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DESIGN FOR BAMBOO BICYCLE FRAMES

A Major Qualifying Project Report

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Abstract

There is a need for cheap transportation in third world countries. Bicycles are a common mode of transportation, however are not affordable for widespread use. Bamboo bicycles are a cheap alternative, however current manufacturing processes are labor and time intensive. Our goal was to design a cost efficient process for manufacturing bamboo bicycles that can be assembled in less than one hour. Axiomatic Design was used to decompose the problem into functional requirements and design parameters. Our primary focus was to develop a more efficient method for creating the bike joints. The result was a metal brace and gusset structure welded together to transfer the loads a bike is subject to. The joints were initially created in SolidWorks individually and assembled to form the bicycle frame in order to run a finite element analysis software. Testing was done on various components of the bike to better understand how they truly function. Our design reduces the cost, skill level, and time it takes to fully assemble a bamboo bicycle.

Acknowledgments

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1. Introduction

1.1. Objective

The objective of this project is to design a bamboo bicycle that is less expensive to manufacture than current bamboo bicycle designs and can be assembled by a consumer in less than one hour.

1.2. Rationale

Improving transportation methods can have a large impact on local economy. Transporting goods between villages in third world countries is done almost entirely by walking. Some countries like Uganda and Burkina Faso have begun using intermediate modes of transportation (IMTs), such as bicycles, and have seen their economies improve as a result (Riverson & Carapetis). Bamboo bicycles are currently being sold in parts of Africa, however due to the manufacturing method used workers can only construct anywhere from two and a half to four per person per eight-hour work day (Millennium Cities Initiative). The new design aims to streamline this process further by making the bicycles both easier and faster to manufacture: it could potentially take less than one hour for a single person to assemble a bicycle, which would more than double the current output of bamboo bicycles.

1.3. State-of-the-Art

1.3.1. Design

The state-of-the-art design for bicycles uses a common shape known as the diamond frame (see Figure 1). This frame can be broken down into two triangles; the main triangle and the rear triangle. The main triangle consists of the head tube, top tube, down tube, and seat tube. The paired rear triangle consists of the seat tube, chain stays, and seat stays (VanAuken, 1977).

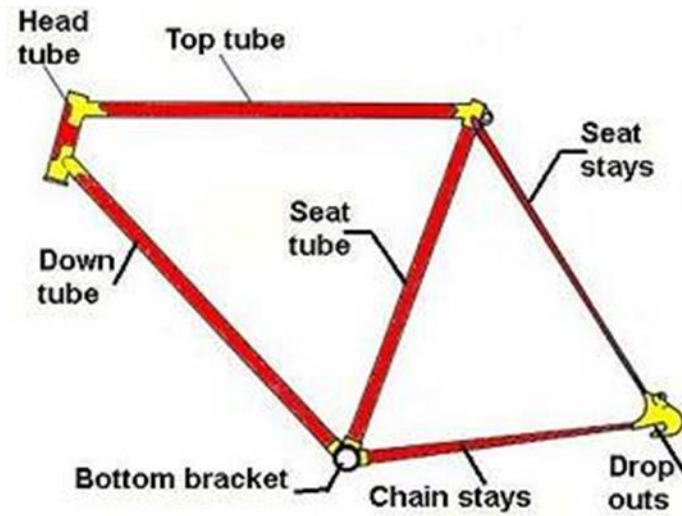


Figure 1: Members of a Diamond Frame

The current bamboo bicycle design process requires each joint to be wrapped by hand with a fiberglass tape and epoxy composite. The bamboo and metal bicycle components are fixed in a jig during this process. Two types of jigs are used during bamboo bicycle production: the tabletop jig and the stand-up jig. Calfee Design, a bamboo bicycle manufacturer, says, “Each of our bamboo frames requires over 40 hours of labor to build” (Calfee, 2014)(see Figure 2).



Figure 2: Calfee Design Bamboo Bicycle 2014

1.3.2. Joint Design

When considering what the state-of-the-art is for bikes, it is important to mention what was accomplished by the previous MQP groups. In 2012, the project group created a vacuum formed PETG plastic shell that was then filled with epoxy to structure the joints at the ends of



Figure 3: 2012 Bamboo Bicycle Frame

the bamboo, Figure 3. The 2013 MQP group used aluminum 6061 for a mold shell over plastic. This was done with 7725 fiberglass that was saturated in aero epoxy ES6209. It was then placed in the metal molds with the bamboo and used to form the bicycle frame.

There are many companies and other projects that have been successful in designing and constructing bamboo bicycles such as Erba Cycles, Panda Bicycles, and Calfee Design. Some of the various methods used for joint making include natural fibers (Calfee, 2014), composite materials (Building a Bamboo Bike, 2014), or metal joints (Bamboo Bicycle Club, 2014).

1.3.3. Materials

Natural fibers that are often used are hemp, carbon or flax fibers, which are typically treated with an epoxy resin. The metal joints, which are typically made from steel or aluminum, are then crimped around the bamboo.

Companies that produce bamboo bicycles usually use bamboo tubes with a diameter of 1 inch. Unlike manufactured materials like aluminum and steel, however, bamboo rods are not of equal diameters. This makes it difficult to acquire the appropriate diameter to fit the conventional steel joints. It is time consuming and unproductive to require workers to screen

through bundles of bamboo for just the right sizes. A more forgiving joint system that would allow for the flexibility of various bamboo diameters would be ideal.

1.4. Approach

1.4.1. Axiomatic Design

This bamboo joining design method is different from the common methods of other bamboo bicycles. Previous bamboo MQP teams used axiomatic design (AD) in order to help achieve their objective. This year's bamboo team also followed AD. Using AD, the team started with a list of customer needs to help create functional requirements (FRs) for each joint. (Suh, 2001). Design parameters (DPs) were then developed from these functional requirements which led to the new joint system and manufacturing process.

The team's approach to reach the final product was to develop new DPs until one has satisfied the corresponding FRs without affecting any other functional requirement. This is important in order to have an uncoupled design, which results in an acceptable design. Also, throughout the project the team had to keep in mind that if there are multiple designs, the one with the least amount of information (i.e., greatest probability of success) is better.

1.4.2. State-of-the-Art Difference

The design will advanced state-of-the-art by a new way of joining the bamboo while maintaining its diamond shaped structure. The new joint design differs from the designs mentioned in the state-of-the-art due to its hose clamps which connect the bamboo to the gusset metal joints. The new design is intended to allow for easier and quicker assembly.

1.4.3. Project Management

There were a total of eight people working on the project. Project management became an important part in the project due to the large number of people. In the beginning of the year, the team was unorganized, which resulted in less work done overall. The main reason why the team was unorganized was because there were no positions assigned. Without positions, it became difficult to meet deadlines.

Rather than assigning positions to people, the team had a project manager. The project manager's duties were to keep track of each team members work progress and to assign tasks for each team member. The team received a list of tasks or assignments from the advisor during the advisor meeting each week. The tasks were then divided up and assigned to each person during the team meetings from the project manager. The manager also divided the group into sub-groups when needed. These sub-groups would be working on the same task together. Following this process along with the updated Gantt chart, helped the team become more organized throughout the project.

Having an outline organized the structure of the report. With this outline, the project manager assigned each team member a section of the paper to write about and assigned a deadline. Once the individual parts of the report were sent, the team-organizer compiled them into one word file. The team-organizer created a word file before the individual parts were sent to make it easy for organization when compiling.

2. Design Decompositions and Constraints

The overall decomposition for the bicycle was split into four parts, one for each joint. The overarching functional requirement (FR0) for each of these decompositions was to transfer the

loads at the joint. The corresponding design parameter (DPO) was a structure to transfer these loads.

There were several constraints in place for the design of the bicycle, however one of the most critical parts of the design process is ensuring the end product is safe to use. The Consumer Product Safety Commission (CPSC) has a Bicycle Compliance Test Manual that details every test a bicycle must pass in order to be deemed safe to ride, however only the frame test is applicable to this project and thus passing it was one of the constraints (Bicycle Compliance Test Manual). A full list of the constraints can be seen in Table 1 below.

Table 1: Table of Constraints

Table of Constraints:

1. Withstand normal loads experienced during bicycle riding
2. Inexpensive (i.e. less than \$200)
3. Take under 1 hour to be manufactured by the consumer
4. Require little to no training to assemble
5. Pass CPSA frame test
6. Aesthetically appealing

2.1. Level 1 Functional Requirements

The level one FRs in each decomposition involved transferring the moments at each joint connection. For example, in the head tube joint decomposition shown below in Figure 4, the two connections are the top tube-head tube connection, and the down tube-head tube connection.

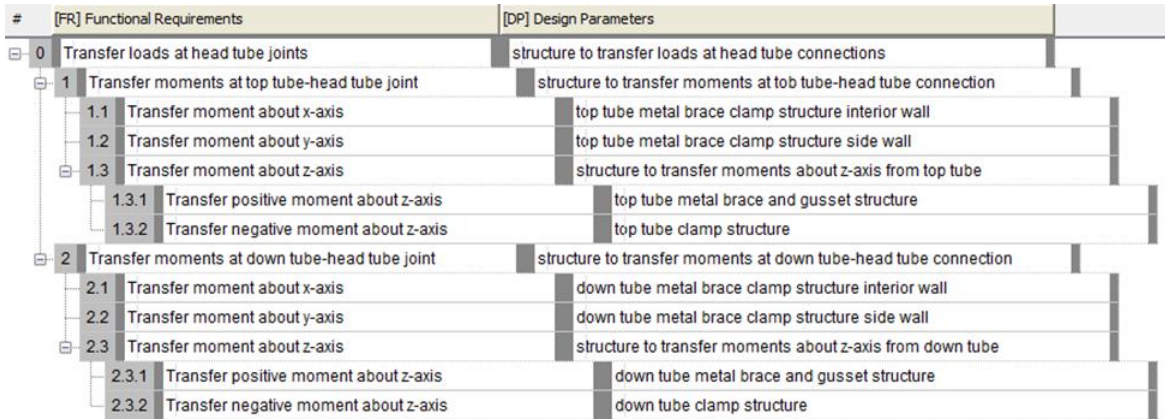


Figure 4: Head Tube Joint Decomposition

These FRs are collectively exhaustive (CE) as they account for all the loads applied to the joint, as dictated by FR0, and are mutually exclusive (ME) because they each account for a different set of loads. The corresponding DPs at level one are to transfer the moments at each joint.

