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MANUFACTURING BAMBOO BICYCLE FRAMES WITH MOLDED COMPOSITE JOINTS

A Major Qualifying Project Report

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By

Nathaniel Gee

Paolo Masakayan

Majd Sbat

Mathew Skerritt

Robert Winthrop

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Approved:

Professor Brown, Christopher A., ME, Advisor

Abstract

Inexpensive bicycles promote better development and improve life in third world countries. One of the easiest ways to produce a cheaper bicycle is to use a cheaper material for the frame. Bamboo is comparable in strength to aluminum alloy tubes, yet has a much lower cost. Bamboo bicycles are currently used as a mode of cheap transportation in third world countries. Currently the most common process used for manufacturing bamboo frames is hand wrapping a composite layup around each joint. This procedure is labor intensive and results in a slow output of bamboo bicycles. The objective of this project is to build a less expensive and easier to manufacture bamboo bicycle frame than ones currently available. Axiomatic design was used thoroughly in this project. A new joint making procedure was designed to promote easier manufacturability of the bike. The joints were modeled in SolidWorks. Finite element analyses with normal static bike loads were performed in ANSYS. The tooling was CNC machined by a group member on Haas machine tools using ESPRIT CAM software provided by DP Technology.

Acknowledgements

We would like to acknowledge our advisor Christopher Brown for his guidance and assistance throughout the project. We would also like to thank Worcester Polytechnic Institute (WPI), Adam Sears, Torbjorn S. Bergstrom, Dr. Adriana Hera, and Don Pelligrino. Thanks to the WPI Manufacturing Laboratory, Haas Automation, Inc., Kennametal Inc., and DP Technology ESPRIT for their help. Thank you to the Bamboo Bike Studio for their guidance and assistance in gaining the necessary materials to succeed in this project. Finally, we would like to thank Axiomatic Design Solutions Incorporated.

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1. Introduction

1.1. Objective

Build a less expensive and easier to manufacture bamboo bicycle frame than ones currently available. The bamboo bicycle must ride and function as a standard bicycle.

1.2. Rationale

Transportation is directly related to development and "immobility and poverty go hand in hand" (Simon, 1996). Columbia University conducted a study on the most affordable means of transportation, other than walking, available to residents living in Ghana. The bicycle was found to be the most efficient mode of transportation (Millennium Cities Initiative, 2008). The use of bicycles in third world countries allows for better development; however, "the purchase of a bicycle, especially if new, represents a substantial capital investment which may be beyond the means of many poor households" (Simon, 1996). It is important that an affordable mode of transportation is available to third world countries in order to expedite their development.

One way to make a cheaper bicycle is to use a cheaper material for the frame. "Bamboo is a cheap alternative to metal and has a higher tensile strength than steel" (Chan et al. 2012). "The strength of bamboo comes from it having no rays or knots in its structure, allowing any stresses applied to be evenly distributed throughout its structure" (Li, 2011). Constructing a bike frame from bamboo would prove to be both an economical and safe alternative.

1.3. State of the Art

The Bamboo Bike Project currently mass-produces bamboo bikes for $55 USD in Ghana and Ecuador. Only two bikes can be crafted per employee each day. Crafting these bicycles is done on a tabletop jig or stand-up jig. The tabletop jig fixes the head tube, bottom bracket support tube, and dropouts in place. The pre-epoxied lugs and bamboo are then placed into the jig to be wrapped. The stand-up jigs fix metal parts, lugs, and bamboo vertically (Chan et al. 2012).

Once the frame is fixed in the jig, fiberglass strips soaked in epoxy are wrapped around the high load paths of the joints. After fifteen minutes, a vinyl tape compression wrap is applied to each joint to prevent air bubbles during curing. Next, the vinyl tape is removed and joints are sanded to remove any sharp edges. Carbon fiber is used to wrap the dropouts instead of fiberglass. This method is tedious and includes many small similar parts, making the joining process complicated (Chan et al. 2012).

The 2012 Bamboo Bicycle Major Qualifying Project (MQP) created vacuumed formed PETG plastic shells for joints. The prefabricated shells were filled with epoxy using a large syringe. This method proved to be messy and led to weak joints. The group also created a jig system that could fasten bike parts while the injected epoxy was curing (Chan et al. 2012).

Another method describes work currently being done on bamboo bicycle joints in Ghana. It explains the use of aluminum and wood molds for joints on bamboo bicycles. In the article, John Mutter said,

> *"The forks that were sent in the container from China have steerer tube lengths shorter than ordered, and that means they do not suit the molds that were made for the lugs for these bikes. Though the metal head tubes can be easily cut down to be suitable, the aluminum molds that were made for this purpose are no longer suitable. So Marty has been busy trying to make a new mold from wood. He has spent a large amount of time on this – even going to the Kumasi Technical Institute (KTI) for help. This way of making a mold requires carving the mold shape from hard wood and goes very slowly*."(Mutter, 2011)

1.4. Approach

This project improves upon the 2012 bamboo bicycle MQP. The MQP recommended that the shell production can be improved by using stronger materials for the shell and epoxy matrix.

The new method includes: aluminum 6061 as a reusable mold instead of plastic shells, West Systems 105/206 epoxy and hardener, and 7725 fiberglass cloth. The fiberglass is saturated with epoxy and then placed in the aluminum molds. The bamboo is then positioned and epoxy is injected into the molds. When the epoxy is cured, the bamboo bicycle frame can be removed from the molds.

The jig system, which holds the correct geometry of the bamboo bike frame, was also modified. In the 2012 bamboo bicycle MQP, acrylic clamps were designed and constructed in order to maintain the geometry while the epoxy cured. This project's jig system was constructed to secure the aluminum molds at the proper heights and angles, which allows the molds to center the bamboo.

1.5. Methods

To accomplish the objective, reusable aluminum molds were designed and manufactured to create molded bicycle joints. These manufactured molds are reusable which enables mass production at a faster rate than current bamboo bicycles. The standard method for manufacturing bamboo bicycles is time consuming and slow. This new method has an optimal manufacturing time of one hour. In order to ensure the optimal frame geometry is met, a jig system is used to secure the bamboo in place.

2. Design Decompositions and Constraints

Axiomatic design was used throughout this project. Axiomatic design is an approach that follows the idea, the best design is one that maximizes the independence of the functional elements, as well as minimizes the information content. All information is then split into two categories: Functional Requirements (FRs) and Design Parameters (DPs). FRs are an objective and the corresponding DP would be the means to solve the objective. FR0 is the objective function. Each FR can branch out into child FRs which are components or sub objectives required to reach the parent or original FR, in this case FR0. Each child can be further broken down into more child FRs. The result is a decomposition, which is a helpful tool in ensuring all the necessary objectives are met during the design process (Brown, 2012).

2.1. Top Level FRs of Main Decomposition

Below are the top level FRs of the main decomposition. The theme of FR0 lies within the words sturdy and third world countries. The goal is to provide a mode of transportation for those in third world countries. The bike is the mode of transportation. However, an issue is that standard bikes are too expensive. This is why the bike frame will be made of bamboo. The goal of this MQP is to produce the bike frame as cheap and as strong as possible.

#		[FR] Functional Requirements		[DP] Design Parameters
0	FR	Provide a sturdy mode of transportation for third world countries.	DP	Bamboo bike
1	FR	Sustain up to 300lb without breaking	DP	Strong frame that can withstand "y" N of force
2	FR	Present optimal joint geometry	DP	Joint geometry
3	FR	Use mechanism to hold the bike frame in position	DP	Jig
4	FR	Prepare bamboo for manufacturing	DP	Bamboo manufacturing method

Figure 1: Core FRs and DPs

2.1.1. FR1: Sustain up to 300lb Static Loading without Breaking

FR1 states that the bike must be able to sustain the weight of the rider. The weight of 300lbs was chosen because it is more than 1.5 times the weight of an average male (CDC, 2012). If the bike cannot hold the weight of the rider it will fail.

2.1.2. FR2: Present optimal joint geometry

FR2 presents the optimal joint geometry. There are many ways to construct a bike frame in terms of tube placements. The goal was to use an available geometry that evenly distributes the stress when the bike is being ridden.

2.1.3. FR3: Use mechanism to hold the bike frame in position

FR3 states that a mechanism to hold the bike frame in position is required. Whenever epoxy is applied to an object it is recommended that the pieces be held in place manually until the epoxy cures. This applies to the bike joints being made. Epoxy molds are being used to hold the joints together, but a mechanism is required to hold the bike frame in position while the epoxy cures.

2.1.4. FR4: Prepare bamboo for manufacturing

FR4 states that it is necessary to prepare the bamboo for manufacturing. Preparations are necessary for the bamboo tubes before they can be used on the bike frame.

2.2. Collectively Exhausted and Mutually Exclusive

The FRs are independent of each other, but when put together they make up FR0. This is important because during the design/manufacturing process if there was a problem with one of the FRs, the problem could be controlled and fixed without affecting other FRs. The matrix below shows the relationships between the core FRs. Figure 2 shows that each FR is independent of one other.

