	7.6		0.0	-0.210	-63.1		0.0
Left Pedal Force	200	1.5	0.200	60.0	-0.600	-180.0	-0.802	-240.7	0.000	0.0
Right Pedal Force	200	1.5	-0.600	-180.0	0.200	60.0	0.000	0.0	-0.800	-240.0
Handlebar	150	2	-0.024	-7.2	-0.024	-7.2	-0.024	-7.2	-0.024	-7.2
Front Brake	300	2	-0.513	-307.9	-0.513	-307.9	-0.196	-117.8	-0.196	-117.8
Front Impact	500	2	0.060	59.8	0.060	59.8	-0.498	-498.2	-0.498	-498.2
Rear Impact	500	2	0.044	43.9	0.044	43.9	-0.363	-363.4	-0.363	-363.4
Combined Brake + Handlebar	200	2	-0.400	-160.0	-0.400	-160.0	-0.200	-80.0	-0.200	-80.0
Combined Front Impact + Handlebar	500	2	-0.042	-42.1	-0.042	-42.1	0.253	253.4	0.253	253.4
MAX TENSION				60		60		253		253
MAX COMPRESSION				-308		-308		-498		-498

Free Body Diagrams and Boundary Conditions

Figure 50 below shows proposed loading and boundary conditions for the FEA. Boundary conditions may have been modified slightly from the original drawings.