2.2. Level 2 Functional Requirements

The level two FR in each decomposition involved transferring the moments about each axis (i.e. x-axis, y-axis, z-axis). These FRs are CEME by definition: the moment about each axis is independent of the other two, and together they account for all the moments experienced at the corresponding joint, as dictated by the level one FRs. Through several iterations, the final DPs were determined, and can be seen in Figure 4 above, as well as in Appendix A. Table 2 below details alternative DPs, and which constraints they violated.

Table 2: Constraint Violations of Alternative DPs

Alternative DP	Violations
Thermoplastic shell (<i>Instamorph</i>) molded around each joint to transfer loads	<ul style="list-style-type: none"> Possible melting/softening issues in higher temperatures could weaken joints Joints may not be strong enough to withstand normal loads experienced during riding
Fiber-epoxy matrix (e.g. carbon-fiber) wrapped around each joint to transfer loads	<ul style="list-style-type: none"> Requires training to assemble Takes far longer than 1 hour to manufacture (see section 1.2 Rationale)

The final design involves a metal brace and gusset system held together by a series of hose clamps. A prototype (see Figure 10) was constructed as a proof of concept, and while it violated some of the constraints—namely cost (2) and aesthetics (6) — the manufacturing process, once optimized and streamlined, has the potential to produce bicycles that meet every constraint (see Table 1).

3. Physical Integration

3.1. Functional Requirements

3.1.1. Level 1 Functional Requirements

The 1st level Functional requirements require a system to transfer the loads at each joint.

The design parameters call for a structure to transfer the expected loads. The system designed was a metal gusset and brace system secured with hose clamps.

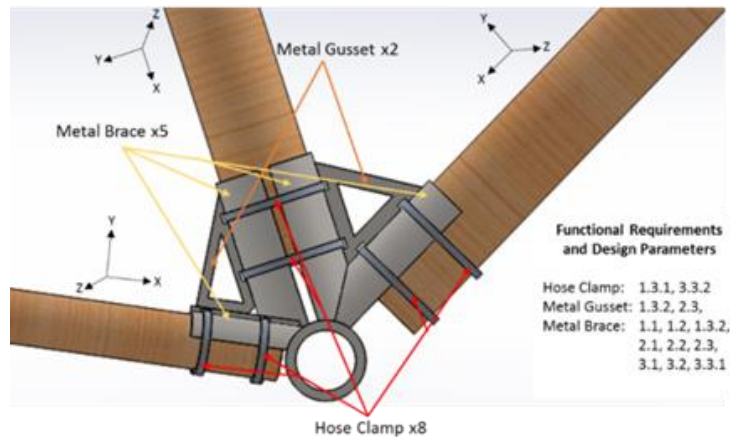


Figure 5: Bottom Bracket SolidWorks Model with DPs

The system for transferring the moments at the bottom bracket can be seen in Figure 5. To transfer the loads, from the crank to the frame, a bottom bracket shell was welded to the rear half of the bottom bracket. This allowed the two halves of the bottom bracket to be pulled

towards and tighten one another around the seat tube. The chain stays gusset was t-shaped to allow clearance between the chain stays and the rear wheel. The system to transfer the loads at the seat joint can be seen in Figure 6. An issue faced by previous MQPs was attaching a seat post to the frame. This had previously remained coupled to the rest of the system and became a weak link in their design. The current design decouples the seat post from the seat tube; this provides a simple solution for mounting the seat, as seen in Figure 6. A spacer was placed between the seat tube and the seat post to allow a hose clamp to pass between the two.

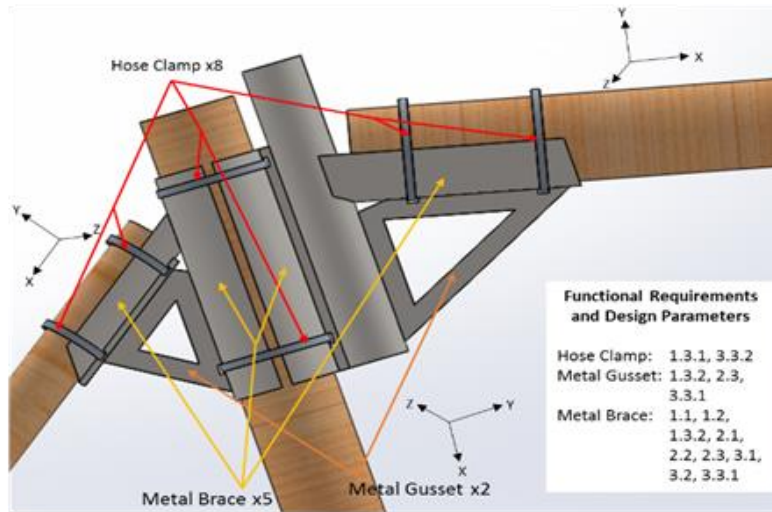


Figure 6: Seat Joint SolidWorks Model with DPs

The system to transfer the moments at the rear dropouts can be seen in Figure 7. A functional requirement of the rear dropout was to transfer the loads from the rear wheel to the frame. Current bike designs attach the wheel to the frame through the rear dropouts. Instead of attaching a dropout to the joint that connects the seat and chain stays, the dropout and gusset were combined. This allowed a simpler DP to satisfy the original FR.

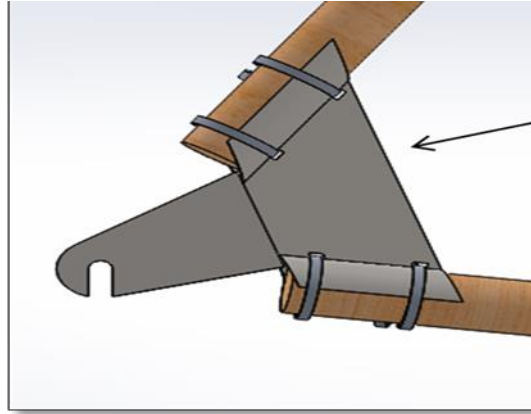


Figure 7: Rear Dropout SolidWorks Model

The system designed to transfer the moments at the head tube joint can be seen in Figure 8. A standard head tube was used to allow standard front forks to be used. This head tube was welded to the gusset to transfer the loads between the head tube, down tube and top tube.

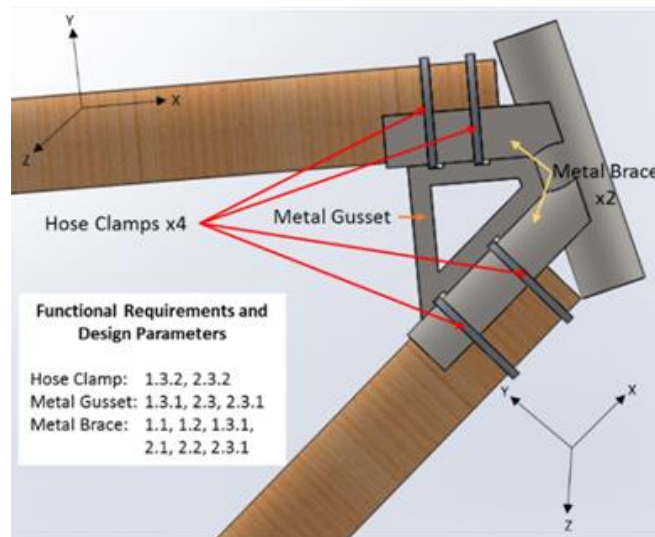


Figure 8: Head Tube SolidWorks Model with DPs

3.1.2. Level 2 Functional Requirements

The 2nd level functional requirements were to transfer the decomposed moments at each tube. Each tube used the same idea to transfer the moments in the x, y, and z-axis. The functional requirements for transferring the moments about the x-axis were satisfied by the friction

between a rubber lining (not shown) placed between the bamboo tubes and the metal braces. A metal brace (not shown) was placed between the bamboo tube and the hose clamps, opposite the metal braces in the joints. This was done to reduce the stress concentration on the bamboo tubes caused by the narrow surface area of the hose clamps. The functional requirements for transferring the moments about the y-axis were satisfied by the edges of the metal brace. The metal braces were cut from low carbon steel tubing, allowing the bamboo tubes to fit concentrically in the metal braces. The majority of the moments seen in the bike frame are about the z-axis. This functional requirement was satisfied with the use of metal gussets and hose clamps. The metal gussets prevent rotation in one direction about the z-axis while the hose clamps prevent rotation in the opposite direction.

3.2. Finite Element Analysis

The SolidWorks Model was run through an FEA program to analyze the design. The purpose of the FEA was to test the joints not the bamboo. To achieve this, bamboo tubes were replaced with steel tubes in the FEA that are stiffer and transmit more of the load to the joints. To test the joints a 1000-lbf load was placed on the crank assembly, a 100-lbf was applied to the top of the seat post, and a 10-lbf was applied to the top of the head tube. The loads applied were

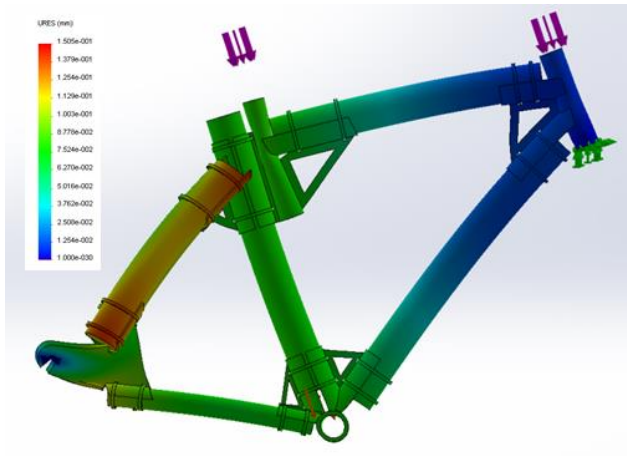


Figure 9: Deformation Plot of the bicycle frame. Red are the highest deformations and blue are the lowest.

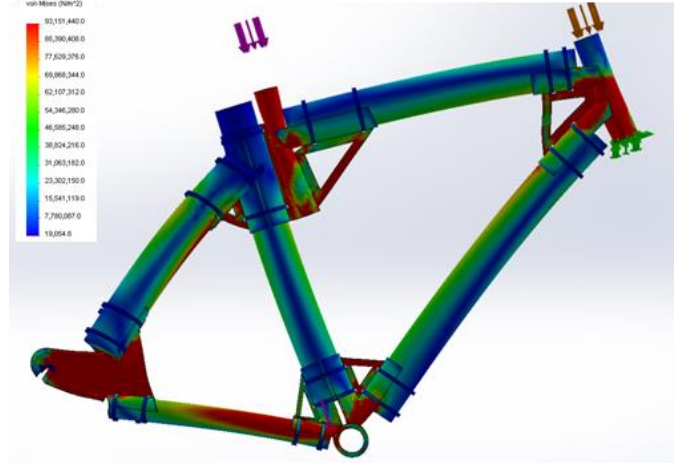


Figure 10: Stress Plot of the bicycle frame. Red is the highest stress while blue is the lowest.

normal to the applied surfaces. The distributions of this FEA can be seen in Figures 8 and 9. With the initially applied loads a safety factor of 2.4 was given by the software and a maximum displacement seen was 0.1505 mm. We were unable to determine loads seen while a bike was in operation so loads were applied to locations on the frame that would have loads during operation. Figures 9 and 10 were loaded ten times the initial amount to show the stress distributions and deflections. The initial stress distribution plot would have shown an entirely blue frame with two small red dots because the maximum stress area was 5 times greater than the next largest stress area. Figure 9 shows values ranging from 10%-100% of the maximum stress value. This was done to better show the stress distribution in the image.