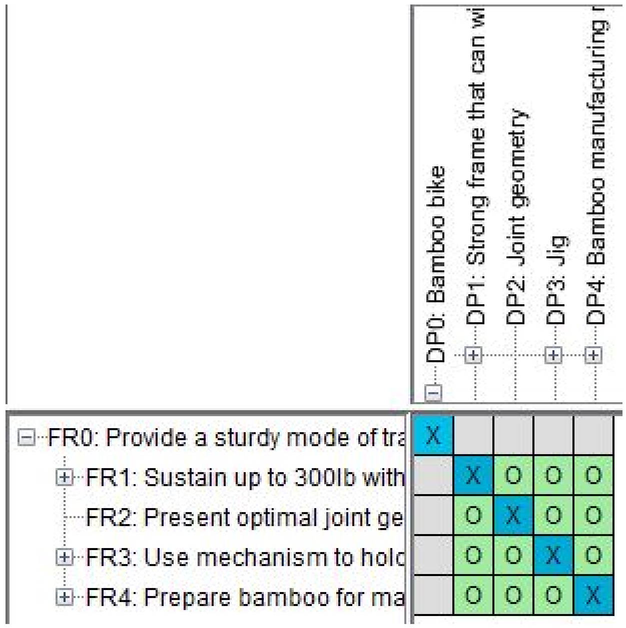

Figure 2: Main Decomposition Matrix

2.3. Additional Conditions

There are two main constraints or factors that can make or break this project throughout the design and manufacturing process, these include: the cost of materials and the strength of the bamboo.

The cost of the materials is an important factor when making a bamboo bicycle for third world countries. A bamboo bicycle's purpose is to provide a cheaper mode of transportation compared to a standard aluminum bike. If the materials required to manufacture the bicycle are too expensive, there would be no need for using the new design.

Even if the design of the actual bicycle is perfect, the bamboo must meet a required strength. Bamboo does not have a standard size. As a result, tolerances need to be determined. The mold designs used must accommodate these tolerances to create a strong frame.

2.4. Top Level FRs for Jig Decomposition

The jig decomposition identifies how the jig is used to manufacture the bicycle. A key point from this decomposition is that the entire joint geometry is held together by a combination of brackets and molds. The distance between each bracket was measured to enable the frame geometry to stay in the optimal shape. The molds fit securely within the brackets which hold and center the bamboo.

#		[FR] Functional Requirements		[DP] Design Parameters
0	FR	Provide stability to all bike components during manufacturing	DP	Jig
1	FR	Steady bike component outline	DP	Jig components all held in place
2	FR	Sustain bike tube placements	DP	Tube holding method (molds)
3	FR	Keep tubes in mold	DP	Screws
4	FR	Maintain mold positions	DP	Jig brackets

Figure 3: Jig Decomposition

2.4.1. FR1: Steady bike component outline

Once the manufacturing of the jig is complete, the bamboo tubes can be placed in the molds. Once the epoxy cures, any movement of the bamboo cannot be corrected. The desired bicycle layout must be held in place throughout the manufacturing process.

2.4.2. FR2: Sustain bike tube placements

The bamboo tubes must be centered throughout the manufacturing process. If a bamboo tube is not centered when the epoxy is injected, the bamboo will not be fully encased in epoxy.

2.4.3. FR3: Keep tubes in mold

When the epoxy is being injected into the mold, the pressure buildup inside the mold will cause the epoxy to leak out. This problem is solved during the manufacturing process by applying a sealant to gaps in the molds. In order to prevent molds from pushing apart, screws are used to secure the mold pieces together. This also helps to control the flow of epoxy.

2.4.4. Maintain mold positions

The molds must be kept in place during the manufacturing process. Once the epoxy cures, the molds must be removed carefully to not to damage the bamboo. The brackets will secure the molds in their prospective locations. That way all attention can be focused on a single mold at a time to minimize the possibility of errors to occur.

2.4.5. Jig core FR/DP Matrix

The four core FRs are shown below to be independent of one another. All four have the combined purpose of providing stability to the overall structure, but each FR keeps its independence by representing a different component of the jig system. For example, FR3 relies on screws, while FR4 relies on brackets.

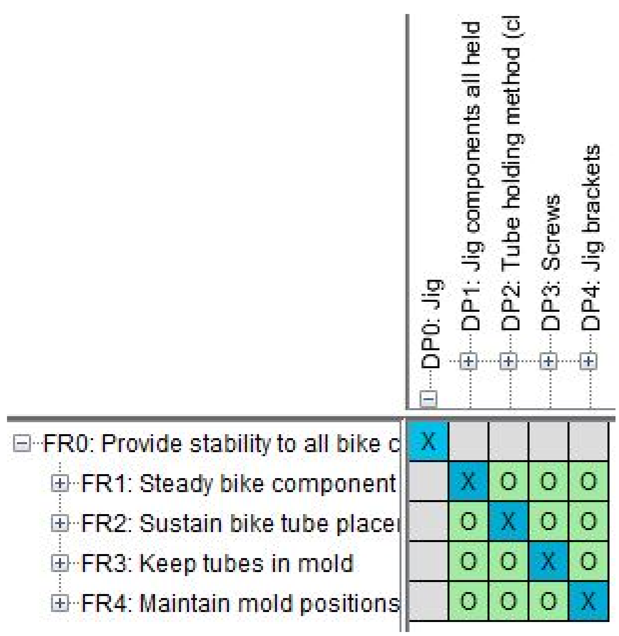

Figure 4: Jig FR/DP Matrix

2.5. Top level FRs for Wet-layup Decomposition

The wet-layup procedure is used to create the epoxy composite joints within the aluminum molds. If the wet-layup is not performed to its specifications, there is high potential for problems to occur later in the manufacturing process.

#		[FR] Functional Requirements		[DP] Design Parameters
0	FR	Build a strong joint structure	DP	Wet-layup Process
1	FR	Form a casing around joints to provide strength	DP	Process to use Aluminummolds
2	FR	Add a layer on top of bamboo before putting in mold to provide strength	DP	Process to apply Fiberglass (7725 Fiberglass Cloth)
3	FR	Set mold pieces in place while the epoxy hardens.	DP	Process to screw molds together to minimize movement.
4	FR	Create a controlled flow for the epoxy when applying	DP	Process to inject epoxy through holes in mold
5	FR	Hold mechanism to hold joint molds in place during manufacturing process	DP	Jig

Figure 5: Wet-Layup Decomposition

2.5.1. FR1: Form an epoxy casing around joints to provide strength

This section of the wet-layup procedure requires epoxy to solidify around the bamboo tubes. Aluminum molds are used to maintain the epoxy and fiberglass around the bamboo while curing.

2.5.2. FR2: Add a layer to the bamboo to provide strength

Even though the epoxy is what encases the joint and keeps the bamboo tubes together, it does not control the overall strength of the joint. Epoxy alone is not able to withstand the weight of the rider. Fiberglass is wrapped around the bamboo before the epoxy is injected to give the bamboo joint strength. Based on the stress values on the joints, they can be wrapped with multiple layers of fiberglass which will further increase their strength.

2.5.3. FR3: Set mold pieces in place while the epoxy hardens

The epoxy takes several hours to cure after the wet-layup process is complete. It is important for the molds to stay in place while the epoxy cures. Screws are used to attach the mold pieces together, allowing the epoxy joint to keep its shape.

2.5.4. FR4: Create a controlled flow for the epoxy when applying

To keep the epoxy around the bamboo tube, the aluminum molds encase the joint completely. In order for the epoxy to be injected, holes were made on the top of the molds. The holes direct the epoxy to the cavity around each of the bamboo joints to circulate and fill the mold. When the cavity inside the mold fills, the epoxy will start to rise out of the other fill holes.

2.5.5. FR5: Holding mechanism to secure the molds

The bamboo tubes must be held in place during the manufacturing process for the bicycle to keep the correct orientation. To accomplish this, a jig table with brackets to hold the molds in place was used.

2.6. Wet-Layup Core FR/DP Matrix

The five core FRs are shown in Figure 6 below and are independent. The FRs keep their independence since each FR is a separate process in the wet-layup procedure. Though required to be done in a certain order, none are dependent on the others.