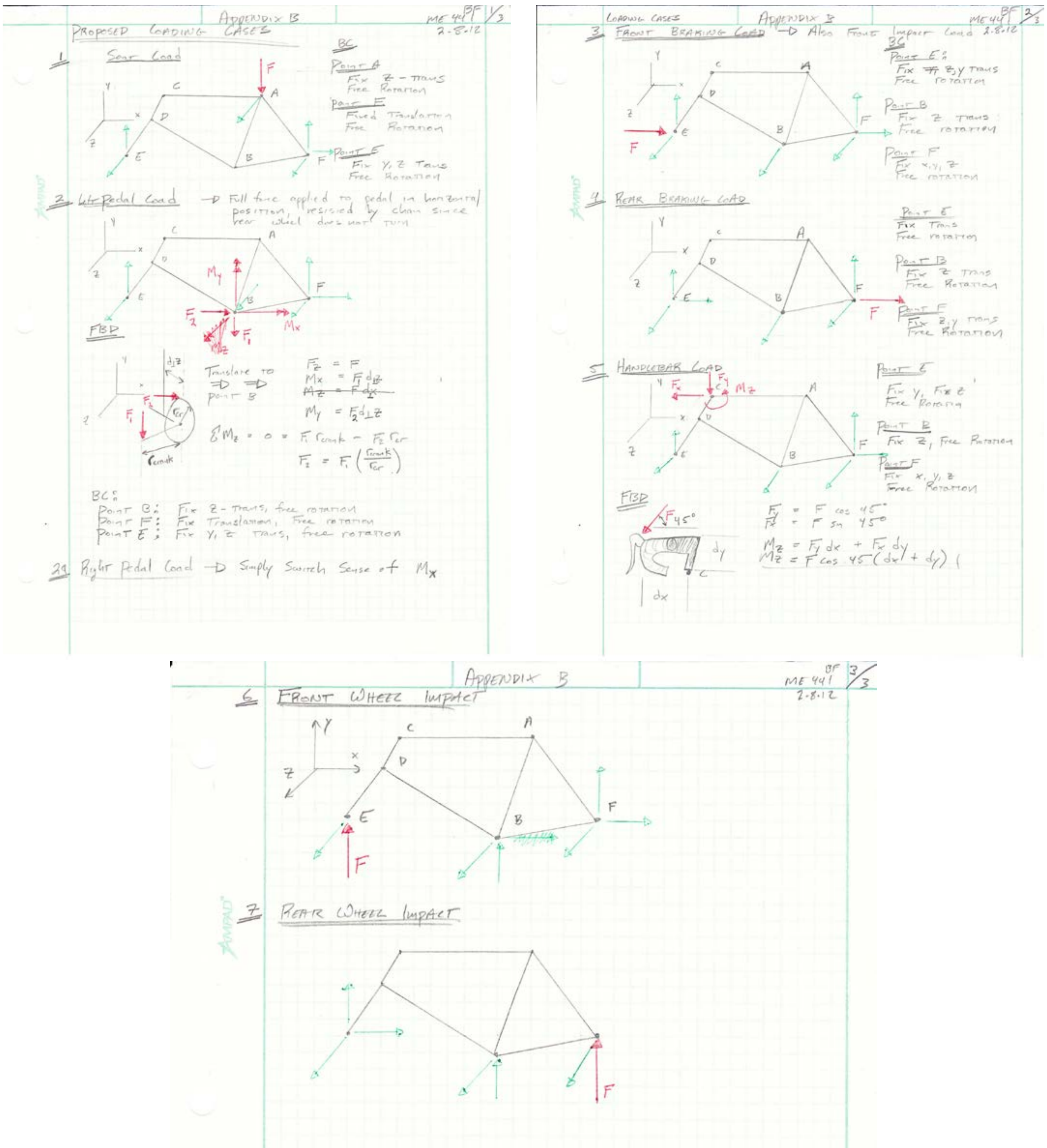


Figure 50. Loading and boundary conditions used in FEA.

Appendix E: Heat Treatment

Samples of Bamboo and actual poles were weighed and measured before and after heat treatments, and the results are presented in Table E-1 below. The mass (m) was measured with a digital scale, while diameter (D) and wall thickness (t) were measured with dial calipers. The processes used for heat treatment are described as follows:

- **Torch:** Samples subjected to propane torch for 3 to 10 minutes depending on size. During this process the surface turned from green to brown, and noticeable amounts of steam was ejected out of the ends of the bamboo.
- **Oven 1:** Samples placed in gas oven (no pre-heating) set to 200 ˚F and cooked for 6 hours.
- **Oven 2:** Samples placed in gas oven preheated to 380 ˚F and cooked for 15 minutes. Samples cooled slowly in oven.
- **Autoclave 1:** Samples placed in autoclave (in Cal Poly composites lab) at room temperature, and heated to 300 ˚F in the time-span of 45 minutes, held at temperature for 15 minutes, and allowed to cool slowly thereafter. Noticable steam was present in the Autoclave, and appeared to slightly deform some samples. The process was executed at atmospheric pressure.
- **Autoclave 2:** Similar to autoclave 1 process above, but used for smaller diameter tubes. A plot of this process is shown in Figure 51 below.