4. Prototype Production

4.1. Computer Aided Design

To begin the prototyping and manufacturing process, a CAD model in SolidWorks was utilized to design the various joint models discussed earlier in the axiomatic design decompositions, as well as the bike frame. There were two assumptions considered as a way to simplify the modeling process. The first assumption was bamboo could be used as a substitute for other bike materials. The second assumption was current bicycle frames on the market have the optimal geometry for withstanding loads during cycling. Therefore, a common bicycle frame will be replicated for this design. These statements can be proven by the success of several bamboo bike industries.

4.1.1. Modeling the Bike Frame

The geometry of the bike frame model was acquired from the measurements of an existing road bike on the market. These frame measurements can be seen in Figure 11. This drawing dictated the sizes of the individual joints, thus leading to the development of the CAD models of the joints.

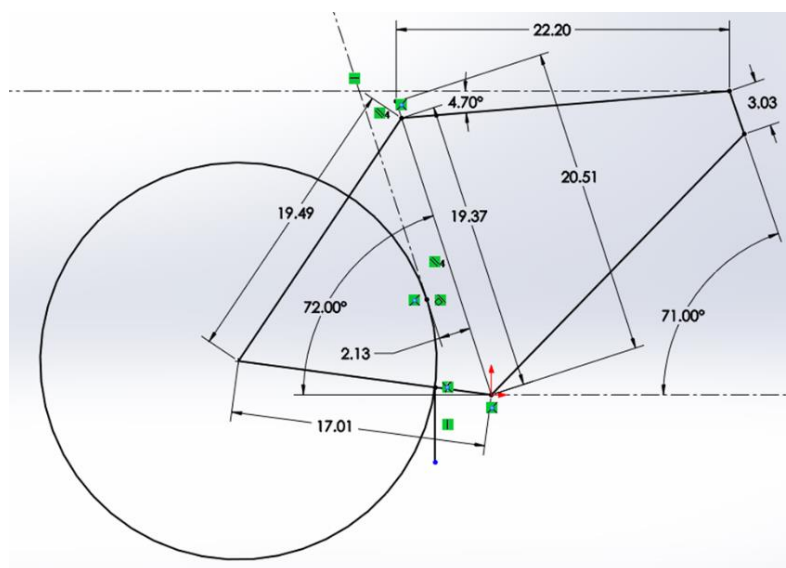


Figure 11: SolidWorks Diagram of Frame Geometry

4.1.2. Modeling the Joints

Four CAD models were made in SolidWorks relative to the four types of joints on a bike.

There are four critical components of a bike: seat tube joint, head tube joint, bottom bracket joint, and drop out joint. These joints are positioned at the four corners of the diamond frame. The head tube joint is critical for steering the system, the seat tube joint is critical for the bike seat, the bottom bracket joint is critical for the crank system, which includes the pedals and chain, and the drop out joint is critical for the rear wheel. Metal braces were designed to fit around the frame tubes at each joint. The frame measurements in Figure 11 dictated the specific angles for the position of the braces.

Triangular gussets were added to the joint assembly filling in the space that was left between two metal braces. The gussets provide support and mechanical stability during cycling. In SolidWorks, top down assemblies were used as a way to easily update any changes to the joints; therefore, allowing the joints to be adjustable for varying bike frames. The individual joint systems can be seen in the previous figures.

4.1.3. Assembling the CAD Bike Model

Once the model of the bike frame geometry and four joints were created in SolidWorks, all parts were ready to be assembled. The final CAD assembly is shown below in Figure 12.

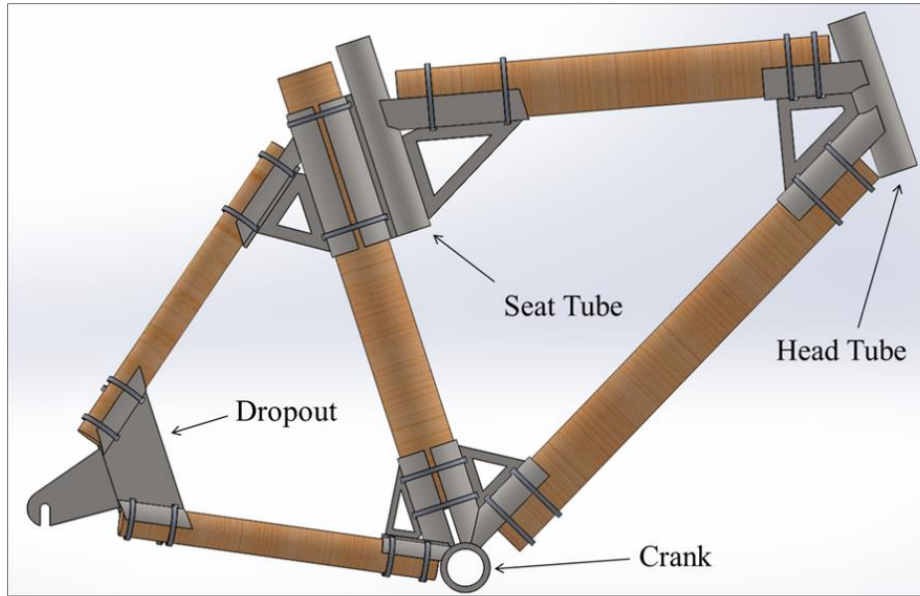


Figure 12: SolidWorks Frame Assembly

4.2. Manufacturing the Prototype

4.2.1. Manufacturing the Metal Braces

To start the manufacturing process the metal braces were cut from 1018 carbon steel tubes to the appropriate dimensions described in Table 3. One low carbon steel tube had an outer diameter of 1.50 inches and the other 1018 carbon steel tube had an outer diameter of 2.50 inches. The seat stay and chain stay tubes were cut from the 1.50 inch diameter steel tube.

The remaining joint tubes were cut from the 2.50 inch diameter steel tube.

Each were cut to the labeled lengths using a horizontal band saw. The tolerances for the tube lengths are shown to be plus/minus 0.15 inches. These tolerances account for possible error when using the band saw to cut the lengths as well as using the bench grinder.

Table 3: Measurements of Metal Braces

Joint	Type of Tube	Outer Diameter (in)	Length (in)	Quantity
Seat	Seat Stay	1.50	4.50 ± 0.25	2
Seat	Top Tube	2.50	5.65 ± 0.25	1
Seat	Seat Tube	2.50	6.00 ± 0.25	2
Head Tube	Top Tube	2.50	4.00 ± 0.25	1
Head Tube	Down Tube	2.50	5.00 ± 0.25	1
Bottom Bracket	Down Tube	2.50	4.00 ± 0.25	1
Bottom Bracket	Seat Tube	2.50	4.00 ± 0.25	2
Bottom Bracket	Chain Stay	1.50	2.85 ± 0.25	2
Drop out	Chain Stay	1.50	3.00 ± 0.25	2
Drop out	Seat Stay	1.50	3.70 ± 0.25	2

Once all joint tubes were cut to the correct length, they were cut into semi-circular tubes (at the radius) using an angle grinder, thus forming the metal braces. With the metal braces completely formed, a bench grinder was used to remove the rough surfaces, chamfer the edges, and round the corners. This process can be seen in Figure 13.



Figure 13: Bench Grinder for Final Touches

For joint assembly purposes, quarter metal braces were also created. The same process was followed to cut the quarter metal braces; however, instead of $\frac{1}{2}$ diameter braces, they are $\frac{1}{4}$

diameter braces. These are placed around the bamboo on the opposite side of the ½ diameter metal braces to secure the bamboo in place. This process is discussed later.

4.2.2. Manufacturing the Gussets

The gusset manufacturing process began by using a laser cutter to cut out acrylic templates.

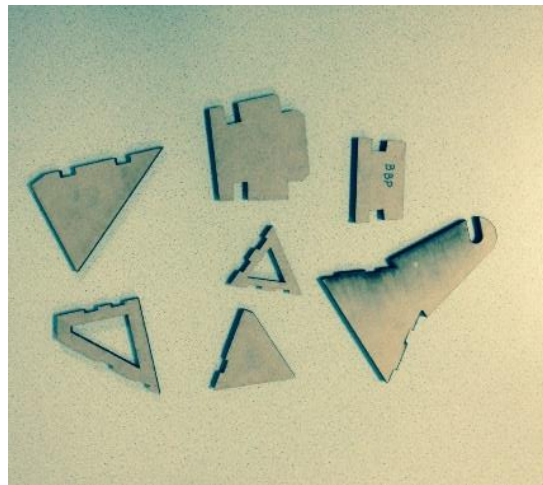


Figure 14: Templates for Gussets

The templates were traced onto a 1018 carbon steel plate (0.125 inches by 6.0 inches). A plasma cutter was first used to cut out the general shape of the individual gussets. A band saw was used to finalize the shape of each gusset, including the rectangular notches. Several notches were cut out of each gusset, creating a space for the hose clamps to fit. Files were used to smooth the surfaces and expand the notches to fit the hose clamps. A bench grinder was used to chamfer the edges and round the corners to finalize each gusset.

4.2.3. Welding the Joints

To help weld the joints together, two jigs were manufactured. The purpose of the jigs were to hold the metal braces and gussets in place to assist alignment for MIG welding. One jig was created for the 1.50 inch diameter metal braces and the other jig was created for the 2.50

inch diameter metal braces. One jig is shown below in Figure 15. The 1.50 inch diameter jig was made of acrylic and the 2.50 inch diameter jig was made of medium-density fiberboard. Each component of the jigs were cut using a laser cutter and then assembled.