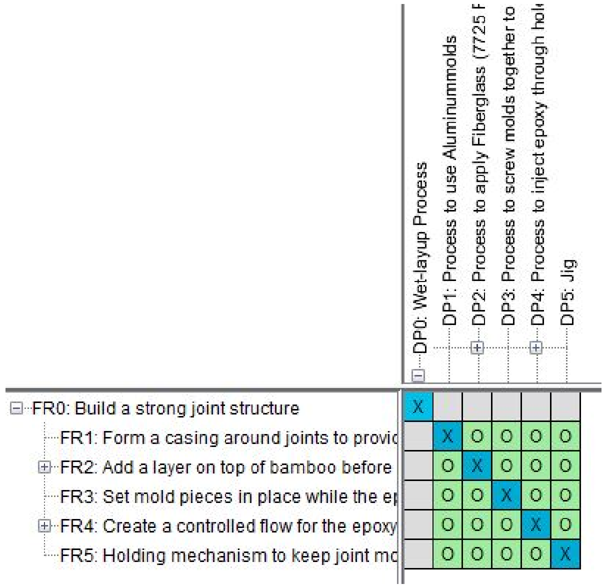

Figure 6: Wet-layup FR/DP Matrix

3. Physical Integration

The completed jig system is shown in Figure 7 below. Lines are drawn showing which FRs from the main decomposition correspond to which parts of the system. The placement is set so the head tube is on the top left, the seat post is at the top middle, the dropouts are on the bottom right, and the bottom bracket in the bottom middle. The FR arrows point to certain parts of the bamboo and jig system. The corresponding FRs can be seen in Table 1.

Table 1: Corresponding FRs

FR #	Functional Requirement
2.1.1	Position Head Tube
2.1.2	Position Dropouts
2.1.3	Position Bottom Bracket
2.3.1	Position Top Tube in Frame Geometry
2.3.2	Position Down Tube in Frame Geometry
2.3.3	Position Seat Tube in Frame Geometry
2.3.4	Position Seat Stays in Frame Geometry
2.3.5	Position Chain Stays in Frame Geometry
3.1.1	Provide Way of Keeping Mold Pieces Attached While Being Filled

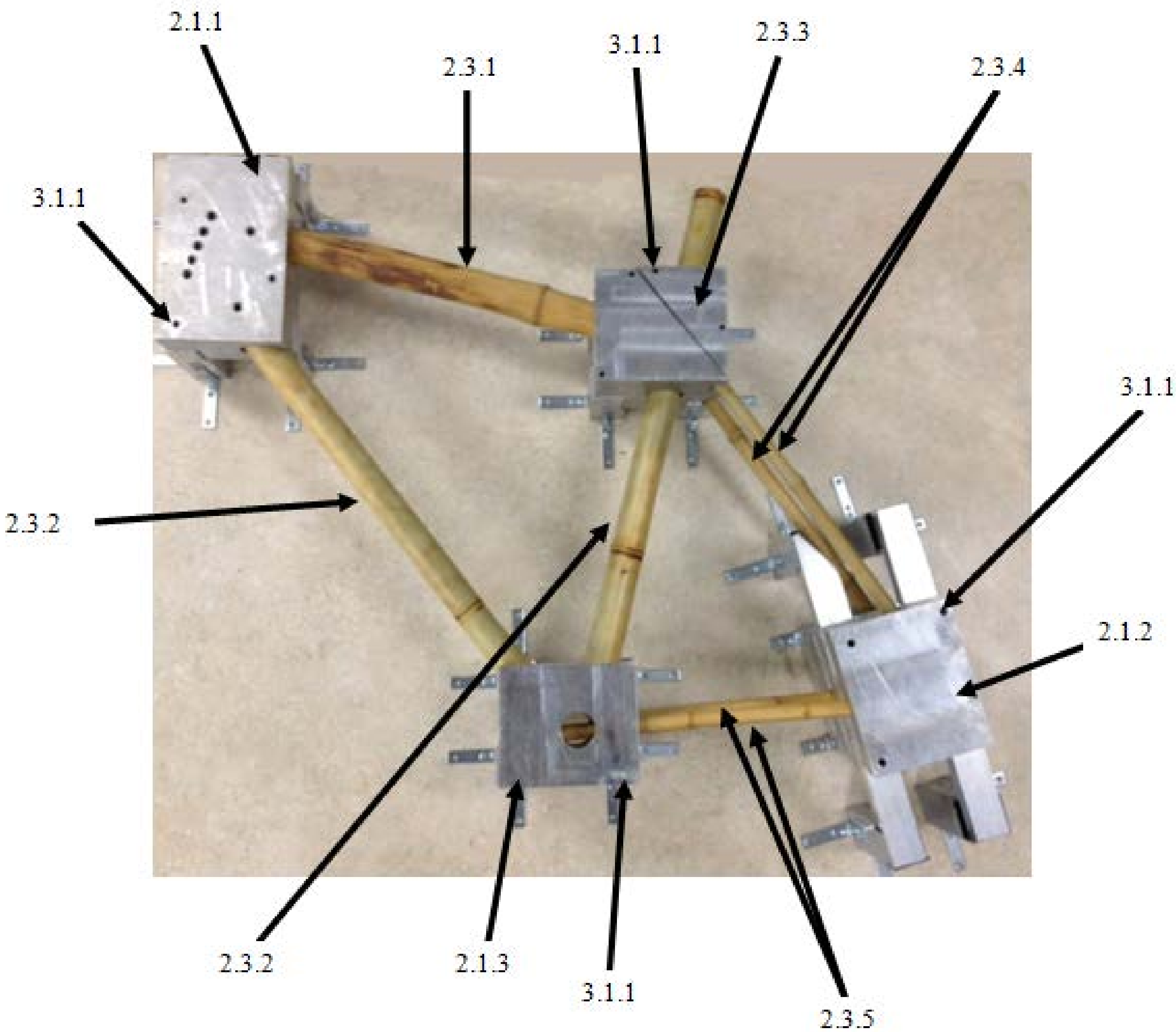

Figure 7: Solid Model FR Integration

3.1 Head Tube

The head tube mold is a two-piece mold. The headset or head tube cylinder lays in the mold with both ends sealed to enable the handlebars to slide through in the assembly process. This mold corresponds to FR 2.1.1, FR 2.3.1, FR 2.3.2, and FR 2.3.3. The head tube was the most basic to create because only two bamboo tubes are required during the molding process. The head tube's top tube diameter is 1.7 inches and the down tube diameter is 1.94 inches. The holes on the top mold of Figure 8 were the locations where the bolts would secure both molds together as shown in FR 3.1.1. In addition, the bike molds created for this project all contain fillets, which reduce concentration fractures within the joints.

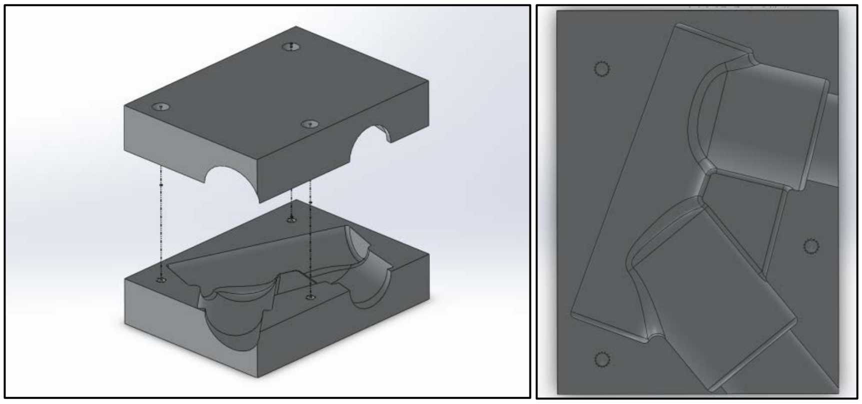

Figure 8: Head Tube Mold

3.2 Bottom Bracket

The bottom bracket is a four-piece mold due to its geometric complexity. This mold connects the seat tube and dropouts. This mold corresponds to FR 2.1.3, FR 2.3.3, FR 2.3.5, and FR 3.1.1. In the center of the mold the bottom bracket cylinder lays with both ends sealed to enable the pedals to enter and rotate. The bottom bracket requires a four piece mold because four bamboo tubes enter this mold. The holes on the top surface of the top mold as indicated in Figure 9 were the locations where the bolts would secure both molds together as shown in FR 3.1.1.