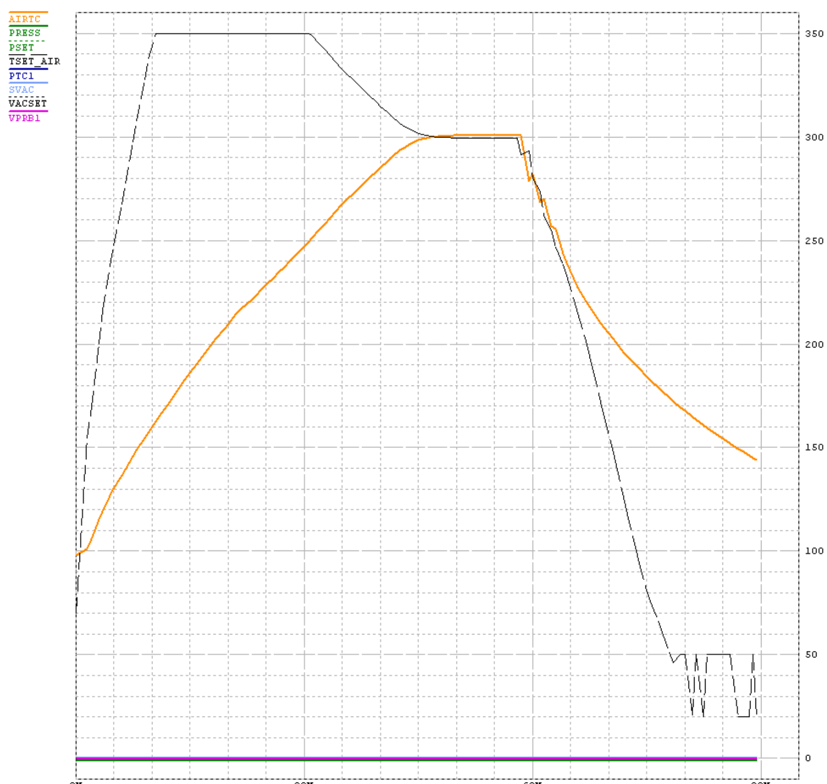


Figure 51. Graphical summary of heat treatment process "Autoclave 2". The orange line shows the actual temperature, and the dashed line shows the autoclave's target temperature.

Table E-1. Mass, diameter and wall thickness of bamboo tubing before and after heat treatment.

	Before Treatment			Processes		After Treatment			Results		
Sample	m (g)	D (in)	t (in)	First	Second	m (g)	D (in)	t (in)	Δm (%)	ΔD (%)	Δt (%)
A1		1.555		Oven 1			1.438			-7.5%	
A2		1.547		Torch	Oven 1		1.550			0.2%	
A3	61	0.840	0.109								
A4	62	0.678	0.980								
B1		1.811		Oven 1			1.601			-11.6%	
B2		1.770		Torch	Oven 1		1.745			-1.4%	
B3	396	1.881	0.281	N/A	Oven 2	367	1.843	0.275	-7.3%	-2.0%	-2.1%
B4	356	1.921	0.219	Torch	Oven 2	292	1.857	0.198	-18.0%	-3.3%	-9.6%
B5	552	1.946	0.174	Torch	Autoclave 1	384	1.809	0.165	-30.4%	-7.0%	-5.2%
E1	237	1.645	0.180	N/A	Oven 2	207	1.607	0.165	-12.7%	-2.3%	-8.3%
E2	264	1.656	0.174	Torch	Oven 2	195	1.605	0.155	-26.1%	-3.1%	-10.9%
E3	560	1.570	0.314								
E4	390	1.641	0.153	Torch	Autoclave 1	248	1.514	0.151	-36.4%	-7.7%	-1.3%
E5	302	1.531	0.125								
E6	239	1.353	0.131								
E7	148	1.153	0.102								
E8	141	0.916	0.097	Torch	Autoclave 2	77	0.896	0.096	-45.4%	-2.2%	-1.0%
E9	89	0.840	0.103	Torch	Autoclave 2	52	0.780	0.100	-41.6%	-7.1%	-2.9%
F1	119	0.741	0.105	Torch	Autoclave 2	76	0.725	0.097	-36.1%	-2.2%	-7.6%
F2	77	0.569	0.098	Torch	Autoclave 2	48	0.560	0.093	-37.7%	-1.6%	-5.1%
G1	675	1.934	0.154	Torch	Autoclave 1	434	1.884	0.146	-35.7%	-2.6%	-5.2%
G2	508	1.770	0.161	Torch	Autoclave 1	307	1.696	0.133	-39.6%	-4.2%	-17.4%
G3	311	1.581	0.133	Torch	Autoclave 1	176	1.488	0.122	-43.4%	-5.9%	-8.3%
G4	253	1.315	0.115	Torch							
H1	127	0.929	0.092	Torch	Autoclave 2	79	0.840	0.089	-37.8%	-9.6%	-3.3%
H2	78	0.641	0.065	Torch	Autoclave 2	52	0.650	0.072	-33.3%	1.4%	10.8%

AVERAGES:	-32.1%	-4.2%	-5.2%

Appendix F: Components

Each component was weighed individually, and the results are recorded in Table F-1 below. The frame was weighed before it was completed, and the amount of weight added since then from additional hemp fiber, the seat tube insert, and the cable routing components is only estimated.