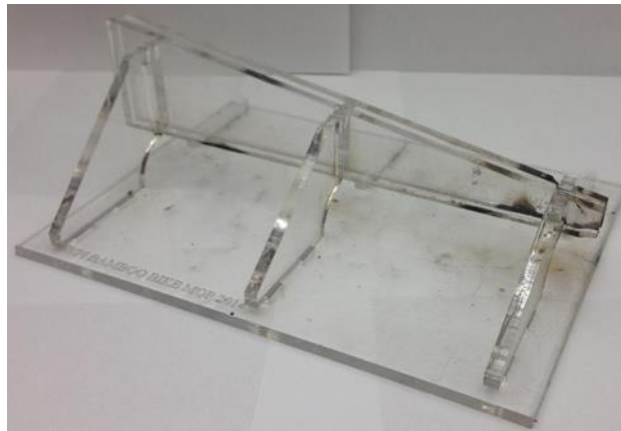


Figure 15: Jig for Welding Joints

To weld the braces and gussets together, the metal brace is inserted through the semi-circle arches at the bottom of the jig. The gussets are inserted in-between the two triangular pieces that run the entire length of the jig. Once aligned correctly, spot welding is completed to join the metal braces and gussets at various spots along the interface. The assembly is removed from the jig and then completely welded together along the entire interface. This process and an example of a welded joint are shown in Figure 16.

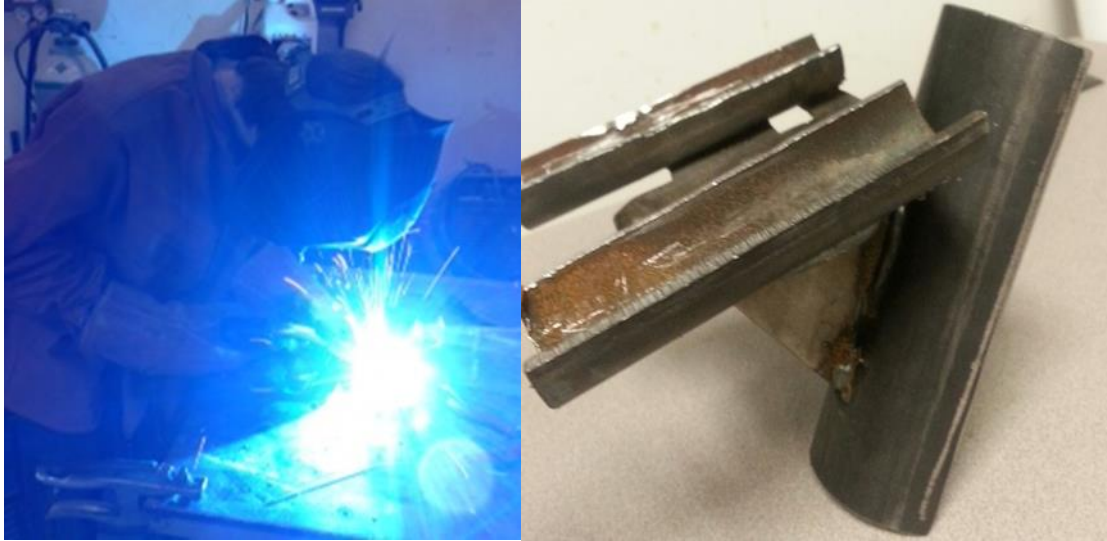


Figure 16: Welding of Seat Stays-Seat Tube Joint

4.2.4. Cutting the Bamboo Tubes

Once all the joints were assembled and welded, the bamboo was cut to the correct length using a hand saw. The dimensions of each bamboo tube are shown in Table 4. The lengths have a tolerance of plus/minus 0.20 inches due to possible hand saw error.

Table 4: Dimensions of Bamboo

Bamboo Tube	Outer Diameter (in)	Length (in)	Quantity
Top Tube	2.00 ± 0.20	22.2 ± 0.50	1
Down Tube	2.00 ± 0.20	23.98 ± 0.50	1
Seat Tube	2.00 ± 0.20	19.37 ± 0.50	1
Seat Stay	1.00 ± 0.20	19.49 ± 0.50	2
Chain Stay	1.00 ± 0.20	17.01 ± 0.50	2

The bamboo tubes create the diamond bike frame as illustrated in Figure 12. They are placed into the metal joints and secured. This process is outlined in the next section.

4.3. Assembling the Bike

To finish the joint assembly, a rubber inlay was inserted into all metal braces. The bamboo tubes were then placed into the metal braces on top of the rubber inlay. Quarter diameter metal braces were then placed on the bamboo opposite from the ½ diameter metal braces. Two or three hose clamps, depending on the joint, were wrapped around the metal braces, rubber, and bamboo. This created a secure joint. Once all joints were assembled, the entire bike frame could be assembled (see Figure17).

To completely assemble all parts of the bike frame together, these steps were followed:

1. Fasten seat stay tubes to the dropout joints using hose clamps
2. Fasten chain stay tubes to the dropout joints using hose clamps
3. Fasten back half of seat tube joint to both seat stay tubes using hose clamps
4. Fasten back half of bottom bracket joint to both chain stay tubes using hose clamps
5. Fasten top tube to head tube joint using hose clamps
6. Fasten down tube to head tube joint using hose clamps
7. Fasten top tube to front half of seat tube joint using hose clamps
8. Fasten down tube to front half of bottom bracket joint using hose clamps
9. Insert seat tube into metal braces
10. Fasten both halves of the seat tube joint and bottom bracket joint together using hose clamps



Figure 17: Full Bicycle Assembly

5. Testing

5.1. Bamboo and Metal Tube Testing

5.1.1. Overview

For our testing procedures we performed several tests to evaluate the strength of different components of our bicycle. These tests allowed us not only to choose materials that would perform successfully, but it also helped us understand how certain components of the bicycle may react when subject to the expected stresses. In order to find the ideal bamboo for our bicycle frame, we tested different types of bamboo in various ways. We also wanted to see how bamboo performed in comparison to steel tubes from a current road bicycle to get an idea of how strong the bamboo must be to withstand the standard forces that a bike frame may be subject to.

Testing occurred once the measurements and weights of each piece were recorded. We cut each piece of bamboo and metal, for the compression test, to a length of 4 inches (0.1016 m) and each piece of bamboo and metal, for the 3-point bending test, to 15 inches (0.381 m) with the 2 outer points of contact set 12 inches (0.3048 m) apart. The measurements recorded included length, outer diameter of each end of the bamboo pieces, wall thickness, and weight. For a full list of each piece and its measurements, see Table 4 and Table 5 in Appendix B.

5.1.2. Compression Tests

Our initial tests were performed using the static loading compression machine in the Civil Engineering lab. The test was set up by placing the piece to be tested vertically on a platform (with the diameter of the cylinder face up). Above the platform was a press with a flat surface that pushed downward and provided the force. The load was gradually increased to the point of fracture. We tested 5 different types of bamboo as well as steel tubes from an old bicycle that

we cut up. The different types of bamboo that we tested were non-treated and heat treated bamboo from Long Island, purchased heat treated bamboo, and bamboo of different diameter taken from the 2013 Bamboo Bike MQP. This test was performed on each material numerous times. Figure 18 shows the setup and machined used in the CE lab for the compression tests and Figure 19 shows the different components that were tested.



Figure 18: Compression Tests



Figure 19: Bamboo from 2013 MQP Main Tube, 2013 MQP Stays, Purchased, Non-Treated, Heat Treated, and Metal Tubing (In Order)

5.1.3. 3 Point Bending Tests

The next test was a 3-point bending test, which we also performed using the static loading compression machine in the Civil Engineering lab. The test was set up by placing two half cylinder metal bars 12 inches (0.3048 m) apart to act as the two outer points in the 3-point test. The piece that was to be tested was then laid across both of the bars horizontally. A third metal bar was then placed on top of the piece to be tested and below the press at the center of the bamboo. This bar allowed us to create the third point at the center of the bamboo. The press then provided the gradually increasing downward force. The load was gradually increased to the point of fracture. We tested the same materials that we tested in the compression test and numerous tests were performed on each material. A picture of the test performed is shown in Figure 20, as well as each material taken before the tests were performed, shown in Figure 21.



Figure 20: 3 Point Bending Tests



Figure 21: Heat Treated, Non-Treated, Purchased, 2013 MQP Stays,
2013 MQP Main Tube, Metal Tubing (In Order)

5.2. Hose Clamp Testing

We had constructed a test to determine the strength of the hose clamps that were used for our bamboo bicycle. The primary force that the hose clamp will experience is a tensile force. In order to test for this, the test joint needed to be fixed to the platform of the static loading compression machine. Our initial idea as to how to fixture the test joint this was similar to the fixture upon which we decided. The primary difference in how we would hold the test joint in place was that our initial idea was for the test joint to be held in place using a vice grip that clamped onto the gusset of the test joint. Unfortunately, this process was not possible because the platform of the machine that we used was not large enough to fit the vice grip.

Instead we screwed two holes in the gusset and attached the gusset to a square metal bar with two holes drilled in it. The metal bar was then secured to the testing platform using a c-clamp. We used nuts and bolts through the two holes to join the metal bar and test joint. We then placed a metal rod in the half cylinder brace of the test joint and secured it in place with two hose clamps. The metal rod extended out from the test joint approximately 10 inches (0.254

m) and created a lever arm, on which a downward force was applied, creating a moment. You can see how the hose clamp test was setup in Figure 22.



Figure 22: Setup for Hose Clamp Test

5.3. Final Bicycle Frame Testing

In order to test the final bicycle frame we first looked into ASTM standard tests, as well as CPSC compliance tests, which are required to approve a bicycle for safety regulations. There are several tests that must be performed before a bike is approved. Due to time constraints and complexity of set up for many of the tests, we decided to do the simplest test. This test was also the most relevant and highest priority test. The test we chose to perform was a compression test in which the bike frame was oriented horizontally. The bicycle frame was placed in a large vice clamp system in which the dropout joints were fixed in place up against a scale that was oriented vertically. The fork at the front of the bicycle was placed at the front of the vice grip. As the vice was screwed the force placed on the bike increased and the bike was compressed. In order for the bicycle to meet the CPSC regulations it must be gradually loaded to a minimum of 200 lb-f (890 N) or until 350 in-lb (39.5 N-m) of energy is absorbed by the frame, whichever results in a greater force. If any noticeable deformation or fracture occurs, or if ability to steer the bicycle is affected after the load is released, the bike has failed to meet standards. Therefore, the bicycle

must be able to withstand a minimum load of 200 lb-f (890 N), while deflecting a minimum of 1.75 inches (0.04445 m), and must then return to its original form when the force is released. The setup for the CPSC frame test can be seen in Figure 23 below.