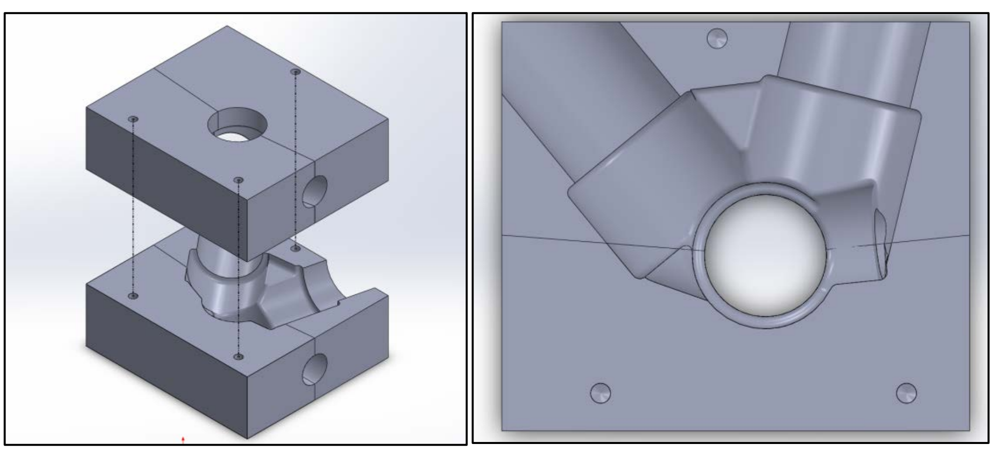

Figure 9: Bottom Bracket Mold

3.3 Seat Joint

The seat joint is also a four piece mold. It connects the bottom bracket and dropouts to the bike frame. The seat joint is also a four piece mold because four bamboo tubes enter this mold. This mold corresponds to FR 2.3.2, FR 2.3.3, FR 2.3.4, and FR 2.3.5. Two bamboo tubes connect to the side of the seat post at an angle of 52.82 degrees. The seat joint inner diameter is 1.5 inches connecting to the dropout with an inner diameter of 1 inch. When removing the bamboo joint from the mold it was discovered that it is difficult to do so because the bamboo has zero degrees of freedom once released. The seat joint mold also required bolts securing the top to the bottom mold and both sides together. This is addressed in FR 3.1.1.

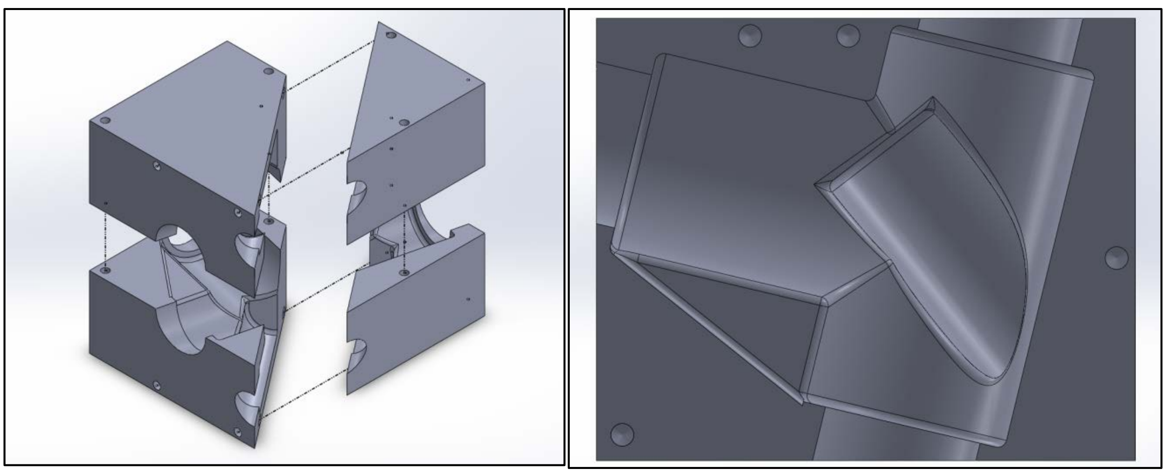

Figure 10: Seat Joint Mold

3.4 Dropouts

There are two dropout molds and each dropout mold consists of two pieces. The corresponding FRs for this mold are FR 2.1.2, FR 2.3.4, FR 2.3.5, and FR 3.1.1. Each dropout mold is unique because it must align the rear wheel axle with respect to the front wheel axle. The distance between both dropout molds is important because the rear wheel requires adequate clearance to operate. The dropout fork would also be placed inside each mold to allow the rear wheel to operate properly. On the top surface of each mold, three bolts were used to secure both molds together as shown in Figure 11. This is addressed in FR 3.1.1.

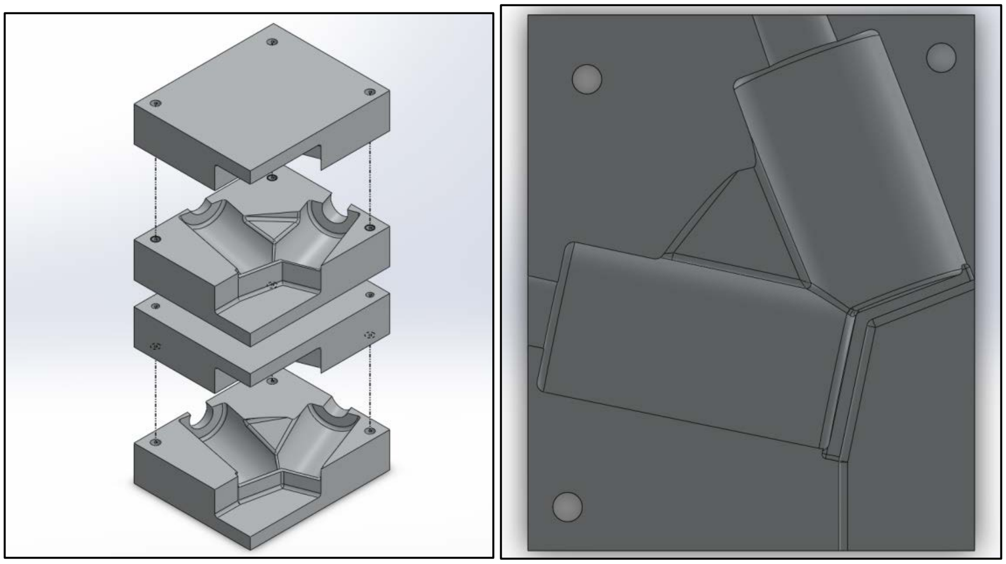

Figure 11: Dropout Molds

3.5 Finite Element Analysis

Finite Element Analysis (FEA) was conducted on the final bamboo frame design. The bamboo properties were obtained using CES Edupack. The composite matrix properties were obtained using formulas done in Appendix D: Joint Material Property Calculations. Since the dynamic loading of a bicycle frame is difficult to replicate in FEA, only static load testing was performed.

The static test was set up to have the dropouts and bottom of the head tube fixed. Then loads of 300lbs were applied vertically down at the seat post, bottom bracket tube, and head tube. The frame setup can be seen in Figure 12. The testing was performed as a maximum load scenario, from someone putting all their weight on seat, pedals, and handlebars. The Von Mises stress and total deformation were calculated for the frame.

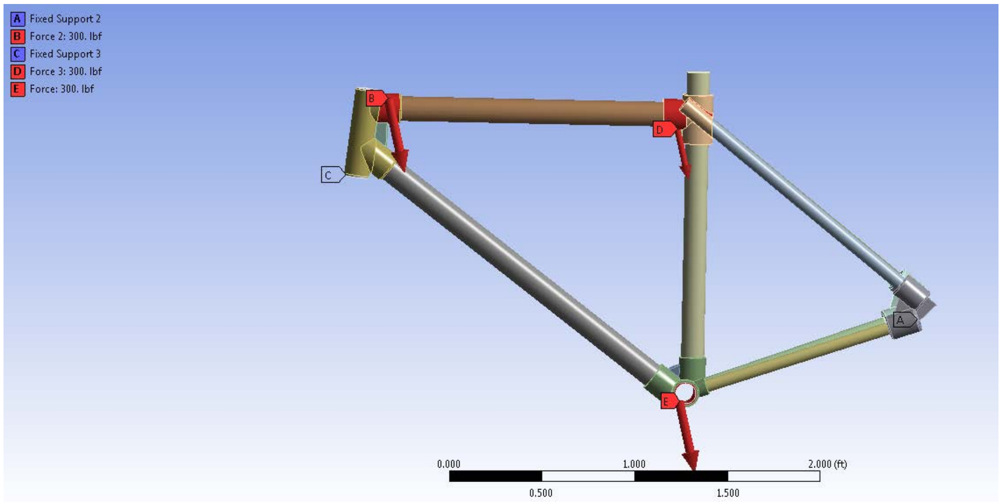

Figure 12: ANSYS Frame Test Setup

The total deformation is shown in Figure 13. The highest deformation is 0.0012835 feet or 0.015402 inches and is near the seat post and is shown in red in the figure below.