Table F-1. Complete list of components used on bicycle, and their masses in grams and pounds.

Frame			
Component	**Description**	**Mass (g)**	**Weight (lbf)**
Frame	Measured at Bike Kitchen 2/29/12 (before completion)	2040	4.497
Additional Weight	Approximate additional weight added with seat insert, cable routing, and hemp fiber	250	0.551
	Frame Total	**2290**	**5.049**
Steering System			
Fork + Headset	Reynolds Carbon Comp 43 mm rake fork, Ritchey Comp-Logic 1-1/8" Headset (without cups), Headset but no Cups	603	1.329
Stem	Specialized Elite Set 110 mm	176	0.388
	Steering System Total	**779**	**1.717**
Drive Train System			
Bottom Bracket	SRAM Rival GXP	106	0.234
Crankset	SRAM Rival 170 mm 53/39	748	1.649
Chain	SRAM PC 951	290	0.639
Rear Cassette	Shimano 9 Speed 12-25	215	0.474
Rear Derailleur	Shimano Ultegra 6600	205	0.452
Front Derailleur	Shimano Tiagra 9 Speed	84	0.185
Shift Cables	Standard Road Cables	40	0.088
Shift Housing	Black	30	0.066
Barrel Adjusters	Jagwire In-line	15	0.033
	Drive System Total	**1733**	**3.821**
Wheels			
Front Wheel	Chris King Hub / Shimano Open Pro Rim	782	1.724
Front Tire	Specialized Armadillo All Condition 700x23	340	0.750
Front Skewer	Titanium Pink	40	0.088
Front Innertube	700 x 23	85	0.187
Rear Wheel	Chris King Hub / Shimano Open Pro Rim	921	2.030
Rear Tire	Specialized Armadillo All Condition 700x23	391	0.862
Rear Skewer	Titanium Pink	43	0.095
Rear Innertube	700 x 23	107	0.236
	Wheels Total	**2709**	**5.972**
Braking System			
Rear Caliper	Shimano Ultegra 6600	168	0.370

Front Caliper	Shimano Ultegra 6600	164	0.362
Brake Cables	Standard Road Cables	40	0.088
Brake Housing	Black	30	0.066
	Braking System Total	**402**	**0.886**
Human Interface			
Handlebars	Specialized Shallow Bend	299	0.659
STI Shifters	Shimano 105 9 Speed	499	1.100
Saddle	Specialized Body Geometry Gel	360	0.794
Seatpost	Bontrager Earl 31.6, Cutoff	253	0.558
Seat Binder	34.9 diameter, allen bolt	31	0.068
Pedals	Old SPD MTB Double Sided	448	0.988
Handlebar Tape		50	0.110
	Human Interface Total	**1940**	**4.277**
	OVERALL TOTAL WEIGHT	**9603**	**21.171**

Appendix G: Accounting & Cost Analysis

FRAME MATERIALS

Item	Description	Source	Price
Bamboo	5 Large Poles + 12 Small Poles	Gavino The Bamboo Man	$60.00
Epoxy	CLR	Entropy Resins	$108.53
Hemp Fiber	Long Strands, 2 kg	Hemp Traders	$53.48
Tubing	Seat Tube for 27.2 Seatpost, Head Tube for 1 1/8 Headset. Both Extra Long	Nova Cycles Supply	$54.03
Seat Post Shim	1.5" OD, 1" ID x 1' Long 6061 Aluminum Tube	McMaster Carr	$24.25
		TOTAL MATERIALS	**$300.29**