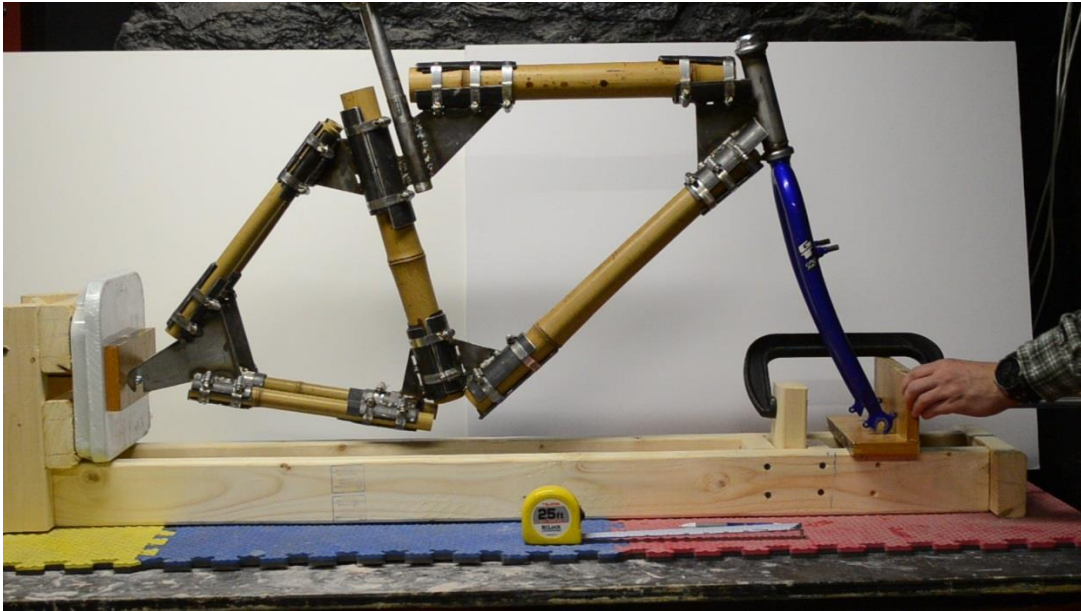


Figure 23: CPSC Frame Test

6. Data Analysis

6.1. Metal vs. Bamboo Test Results

After completing the compression and 3-point tests on the various types of bamboo and the steel tubes, several observations were made. Obviously, one observation was that the strength of the metal was significantly higher than the strength of the bamboo in both tests. The steel experienced a peak load of 919 lb-f in the 3-point test and 9,791 lb-f in the compression test. The strongest bamboo, which was the bamboo from the 2013 Bamboo Bike MQP, experienced a peak load of 467 lb-f in the 3-point test and 6,588 lb-f in the compression test shown in Figure 24 and Figure 25. The peak loads of the heat treated bamboo tubes were similar to those experienced by the strongest bamboo. As for the rest of the bamboo tubes with a smaller outer diameter (non-heat treated, purchased bamboo, and the bamboo stays from the 2013 Bamboo Bike MQP) they all experienced similar peak loads to each other, aside from the non-heat treated bamboo. The strongest bamboo tube that had smaller outer diameter was from the 2013 Bamboo Bike MQP. This bamboo experienced a peak load of 333 lb-f in the 3-point test and 4,290 lb-f in the compression test.

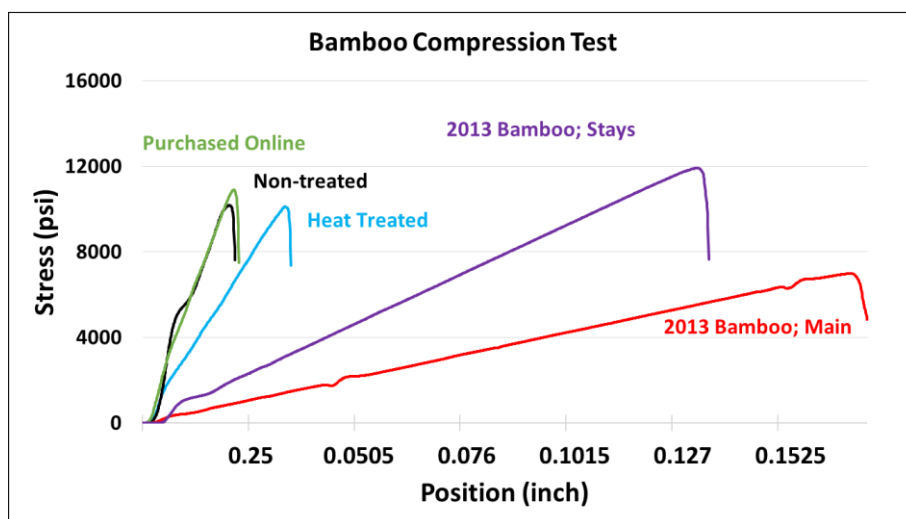


Figure 24: Results from Compression Tests

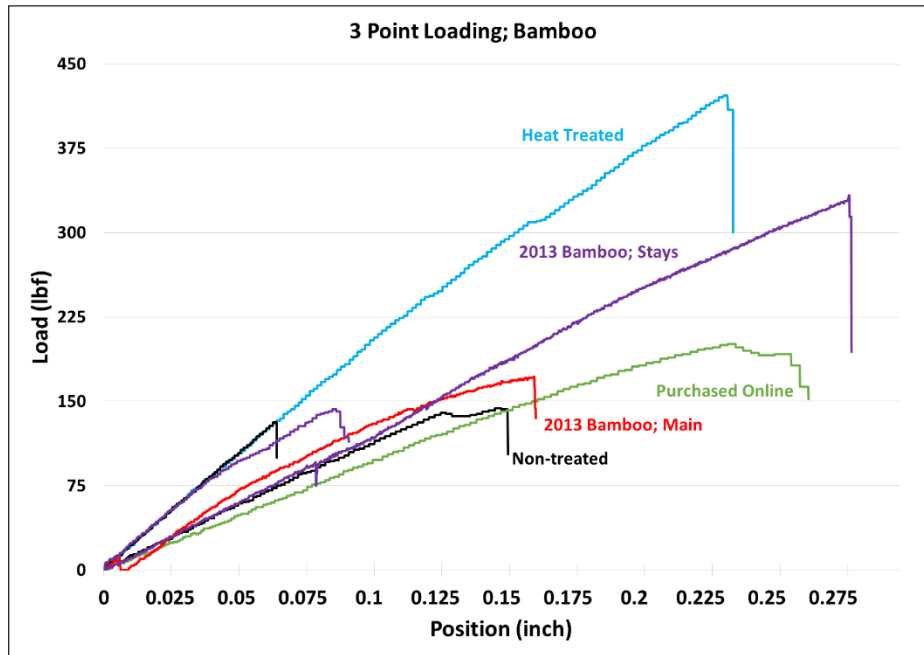


Figure 25: Results From 3 Point Loading tests

Naturally we expected the metal to be stronger, however we did not expect the difference to be so significant. Based on the fact, however, that the bamboo used for last year’s Bamboo Bicycle MQP proved to be strong enough to withstand large forces without failure we felt that the metal bicycle was likely over-qualified and could withstand forces far larger than it would likely experience. Examples of components after testing occurred are shown in Figure 27 and Figure 26, where the rest of the components, after testing, can be found in Appendix C.



Figure 26: Heat Treated Bamboo #3 After Compression



Figure 27: Heat Treated Bamboo #1 After 3 Point Loading

Another observation was that all of the different types of bamboo aside from the non-heat treated bamboo, varied slightly in strength for both tests, aside from a few outliers. The outliers of the tests may have occurred for several reasons. One reason is that a few of the pieces of bamboo from last year's bicycle were compromised because some of the epoxy that was used for their joints leaked into the bamboo and may have weakened it as a result. Some of the pieces were also compromised due to cracks that resulted from trying to remove the epoxy that had leaked into the tubes. Aside from these few outliers, the strength of the different types of bamboo were much the same. The primary reason there was variance in the strength of the different types of bamboo was due to their different diameters. Through these observations we concluded that any of these types of bamboo, aside from the non-heat treated bamboo, would be sufficient to use for a bicycle frame. As long as we purchased a bamboo of similar quality that is heat treated and has a large enough outer diameter, we felt that it would be sufficient and could withstand the loads that the bicycle would experience.

6.2. Hose Clamp Test Results

Initial tests of the hose clamps proved that our fixture that held the test joint in place was inefficient. After completing the test we realized that it was neither the test joint nor the hose clamp that experienced the failure. The parts of the test that had failed were the two bolts that held the test joint in place. After unscrewing the test joint from the fixture, we realized that the bolts had been deformed. We tested the mechanism twice and neither time were the test joint

or the hose clamps compromised. The peak load between the two tests was 447 lb-f initially. Due to the failure of the bolts used to hold the test joint in place the test was invalid and we had to retest with more durable screws. In order to achieve this we had to use larger bolts to withstand the stresses.

After the modifications of the fixture were made, we successfully tested the hose clamp. Our results were that the hose clamps experienced a peak load of 775 lb-f before failure, shown in Figure 28. We were surprised to find, however, that the failure had occurred with the hose clamp strap (see Figure 29), rather than with the hose clamp screw as we had predicted. We applied 200 lb-f per minute and the lever arm extended approximately 9 inches from the end of the half cylinder.

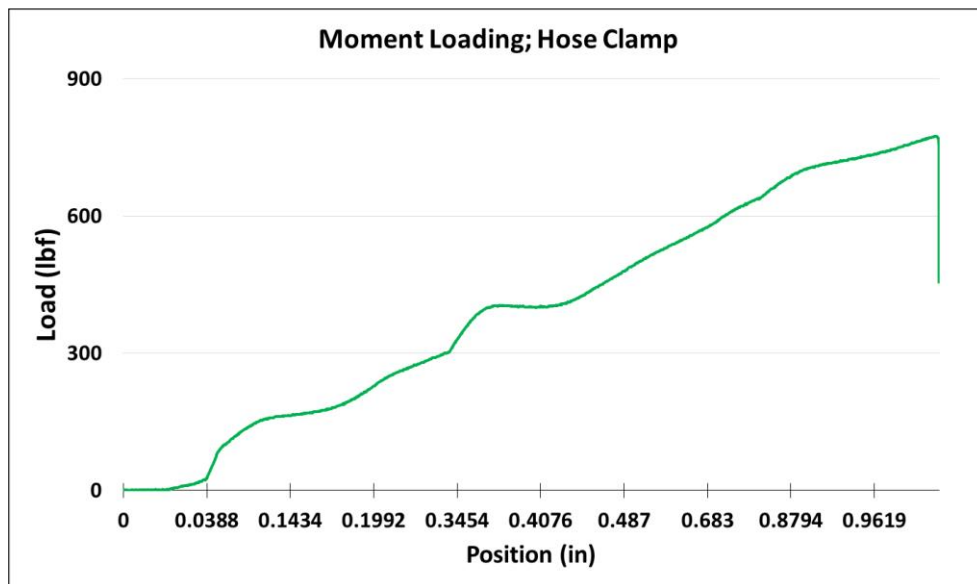


Figure 28: Results from Hose Clamp Test



Figure 29: Failure of Hose Clamp after Testing

6.3. Bicycle Frame Test Results

The bicycle broke at the head tube weld (see Figure 30) with an applied load of approximately 150 lbf and a displacement of 1.5 in. The failure of this weld was sudden and the fork was launched away from the frame. The bicycle absorbed approximately 225 in-lb of energy at failure. The bicycle failed this test.