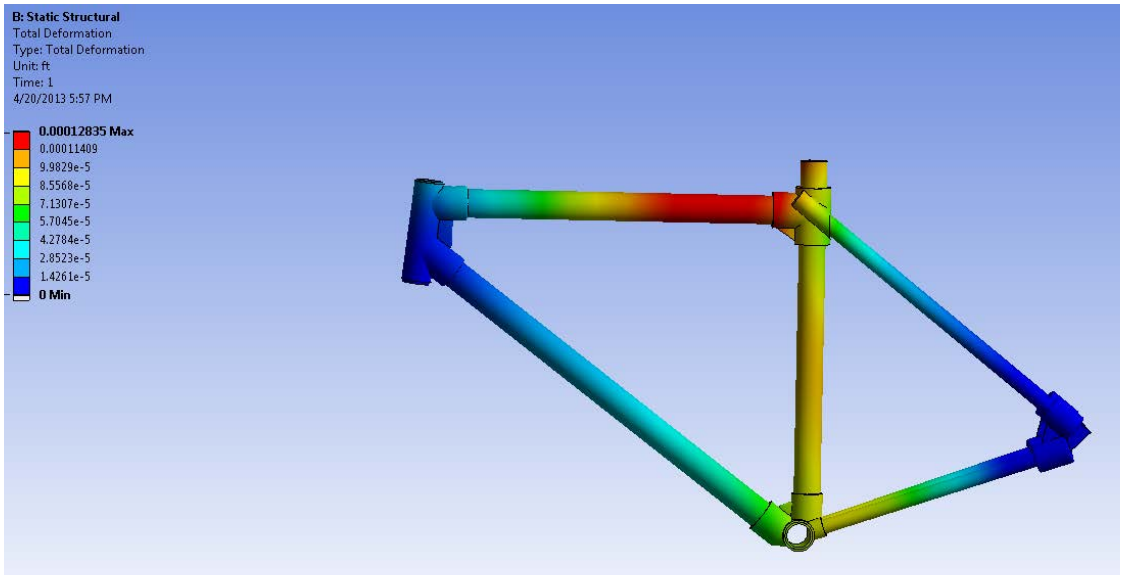

Figure 13: Total Deformation

The Von Mises stress is shown in Figure 14. The minimum stress is at the lowest dropout bamboo and is 0.0475 psi. The maximum stress is at the seat joint and is 6710.5 psi.

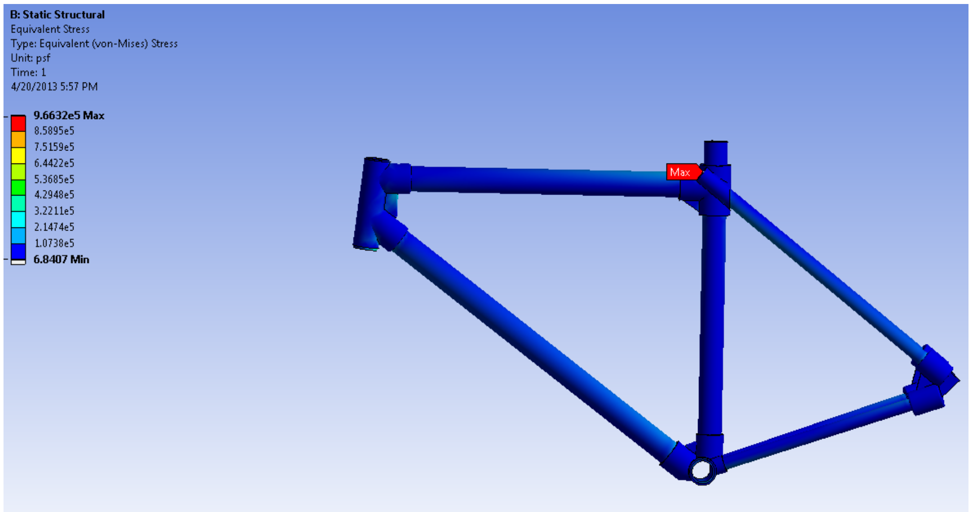

Figure 14: Von Mises Stress

The stresses based on actual testing seemed to work closely to the FEA. The bamboo bike could hold the same weight as in the FEA.

4. Prototype Production

Bamboo bicycle frame geometry was required to create the product. The Trek 3700 mountain bicycle frame geometry was used by the Bamboo Bike Studio. The molds were made in SolidWorks from this geometry. Once created with the desired features, the molds could be manufactured.

4.1 Prototype Manufacturing

In order to build a prototype, bamboo and bike parts currently used by the Bamboo Bike Studio were obtained. The kit included a top tube, seat tube, down tube, two chain stays, two seat stays, two steel dropout forks, a head tube, and a bottom tube.

The SolidWorks models were then merged into DP Technology ESPRIT. ESPRIT allows solid models to be programmed for machine tooling. Every mold needed to be machined. There were eighteen programs created in ESPRIT to achieve this.

4.1.1 Mold Making Procedure

To make the molds, 6061 aluminum blocks were cut to the depth size using a ban saw. The blocks were rough cut and not precisely squared when removed from the ban saw. To fix this the blocks were placed into the vise of the CNC machine as seen in Figure 15. Once they were in the vise, a face mill squared the top face of the block in 0.005 inch steps. Then the block was flipped to square the opposite side.

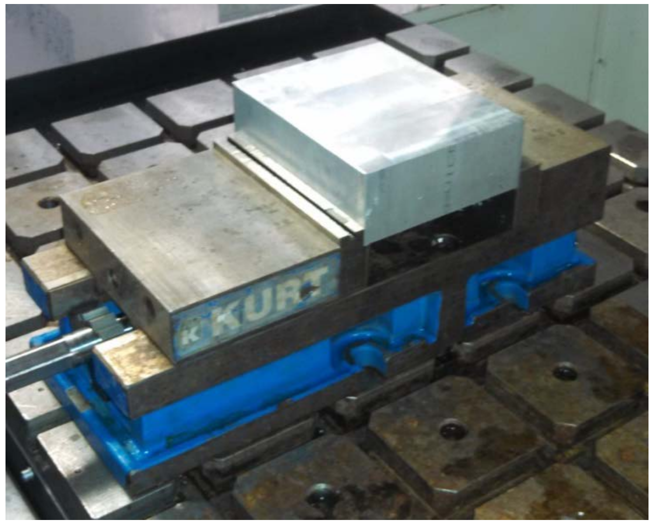

Figure 15: CNC Vise

There were ten blocks of aluminum that needed to be squared. Once the blocks were squared, the depth was measured and placed into ESPIRT. When using the ESPRIT program the SolidWorks models could be merged to keep all geometric features. The solid aluminum block with the correct depth is the starting model for the machining.

To get the desired geometry machined, certain operations were needed. First, the three connection holes needed to be spot drilled. A 3/8 inch drill bit was used to drill a spot hole. Next an F drill bit was used to drill down to the bottom surface of the mold. The inner mold first needs a roughing pass with a 1/2 inch end mill to clear most of the material. The next step is to use a 3/8 inch bull nose end mill to do a parallel planes finishing pass which will create a smooth surface on the inside of the mold. After all these operations are created the final tool path will resemble Figure 16.

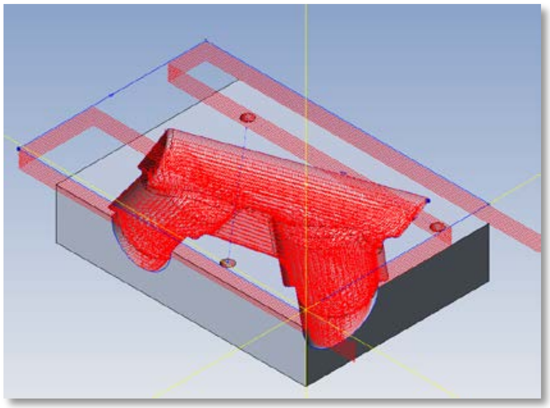

Figure 16: ESPRIT Tool Path

In order to make sure the tool path is correct a CNC machine simulation should be performed. In Figure 17 the machine is following the correct path. If there is a problem with the machine or tool hitting the mold, the program will blink red and give a reason why the operation failed. The green color shows the roughing operation and one can see that it takes material off by a certain z-level each pass. The grey is the parallel planes finishing pass.

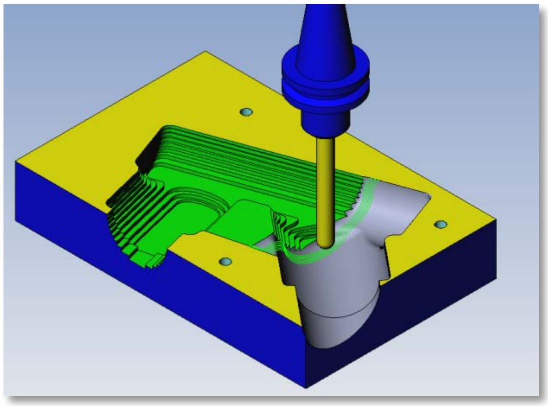

Figure 17: ESPRIT Machine Simulation

The next step is to place the square aluminum block in the CNC machine vise to be machined. The ESPRIT program is converted into an NC code which allows the Haas CNC machine to create the molds. With the program uploaded, the tools and solid block needs to be probed by the machine. Once these steps are completed, the machine can be started as shown in Figure 18.