COMPONENTS

Item	Description	Source	Price
Fork	Ritchey Carbon, 300 mm steer, 43 mm rake, 1 1/8 head tube, 700c wheel size	Ebay	$105.78
Chain	SRAM 9 Speed Power Link	Ebay	$23.70
Headset	Ritchey Comp Logic 1 1/8" Black	Ebay	$32.86
Brakes + Derailleurs	Shimano Ultegra 6600. 34.9 Clamp Front Derailleur, 10 speed	Josh from Craigslist	$145.00
Seatpost	Bontrager Earl, 31.6 x 330 mm	Ebay	$15.00
Seat Binder	34.9 inner diameter	Ebay	$9.70
Crankset + BB	SRAM Rival 170mm 53-39	Ebay	$115.95
Handlebars, Stem, Seat Binder, Front Derailleur	Specialized Stem with Adjustable Angle, Specialized Bars with Flat Grip, 34.9 Seat Binder, Braze on Tiagra FD	SLO Bike Kitchen	$20.00
Cables	All Cables, Housing, Ferrules	Foothill Cyclery	$28.00
Handlebar Tape	White	Foothill Cyclery	$17.00
Barrel Adjusters	Inline for Derailleurs	Ebay	$8.00
		TOTAL COMPONENTS	**$520.99**

DISPOSABLES

Item	Description	Source	Price
Acetone	1 Pint	Miner's Ace Hardware	$5.99
Electrical Tape	To be perforated for wrapping joints	Miner's Ace Hardware	$2.59
Brushes	4 Metal Brushes	Miner's Ace Hardware	$0.76
Nitrile Gloves	100 Pack, Large, Non-powdered	Miner's Ace Hardware	$12.99
Electrical Tape	4 rolls	Flea Market	$2.00
Sandpaper	60 and 80 grit	Miner's Ace Hardware	$5.56

Axle	Nuts + Bolts to Keep Droputs Spaced	Miner's Ace Hardware	$4.10
Propane		Miner's Ace Hardware	$8.05
MDF	For the Jig	Miner's Ace Hardware	$10.00
Plastic Cups	For mixing Epoxy	Albertson's	$2.99
U-Bolts	1 1/2" and 1 3/4" for jig	Miner's Ace Hardware	$8.00
Axle	This one actually long enough	Miner's Ace Hardware	$2.50
Spray Adheisive	For Tacking Hemp Fiber	Miner's Ace Hardware	$9.00
Electrical Tape	Always Precious	Miner's Ace Hardware	$5.18
Misc.	Sandpaper, Brushes, Plastic Sheet	Miner's Ace Hardware	$15.00
		TOTAL DISPOSABLES	**$94.71**

TOOLS

Item	Description	Source	Price
Dremel Rotary Tool	If it wasn't for this I'd still be sanding a month from now	Miner's Ace Hardware	$90.00
Spring Clamps	2 of them, 2", Stiff as hell	Miner's Ace Hardware	$6.98
Propane Torch	Used for several parts of the project	Miner's Ace Hardware	$30.00
Scale	3 lbf limit, accurate to 1 g	Staples	$32.31
Bar Clamps	4 x 24"	Flea Market	$12.00
Pipe Clamps	2 x 40"	Flea Market	$10.00
Protractor	6" arm	Miner's Ace Hardware	$12.99
Respirator	Cheap One, for Dust Particles, Not for spraypaint, etc.	Miner's Ace Hardware	$15.99
T-Square	For making jig	Miner's Ace Hardware	$15.99
Angle Finder	For copying and finding angles	Miner's Ace Hardware	$12.99
Cut off Wheels	For Dremel	Miner's Ace Hardware	$19.99
Sanding Wheels	For Dremel	Miner's Ace Hardware	$10.00
		TOTAL TOOLS	$269.24

SERVICES RENDERED

Item	Description	Source	Price
Specialiezed Tools	Chase Bottom Bracket, Install Headset	SLO Bike Kitchen	$15.00
Parking Citation	Parked at Hangar on 3/8/12 to measure inertia moment and weight distribution, forgot to display parking permit. Thanks Cal Poly Police, I love you too.	Cal Poly	$38.00
		TOTAL SERVICES	**$53.00**
		GRAND TOTAL	$1,253.23

Appendix H: Additional Photos (Bike Porn)


Ritchey Carbon