Figure 30: Failed Head Tube Weld from Frame Test

6.4. Testing Videos

Videos were taken of all the aforementioned tests and were posted to Youtube for easy sharing. Just search “Bamboo Bike MQP” or go to

https://www.youtube.com/results?search_query=bamboo+bike+mqp

7. Discussion

7.1 Accomplishments

This design process provides the best solution for manufacturing bamboo bicycle frames. The assembly process is simple enough that most could interpret it from looking at the components. Training to learn the complex fiber wrapping methods and nature of resin systems are traded for a simple screwdriver and a diagram of which joints connect to which bamboo tubes. This also trades the tricky and permanent nature of resins for a forgiving and adjustable joint assembly.

The most time consuming and labor intensive part of the assembly process, fabricating the joints, is prefabricated and streamlines the overall process. Shortening that step allows this design to be assembled in 31 minutes. There are no time-sensitive steps in this process; the wrapping method requires the mixing and application of resins within a specific timeframe along with an additional timeframe for curing.

7.2 Design Method

Axiomatic design was a powerful tool used in the design process of this project. Early on, the team did not fully understand axiomatic design and refused to follow it. As the project progressed, the advisor explained the importance of axiomatic design and why the project must follow this design method. Once our team implemented AD a near complete design was created in two days. At this point we understood the significance of AD that our advisor was trying to communicate to us. Although our prototype failed to reach the cost aspect of our objective, our implementation of AD allowed our design to have a faster and simpler assembly process than current processes.

7.3 Constraints

Many of the original constraints were not met with the final design. Normal loads experienced during bicycle riding were not determined and therefore were not able to be tested. The prototype bicycle assembly cost more than the constraint set for \$200. Time and training required to assemble the prototype were both met; the prototype was assembled in 31 minutes with a screwdriver and no instructions. This prototype failed the CPSC frame test and the aesthetics of the bike are still up for debate.

7.4 Impact

As stated in section 1.2 Rationale, providing third world countries with bamboo bicycles can have a large impact on local economies, as it greatly reduces the time for goods to be transported between villages. These benefits can already be observed in some countries like Uganda and Burkina Faso, which have begun to use intermediate modes of transportation like bamboo bicycles more prevalently. With an assembly time four to six times faster than the most common fiber-wrapping method, our design has the potential to greatly increase the availability of bamboo bicycles. The increased availability of cheap transportation could help rapidly progress the economies and societies of third world countries.

7.5 Improvements to Prior Art

This design improves upon the time and effort required to manufacture bamboo bicycle frames used in current fiber wrapping methods. The joints can be removed to allow damaged frame tubes to be replaced without replacing the entire frame. Full disassembly of the frame allows it to take up less space than a fully assembled frame; it can be packed in a bag or several can be shipped in a box that would hold a full frame.

7.6 Potential Commercial Use

This design process is versatile and can be applied to several bicycle applications. It serves to satisfy the role of a bamboo bicycle, but could also minimize the travel and shipping size of conventional bicycles. This modular-style bicycle design might also extend the life of the common bicycle, allowing worn or broken components to be replaced rather than the entire frame. Most parts on a bicycle are interchangeable already; the frame can be as well.

8. Concluding Remarks

8.1 Major Design Accomplishments

- This design satisfies the two axioms.
- This design process has a simple assembly method.
- A prototype of this design was assembled in 31 minutes; the common fiber wrapping method takes 2.5-4 hours.
- The assembled prototype was able to hold the static load of the heaviest team member sitting on the seat without failure.

8.2 Including Issues Remaining

- Critical alignments are yet to be determined.
- Tolerances are yet to be determined.
- Full bicycle assembly has not been completed.
- The prototype frame failed the CPSC 5.15 regulation fork and frame test.

10. References

- BambooWrappingDraft3.pdf - Google Drive. (n.d.). *BambooWrappingDraft3.pdf* - Google Drive. Retrieved November 17, 2013, from https://docs.google.com/file/d/1L-dR3avAGYTpc3EyWs00oBAAWLoOQOKTzQ1EsjCPO-u4TvR_vunekydMOFvU/edit?usp=drive_web&pli=1
- Efford, M. (2010, December 30). Bamboo Bike Frame Deflection Strength Test #2 - Daisy. *YouTube*. Retrieved January 23, 2014, from http://www.youtube.com/watch?v=dNDub_EyUDg
- Find raw materials faster. (n.d.). *IDES is now Prospector*. Retrieved November 21, 2013, from <http://www.ides.com/resinpricing/Secondary.aspx>
- Making Joints. (n.d.). *Building A Bamboo Bike*. Retrieved October 4, 2013, from <http://bamboobike.wordpress.com/42-2/>
- Material Properties. (n.d.). | *Plastics International*. Retrieved November 13, 2013, from http://www.plasticsintl.com/sortable_materials.php?display=mechanical
- Meyer, K., Taylor, A., & Santosh, S. (2008). Bamboo Bicycles in Kumasi, Ghana. *KPMG*, 123, 1-27. Retrieved March 28, 2014, from <http://www.vcc.columbia.edu/pubs/documents/kpmg-bamboobikes-final.pdf>
- Peterson, L., & Londry, K. (n.d.). Finite-Element Structural Analysis: A New Tool for Bicycle Frame Design. *Harris Cyclery*. Retrieved January 7, 2014, from <http://sheldonbrown.com/rinard/fea.htm>
- Plastic Material - When and Where You Need It. (n.d.). *Plastics Supplier of Plastic Sheet Rod Tube, Plastic Films, Adhesives, Sealants, Prototyping Materials, Vespel*. Retrieved November 20, 2013, from <http://www.curbellplastics.com/>

Riverson, J. D., & Carapetis, S. (1991). Intermediate Means of Transport In Sub-Saharan Africa. *Africa Technical Department Series, 161*, 1-22.

Strength | Plastic Properties Tables | Plastics Technical Properties | Dotmar. (n.d.). *Strength* | *Plastic Properties Tables* | *Plastics Technical Properties* | *Dotmar*. Retrieved November 20, 2013, from <http://www.dotmar.com.au/strength.html>

11. Appendices

11.1. Appendix A: Decompositions

#	[FR] Functional Requirements	[DP] Design Parameters
0	FR Transfer loads at head tube joints	DP structure to transfer loads at head tube connection
1	FR Transfer moments at top tube	DP structure to transfer moments at top tube
1.1	FR Transfer moment about x-axis	DP top tube metal brace clamp structure interior wall
1.2	FR Transfer moment about y-axis	DP top tube metal brace clamp structure side wall
1.3	FR Transfer moment about z-axis	DP structure to transfer moments about z-axis
1.3.1	FR Transfer positive moment about z-axis	DP top tube clamp structure
1.3.2	FR Transfer negative moment about z-axis	DP top tube metal brace and gusset structure
2	FR Transfer moments at down tube	DP structure to transfer moments at down tube
2.1	FR Transfer moment about x-axis	DP down tube metal brace clamp structure interior wall
2.2	FR Transfer moment about y-axis	DP down tube metal brace clamp structure side wall
2.3	FR Transfer moment about z-axis	DP structure to transfer moments about z-axis
2.3.1	FR Transfer positive moment about z-axis	DP down tube metal brace and gusset structure
2.3.2	FR Transfer negative moment about z-axis	DP down tube clamp structure

Figure 31: Head Tube Decomp

#	[FR] Functional Requirements	[DP] Design Parameters
0	FR Transfer loads bottom bracket joints	DP structure to transfer loads at bottom bracket connection
1	FR Transfer moments at down tube	DP structure to transfer moments at down tube
1.1	FR Transfer moments about x-axis	DP down tube metal brace clamp structure interior wall
1.2	FR Transfer moments about y-axis	DP down tube metal brace clamp structure side wall
1.3	FR Transfer moments about z-axis	DP structure to transfer moments about z-axis
1.3.1	FR Transfer positive moment about z-axis	DP down tube clamp structure
1.3.2	FR Transfer negative moment about z-axis	DP down tube metal brace and gusset structure
2	FR Transfer moments at seat tube	DP structure to transfer moments at seat tube
2.1	FR Transfer moments about x-axis	DP seat stay metal brace clamp structure interior wall
2.2	FR Transfer moments about y-axis	DP seat stay metal brace clamp structure side wall
2.3	FR Transfer moments about z-axis	DP seat stay metal brace and gusset structure
3	FR Transfer moments at chain stay	DP structure to transfer moments at chain stay
3.1	FR Transfer moments about x-axis	DP chain stay metal brace clamp structure interior wall
3.2	FR Transfer moments about y-axis	DP chain stay metal brace clamp structure side wall
3.3	FR Transfer moments about z-axis	DP structure to transfer moments about z-axis
3.3.1	FR Transfer positive moment about z-axis	DP chain metal brace and gusset structure
3.3.2	FR Transfer negative moment about z-axis	DP chain stay clamp structure

Figure 32: Bottom Bracket Decomp

#	[FR] Functional Requirements	[DP] Design Parameters
0	FR Transfer loads at seat tube joints	DP structure to transfer loads at seat tube connection
1	FR Transfer moments at top tube	DP structure to transfer moments at top tube
1.1	FR Transfer moment about x-axis	DP top tube metal brace clamp structure interior wall
1.2	FR Transfer moment about y-axis	DP top tube metal brace clamp structure side wall
1.3	FR Transfer moment about z-axis	DP structure to transfer moments about z-axis
1.3.1	FR Transfer positive moment about z-axis	DP top tube clamp structure
1.3.2	FR Transfer negative moment about z-axis	DP top tube metal brace and gusset structure
2	FR Transfer moments at seat tube	DP structure to transfer moments at seat tube
2.1	FR Transfer moment about x-axis	DP seat tube metal brace clamp structure interior wall
2.2	FR Transfer moment about y-axis	DP seat tube metal brace clamp structure side wall
2.3	FR Transfer moment about z-axis	DP seat tube tube metal brace and gusset structure
3	FR Transfer moments at seat stay	DP structure to transfer moments seat stay
3.1	FR Transfer moment about x-axis	DP seat stay metal brace clamp structure interior wall
3.2	FR Transfer moment about y-axis	DP seat stay metal brace clamp structure side wall
3.3	FR Transfer moment about z-axis	DP structure to transfer moments about z-axis
3.3.1	FR Transfer positive moment about z-axis	DP seat stay metal brace and gusset structure
3.3.2	FR Transfer negative moment about z-axis	DP seat stay clamp structure