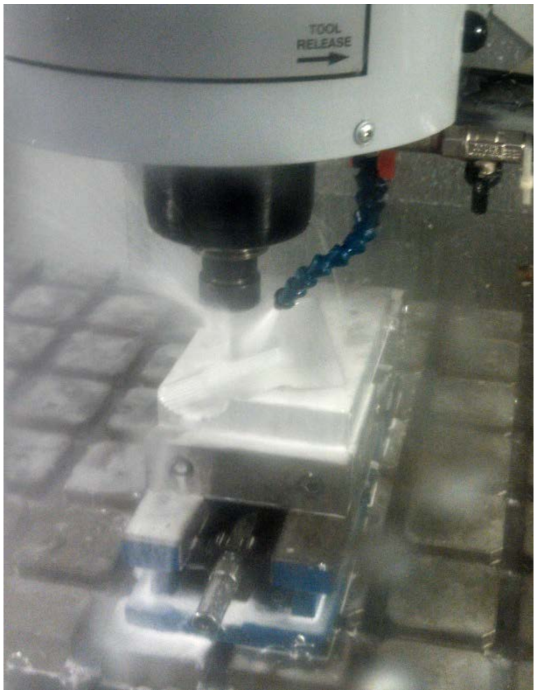

Figure 18: Machining of Molds

Once the machine portion of the mold making procedure is completed, the holes for screws must be drilled through on the drill press with an F-Drill. The holes then need to be tapped with a 5/16”-18 tap. The finished mold should look like Figure 19.

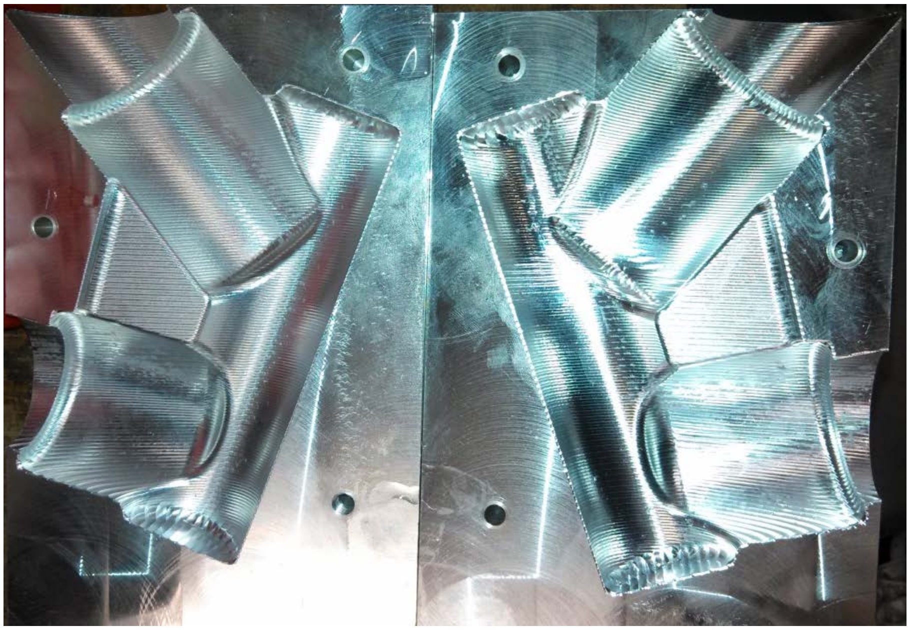

Figure 19: Finished molds

4.1.2 Jig making procedure

The jig was constructed to hold the bike frame in position while the epoxy was curing in the molds. It was designed as a 3x4 foot table which has a laminate surface finish.

To hold all the bike frame bamboo in their proper height positions while curing, small hollow aluminum square shaped tubes were cut in different sizes as legs for each particular mold. These were used to secure the molds to the table. The brackets were cut to provide the proper height for each mold and to maintain only one degree of freedom for each bottom mold. This was achieved by cutting only two of the four walls of the square shaped tube. This created an edge to secure the bottom piece mold in its appropriate place. An L-shaped bracket mounted the mold support brackets to the table. This is seen in Figure 20.

Figure 20: Mold support brackets

The dropout molds had a different approach. They were placed at an angle off the table. The right dropout mold was secured on the jig by a cut out aluminum surface with different support heights to provide the correct angle. This aluminum surface was bolted onto the bottom mold, and was also secured to the table by the L-shaped brackets.

The left dropout mold mirrored the right dropout mold. It had an aluminum support with different leg heights to provide the correct angle. However, the left dropout mold must be at a certain height directly over the right mold. In addition, four aluminum hollow square shaped tubes were cut to provide the height and were mounted into the table by the L-shaped brackets. In order for the bottom dropout to be accessible these brackets were widely spread apart around the bottom dropout. Aluminum rails were then constructed, to connect the brackets. The rails must contain locations for the left dropout mold to lay directly over the right dropout mold. The dropout molds set up is seen in Figure 21.

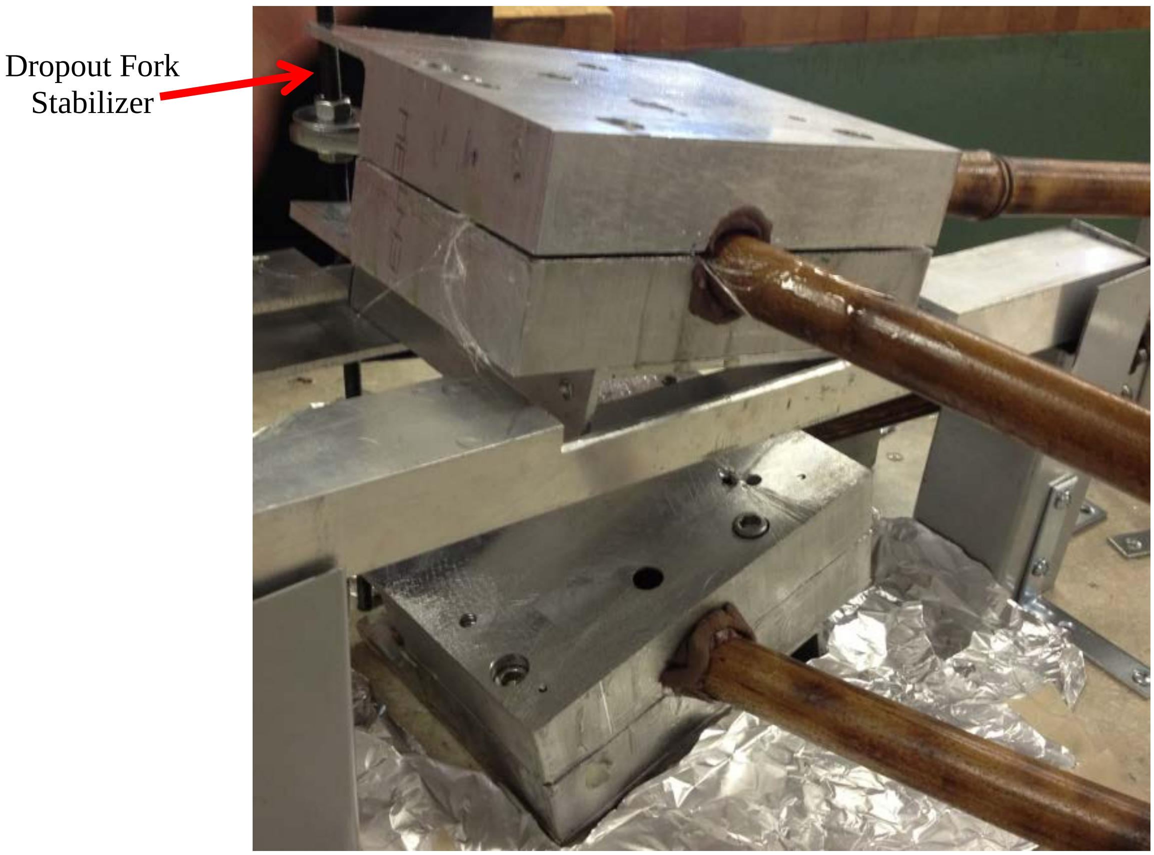

Figure 21: Dropout Mold Set Up

In order to ensure the dropout forks in each mold are exactly horizontal, a cylindrical threaded rod was mounted onto the jig. There are two washers and two nuts on the rod to screw/lock each dropout fork in place. This stabilizing rod is shown by a red arrow in Figure 21.

4.1.3 Joint making procedure

Each mold was located on the jig where it can easily be worked upon. Mold release spray was applied to the molds. In order to create the joint, the epoxy was mixed until both the resin and the hardener were fully combined. The pieces of fiberglass were saturated in epoxy. While the fiberglass was being saturated, epoxy was applied to the bottom mold. The saturated fiberglass was laid in the bottom mold. The bamboo and bike components were placed into the mold at this time. Epoxy was then applied to the top of the bamboo. The fiberglass was placed over the top of the bamboo and bike components. The top piece of the mold was placed on and bolted shut. Once the mold was sealed, more epoxy was injected until the mold was completely filled. The epoxy was allowed to cure. The steps are listed in great detail in Appendix A: Detailed Joint Making Procedure and in Figure 22.