Figure 33: Seat Post Decomp

#	[FR] Functional Requirements	[DP] Design Parameters
0	FR Transfer loads at each chain/seat stay joints	DP structure to transfer loads at each chain/seat stay connection
1	FR Transfer the moments at the chain/seat-stay	DP structure to transfer the moments at the chain/seat-stay
1.1	FR Transfer moment about x-axis	DP chain/seat stay metal brace clamp structure interior wall
1.2	FR Transfer moment about y-axis	DP chain/seat stay metal brace clamp structure side wall
1.3	FR Transfer moment about z-axis	DP structure to transfer moment about z-axis
1.3.1	FR Transfer positive moment about z-axis	DP chain/seat stay metal brace and gusset structure
1.3.2	FR Transfer negative moment about z-axis	DP chain/seat stay clamp structure

Figure 34: Drop-Out (Chain Stay-Seat Stay Joint) Decomp

#	[FR] Functional Requirements	[DP] Design Parameters
0	FR Manufacture Bike	DP Tools
1	FR Manufacture Joints	DP Manufacturing Lab Equipment
1.1	FR Manufacture gusset stencil	DP Laser Cutter
1.2	FR Miter tubes	DP Drill Press
1.3	FR Cut gusset and tubes	DP Dremil
1.4	FR Maintain Alignment	DP Jig
1.5	FR Weld pieces	DP MIG Welder
1.6	FR Dull edges	DP Grinder
2	FR Cut bamboo	DP Chop Saw

Figure 35: Manufacturing Decomp

11.2. Appendix B: Tables of Testing Components Dimensions

Table 5: Dimensions of Compression Test Components

Compression Tests					
Component	Length (in)	Diameter Side 1 (in)	Diameter Side 2 (in)	Thickness (in)	Weight (g)
Heat Treated Bamboo #1 (with node)	4	1.15	1.23	0.130	27.8
Heat treated Bamboo #2 (without node)	4	1.23	1.23	0.119	19.8
Heat Treated Bamboo #3 (without node)	4	1.20	1.22	0.112	19.8
Non-Treated Bamboo #1 (without node)	4	1.02	1.08	0.099	14.2
Non-Treated Bamboo #2 (with node)	4	0.85	0.85	0.107	18.4
Non-Treated Bamboo #3 (without node)	4	0.91	0.92	0.111	16.6
Bamboo Purchased Online #1 (with node)	4	0.82	0.81	0.139	17.8
Bamboo Purchased Online #2 (without node)	4	0.79	0.81	0.115	14.9
Bamboo Purchased Online #3 (without node)	4	0.81	0.79	0.105	13.5
Bamboo from 2013 MQP #1 (seat/chain stays)	4	0.85	0.85	0.162	13.0
Bamboo from 2013 MQP #2 (seat/chain stays)	4	0.84	0.86	0.169	13.8
Bamboo from 2013 MQP #1 (head tube/seat tube/ top tube)	4	1.63	1.63	0.147	26.3
Bamboo from 2013 MQP #2 (head tube/seat tube/ top tube)	4	1.62	1.64	0.141	25.1
Bamboo from 2013 MQP #3 (head tube/seat tube/ top tube)	4	1.61	1.63	0.175	24.2
Metal Tubing from Road Bike	4	1.01	1.01	0.050	72.1

Table 6: Dimensions of 3 Point Loading Test Components

3 Point Loading Tests

Component	Length (in)	Diameter Side 1 (in)	Diameter Side 2 (in)	Thickness (in)	Weight (g)
Heat Treated Bamboo #1	15	1.0	1.16	0.134	76.5
Heat treated Bamboo #2	15	1.18	1.15	0.115	84.3
Non-Treated Bamboo #1	15	1.21	1.15	0.117	80.8
Non-Treated Bamboo #2	15	0.93	0.97	0.111	56.1
Bamboo Purchased Online #1	15	0.79	0.77	0.112	57.0
Bamboo Purchased Online #2	15	0.78	0.80	0.122	58.0
Bamboo from 2013 MQP #1 (seat/chain stays)	15	0.84	0.84	0.096	33.2
Bamboo from 2013 MQP #2 (seat/chain stays)	15	0.77	0.82	0.088	61.8
Bamboo from 2013 MQP #1 (head tube/seat tube/ top tube)	15	1.67	1.71	0.368	95.4
Bamboo from 2013 MQP #2 (head tube/seat tube/ top tube)	15	1.75	1.72	0.365	97.5
Metal Tubing from Road Bike	15	1.125	1.125	0.056	322.3