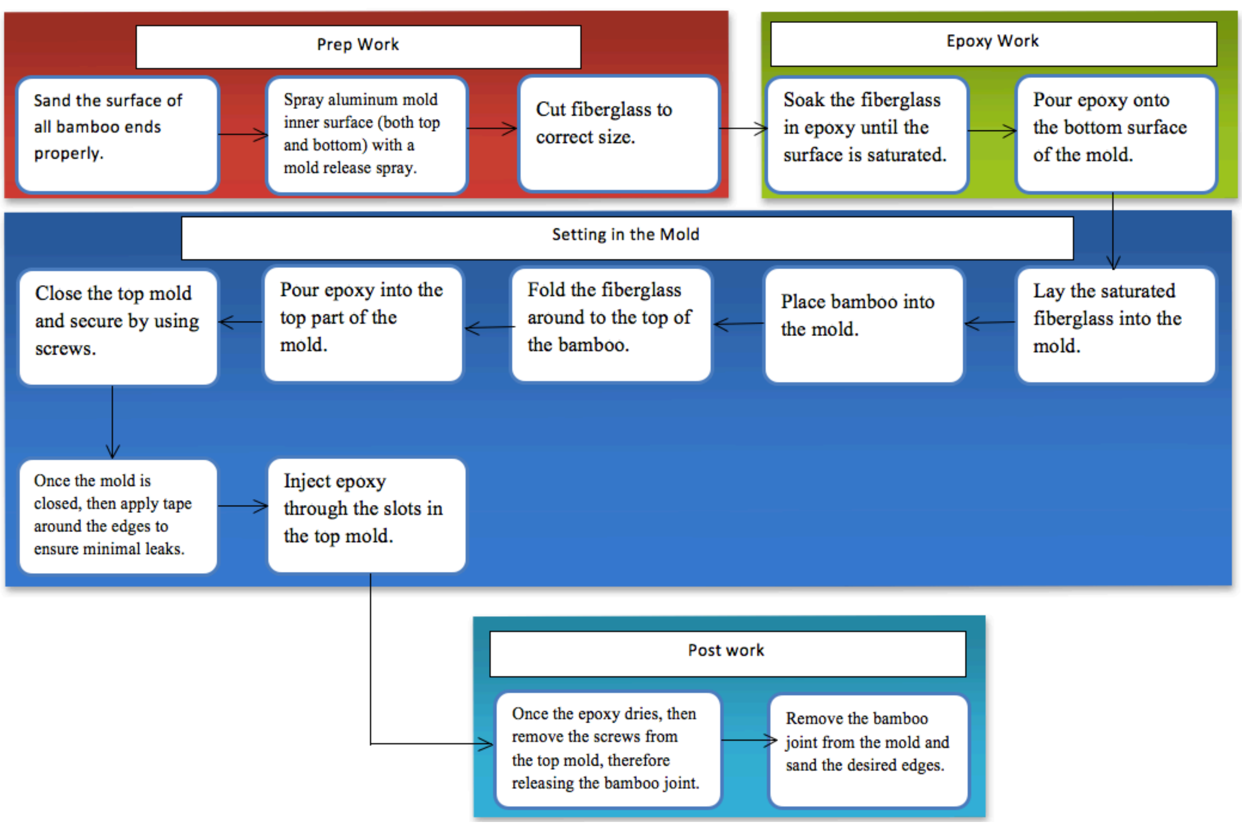

Figure 22: Joint Making Procedure

5. Testing and Analysis

Various forms of testing were used once the bike joints were molded. These included using an Instron as well as simply applying a load to the bike postproduction. After testing conclusions were drawn on the bike frame.

5.1. Prototype testing

Two head tube joints were constructed, the first with one layer of fiberglass and the second with two layers of fiberglass in the mold. These head tube joints were placed in an Instron machine for a static failure test. A downward force was applied to the horizontal bamboo tube as seen in Figure 23 below. The first head tube joint was able to hold a max load of 458 pound force before failure. The second was able to maintain a max load of 583 pound force before failure. The test results are located in Appendix F: Instron Head tube Results. This test demonstrated the effects that the fiberglass has on the joint. Further calculations were made to determine the strength of each joint with varying amounts of fiberglass. It was determined that two to three layers of fiberglass would be optimal for each joint. These calculations can be found in Appendix D: Joint Material Property Calculations.

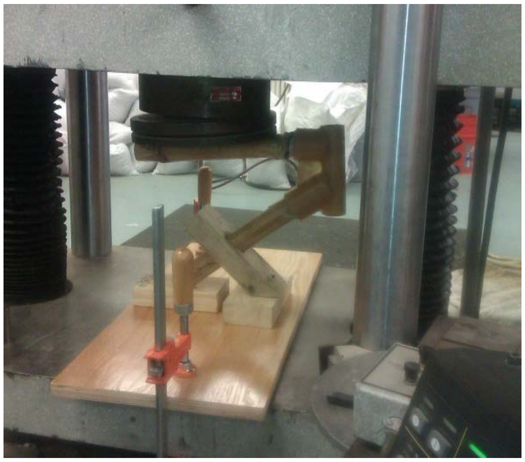

Figure 23: Instron Testing

Once the full bike was constructed a static load was applied to the seat joint area. The bike was able to hold 300 pounds. The bike however, showed no signs of failure under this load. Testing can be seen in Figure 24.

Figure 24: Static Loading Test

Dynamic loading tests were not performed on this bike. This is crucial to see how the bike would operate under riding conditions over various terrains. However, it is known that the bike can maintain more than the weight of an average male, which is approximately 194.7 pounds (CDC, 2012).

5.2. All FRs Satisfied

The final bicycle design satisfies all FRs that were decomposed through axiomatic design. FR1: Sustain up to 300 pounds without breaking, was realized by the bike being able to hold 300 pounds once it was made. FR2: Present optimal joint geometry, was met due to the bicycle's geometry staying together. However, since some of the geometry was altered post production, it was unable to definitively state that the geometry used was optimal. The reason behind this was the seat joint angle was slightly altered and the bicycle was not perfectly in line. FR3: Use mechanism to hold frame in position, was achieved through the creation of the jig system. This system was able to hold the bamboo in place with each mold. It also allows for the geometry to remain the same for every bike made. FR4: Give a standard manufacturing method, has been achieved through the joint making procedure found in Appendix A: Detailed Joint Making Procedure. This explains the process for creating a bamboo bike using the method developed. Ultimately all of these functional requirements add up to fulfill FR0: Provide a sturdy mode of transportation for third world countries. When all the functional requirements were met a bamboo bike was created. This bike can provide a sturdy mode of transportation for third world countries.

5.3. Improvements of Final Method

The method developed has a faster manufacturing process than the hand wrapping process currently used in third world countries. Currently the workers have to hand-wrap each joint with epoxy soaked fiber strips. Then wait fifteen minutes to apply vinyl tape around each joint. The process is time consuming and can be complicated (Chan et al. 2012). The new process removed the hand-wrapping of each joint. Through the method developed it can greatly decrease the time that is needed to create each bike. Additionally the worker does not need to wait fifteen minutes to wrap the bike joints again and can simply move on to another jig to manufacture another bike.

The method provided is also an improvement upon the 2012 Bamboo Bike MQP. That process included shrink wrapping plastic around a male mold to create a plastic shell. The shell was then placed around the bamboo and injected with epoxy. Additional equipment was also needed on the jig to hold the bamboo in place (Chan et al. 2012). The process was improved because fiberglass was fit into the mold and greatly increased the strength of each joint, allowing for a stronger bicycle. The molds were able to hold the bamboo in place so there was no need for extra equipment. The molds created are reusable therefore many bikes can be made with the same molds.

6. Iteration

The original design had changed throughout the project in various ways due to testing and failures.

6.1. Plastic mold failure

According to the original joint procedure, the joint molds were going to be made from plastic. These plastic molds were made from Dimension SST 1200ES Rapid Prototype Machine; a type of 3D printer. The printed mold was disappointing. The material was thin and weak. When a joint was made with this mold the plastic cracked and the mold broke. The price to make the part was $8.00 per cubic inch, including space around the plastic. This was deemed to be expensive for such a fragile mold. A new material was needed.

6.2. Aluminum mold

Though the material itself was more expensive, it was decided to make the molds out of 6061 – T6511 Aluminum. The main advantage of this material is that it is easy to machine mold parts. This allowed multiple parts to be made and it allowed a much greater margin of error since parts could be remade. Furthermore, since the molds were metal they were stronger.

6.3. Injection

The original plan was to inject epoxy into the mold and have it fill from the top down. Holes were drilled into the top of the mold. The plan was for epoxy to be injected into the injection holes. This would fill up the inside of the mold around the bamboo until epoxy leaked out of another fill hole. The flow of epoxy could not be controlled. Overtime it would settle down and leave an uneven distribution of epoxy.

6.4. Filling molds beforehand

Branching off from the previous method, the epoxy was filled into each of the mold halves and then the bamboo was inserted. This worked quite well. However, there were still some air pockets in the top of the mold due to settling.