11.3. Appendix B: Components after Testing



Figure 36: Non-Treat Bamboo #1 after Compression



Figure 37: Purchased Bamboo #1 after Compression



Figure 38: Bamboo Stays #1 from 2013 MQP after Compression



Figure 39: Bamboo Main #3 from 2013 MQP after Compression



Figure 40: Steel Tubing #1 after Compression



Figure 41: Heat Treated Bamboo #1 after 3 Point Loading



Figure 42: Non-Treated Bamboo #1 after 3 Point Loading



Figure 43: Purchased Bamboo #2 after 3 Point Loading



Figure 44: Bamboo Stays #2 from 2013 MQP after 3 Point Loading



Figure 45: Bamboo Main #2 from 2013 MQP after 3 Point Loading



Figure 46: Steel Tubing #1 after 3 Point Loading

11.4 Gusset Dimensions

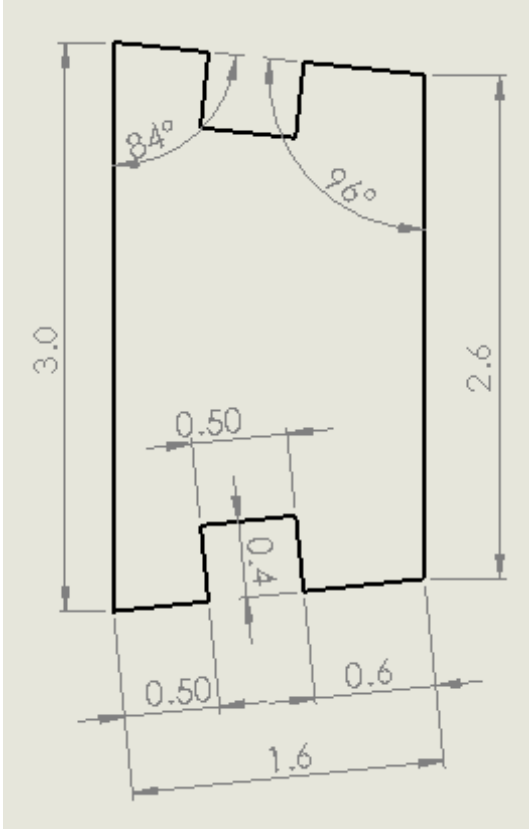


Figure 47: Chain Stay Plate

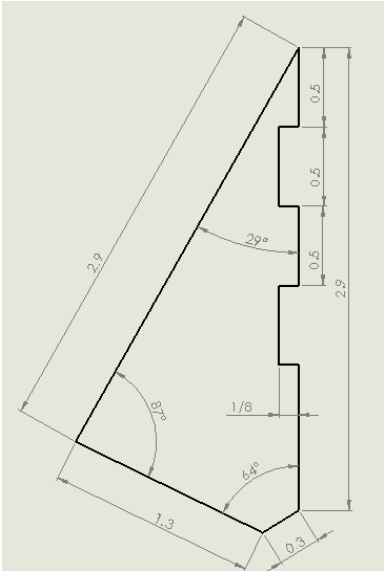


Figure 48: Chain Stay Gusset

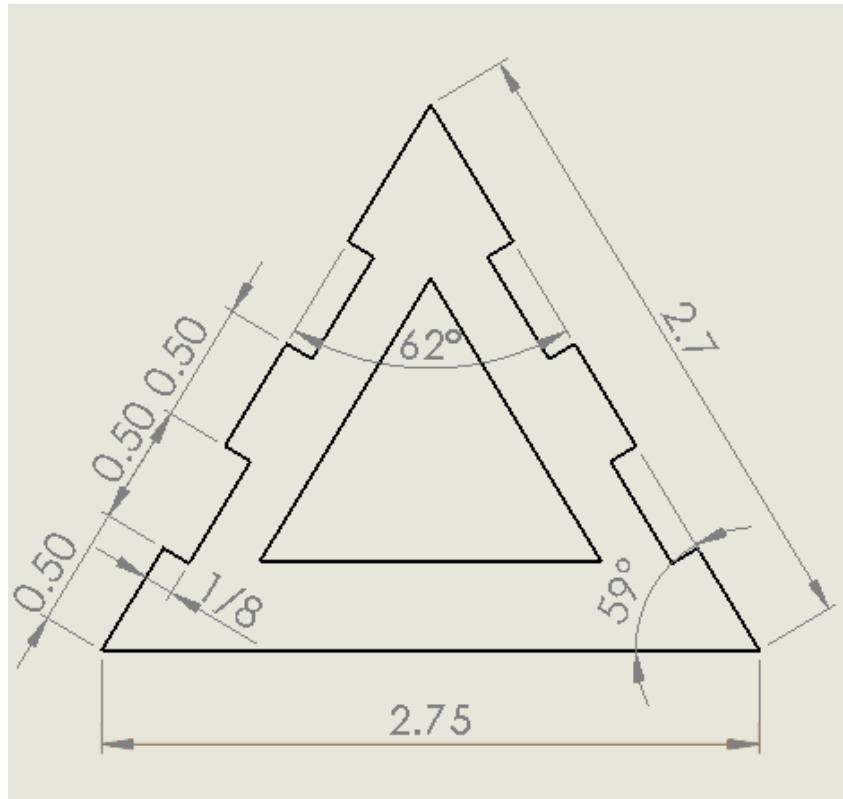


Figure 49: Down Tube Seat Tube Gusset

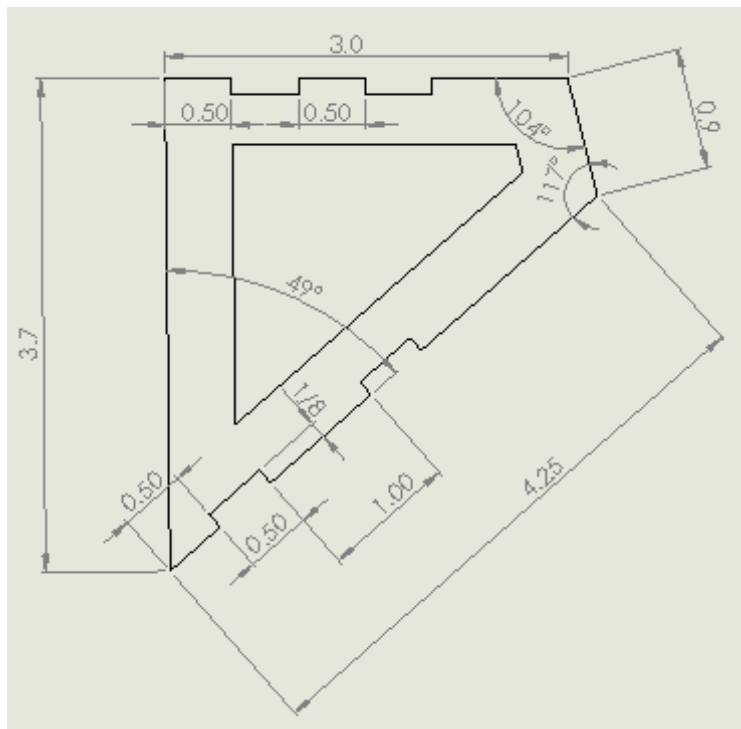


Figure 50: Head Tube Gusset

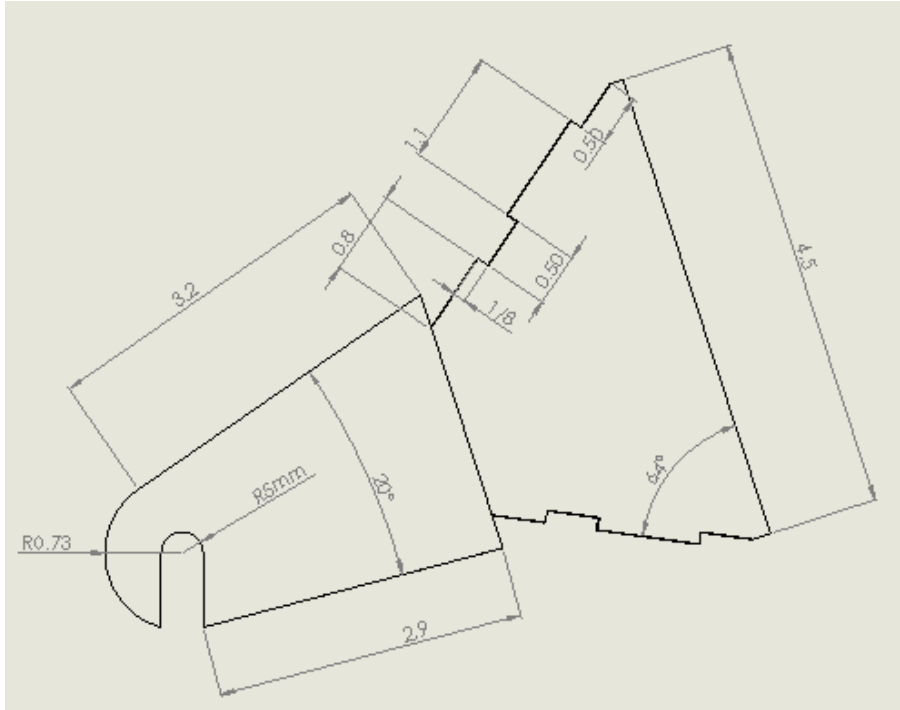


Figure 51: Rear Dropout

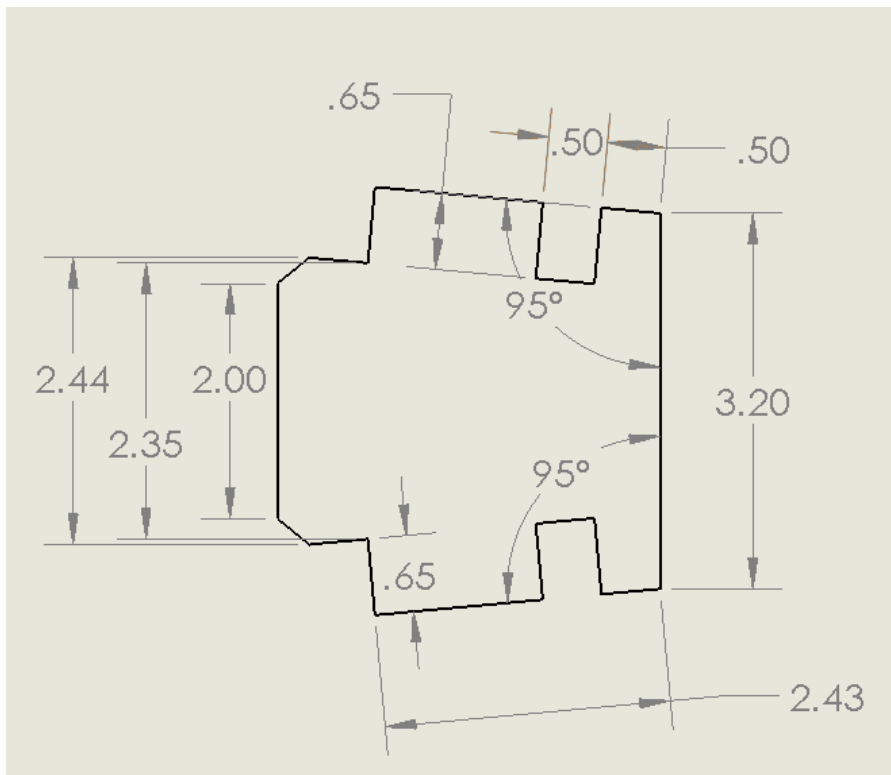


Figure 52: Seat Stay Plate

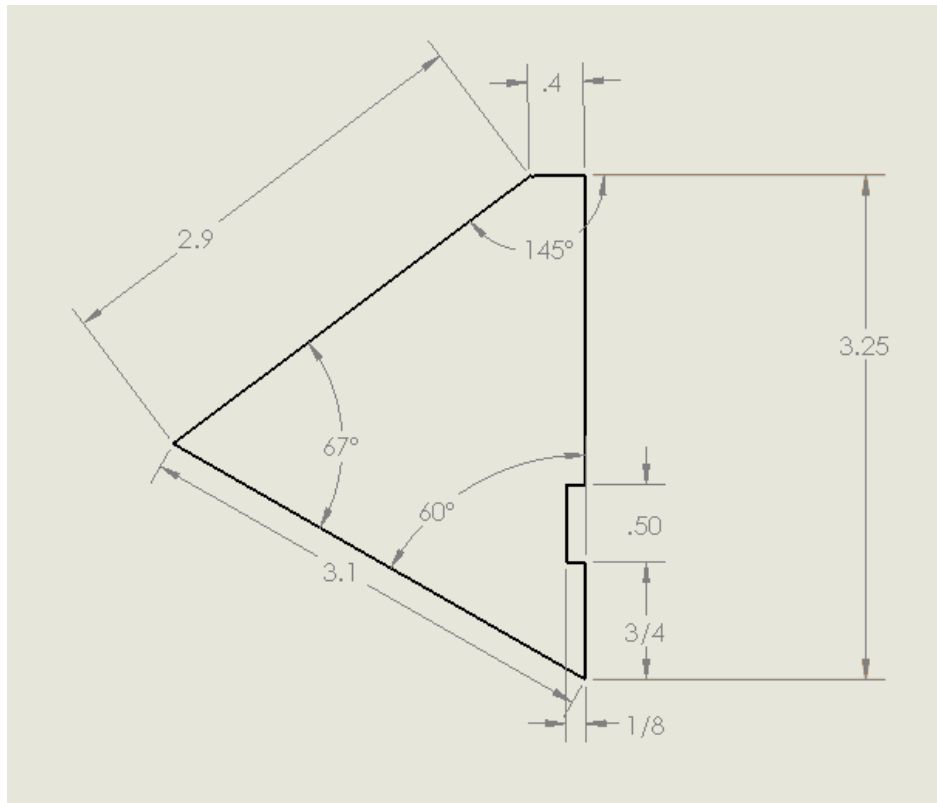


Figure 53: Seat Stay Gusset

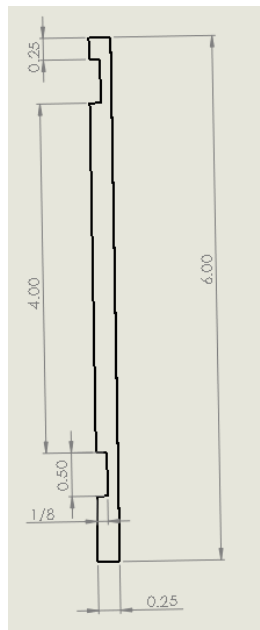


Figure 54: Seat Tube Spacer

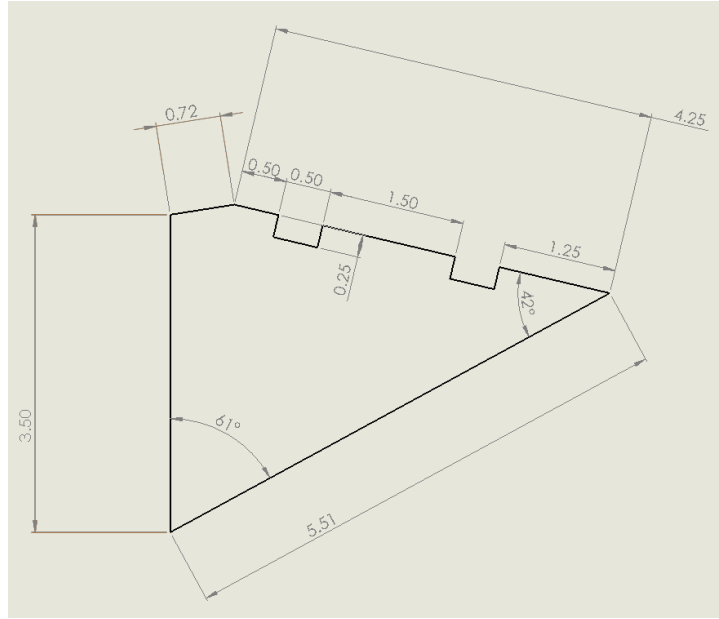


Figure 55: Top Tube Seat Tube Gusset