6.5. Final Method

The last method involved filling the molds beforehand and then injecting epoxy. The reason this worked was because the molds were already near filled before the injection began. This allowed the injection to fill in the air pockets without injecting the entire mold. This was discovered to be the best method.

7. Discussion

7.1. Evaluation of the Final Design

The design fulfills the original objective since the joints can withstand the weight of a rider. The key point of the design is that the areas which receive the greatest amount of stress are reinforced. This is crucial in making a strong bicycle that is not bulky.

The process of laying fiberglass in the mold then adding the epoxy is a method to speed the manufacturing process while still keeping the desired bicycle strength. By using the aluminum we are able to have strong molds that can withstand most accidents that may happen during the manufacturing process. The same could not be said of the original test molds made out of a plastic material.

Aluminum molds can be easily machine adjusted if any modifications are required. If the molds were made of plastic any imperfections would result in remaking the part. The lifespan of an aluminum mold is greater than a plastic mold's.

The main concern lies in the material required and its weight. The molds are made of aluminum which makes the jig heavy. The jig itself is made of a multitude of support parts that have to be put together properly.

The main challenge that occurred during the manufacturing process was making sure the bamboo is of proper length and size. We then had to make sure that the whole mold was filled with epoxy. The success of this bike design is highly dependent on following the epoxy lay-up process.

7.2. Meeting the Original Objective

The original objective of this project was to improve the manufacturing methods of bamboo bicycles so that they could be made at a cheaper cost. The final design uses a high amount of aluminum for the molds. If they are only used to manufacture one bicycle the original objective would not be met. Both the aluminum and the cost to machine the molds are much greater than the cost of other bamboo bicycle manufacturing methods.

Once the molds and jig are built, they can be reused to manufacture a large quantity of bicycles in less time. This results in a more efficient manufacturing process.

7.3. Constraints

In order to fulfill the objective many constraints had to be considered and accounted for.

7.3.1. Cost of Materials

The cost of everything as a whole is expensive. Most of the expenses were startup costs. After the aluminum molds and the jig are made they can be used to make bicycles with minimal extra costs. Therefore, this final design is expensive for one bicycle. However, with mass production the cost can be recovered.

7.3.2. Bamboo strength

It is important to have strong bamboo. Even if the joints themselves are strong enough to withstand the applied stress, the bamboo can still break. During testing, a head tube test piece of bamboo failed before the composite joint showed any sign of failure. This was seen at approximately 450 pounds.

7.4. Potential of a Global Scale

The mold designs can easily be made anywhere with proper machinery and are durable enough to be transported to various locations. Since the molds can be reused, it is simple to assemble a jig and produce bamboo bicycles.

7.5. Flaws

The first flaw encountered was that if the mold is not filled completely with epoxy and fiberglass it will be weaker than desired. Often times the epoxy would come out of a fill hole without having filled the entire mold. This resulted in air bubbles as shown in Figure 25.

Figure 25: Air Bubble Flaw

The second flaw was that the seat joint could not be removed from the mold due to the current four piece mold. The design of the mold limited the degrees of freedom once the epoxy cured. This made it difficult to remove the mold pieces without damaging the joint as shown in Figure 26.

Figure 26: Seat Joint Flaw

The third flaw was that the molds had to incur damage before they could be fully removed. The cured epoxy expanded into the molds preventing ease of release. A wedge was required to separate the mold pieces resulting in damage to the molds.

The final flaw was leaking of epoxy from the molds. The leaking epoxy required us to inject more epoxy into the mold than necessary. The excess epoxy also contributed to the difficulty in separating the mold pieces as shown in Figure 27.

Figure 27: Leaking Flaw

Solutions to these flaws are listed in the recommendations section of the report.

8. Recommendations

A bamboo bike prototype was designed and constructed. However, there are a few concepts that we would recommend to further bamboo bike MQP groups.

To make sure there are no air bubbles after the epoxy cures, a funnel can be left in a fill hole after injection to make up for any settling epoxy.

The current four piece seat joint mold should be replaced with a six piece mold. As explained in prior sections, the four piece mold restricted the degrees of freedom of the joint. This limited the joint removal from the mold.

In addition to easing the release of the joints from the molds, slots on either side of the molds should be constructed. This would enable one to easily pry the molds apart from one another.

Table 2: Problems and Solutions

Problems	Potential Solutions
Air bubbles in epoxy	A funnel can be left in a fill hole after injection
Seat joint De-molding	Redesign of seat joint mold to be in a six piece mold
De-molding damage	Machine slots on mold edges for easy access prying
Epoxy leakage	Plastic inner mold design

The process of creating the bike on the jig can also be accelerated by creating inner-plastic molds for each joint. These plastic molds can be constructed by either creating SolidWorks models or heating acrylic and forming it to the existing aluminum molds. In normal conditions the curing time for the West Systems epoxy is six hours. This method would cut the overall working time in half, enabling the joints to be removed from the molds before full cure time. This allows an increased production of bicycles.

Leaking of epoxy during molding can be addressed in various ways. A gasket could be used around the outer edge of the mold impression. Also the plastic molds, as mentioned earlier, could be used to combat leaking of epoxy. This will decrease manufacturing time and save epoxy.

Lastly, hemp and bamboo fibers for composite materials are common in countries that produce bamboo. These materials are useful in reinforcing the bamboo bike molds and can be added to the wet layup procedure. Research on these materials and their uses is recommended to further the project.

9. Conclusions

The bamboo bicycle frame was strong enough to withstand the static loading. If the seat joint mold is fixed, the bamboo bicycle frame could be tested even further. This testing could include dynamic loading tests along with specific impact tests. From these tests a better understanding of the resin or epoxy amount in each mold could be obtained. There will be an efficient manufacturing process if all the recommendations are achieved. A provisional patent is being filed for the bamboo molded composite joint process.

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Appendix A: Detailed Joint Making Procedure

Table 3: Joint Making Procedure

#	Procedure
1	Sand the surface of all bamboo ends properly.
2	Spray aluminum mold inner surface (both top and bottom) with a mold release spray.
3	Cut fiberglass to correct size.
4	Soak the fiberglass in epoxy until the surface is saturated.
5	Lay the saturated fiberglass into the mold.
6	Place bamboo into the mold.
7	Pour epoxy over the bamboo.
8	Fold the fiberglass around to the top of the bamboo.
9	Close the top mold and secure by using bolts.
10	Once the mold is closed, apply clay around the edges to ensure minimal leaks.
11	Inject epoxy through the fill holes in the top mold.
12	Once the epoxy cures, then remove the bolts from the top mold, therefore releasing the bamboo joint.
13	Remove the bamboo joint from the mold and sand the desired edges.

Sand the surface of the bamboo ends that will be placed into the aluminum molds. This increases surface roughness making the epoxy bond to the bamboo. Spray mold release (Mann Release Technologies, Ease Release 200) onto the inside surfaces of the aluminum molds (AMTS, 2008). Also spray mold release into the injection holes on the top of the aluminum mold. Lay the fiberglass (7725 Fiberglass Cloth, 38" length) evenly inside the mold and cut it to fit properly. Soak the cut fiberglass in epoxy until it becomes saturated. Then place the saturated fiberglass into the bottom mold. Place the bamboo into the mold. Wrap the fiberglass around the remaining bamboo. Place the top part of the mold on the bottom and secure with bolts. To ensure minimal leaks apply clay to the location where both aluminum molds meet. Once the entire mold is closed, inject epoxy into the holes located at the top of the mold. Do this until epoxy overflows the other holes. Wait for the epoxy to cure. Once the epoxy cures, remove all bolts from the aluminum mold, releasing the bamboo joint (AMTS, 2008). Some of the molds might require the removal of the supporting brackets.

Appendix B: Axiomatic Design Case Study

Our First Step: Our first decomposition was a basic outline of our goal and what we needed to do to achieve it. The main problem besides its lack of depth was, the FRs and DPs wording. The FRs needed to start with verbs and the DPs needed to start with nouns. FR0 was poorly worded since it didn't really describe our project accurately.

Eventually: We copied over the decomposition from 2012 Bamboo Bicycle MQP since we were basically doing the same thing. We worked on modifying it, and spent a lot of time focusing on the wording of each FR. We learned that the wording of each FR was important. When the FRs are put together they should lead to the FR they branch off from. This required numerous trial and errors as certain wording that seemed perfect at first, eventually did not work with the other FRs.

As the decomposition got larger: The idea of a decomposition is to organize our thoughts and goals. When we got to the point where we were had a lot of components, we started making separate decompositions for each of the separate components, more specifically the jig and the joint molds.

Guide to writing a decomposition:

1) **Learn the difference between an FR and a DP:**
    - **a.** FRs are in a sense a goal or objective. DPs are methods for achieving each FR.
    - **b.** When writing an FR, make sure to always start with a verb. When writing the corresponding DP, make sure to always start with a noun.
    - **c.** Try avoiding being wordy as much as possible. Be clear and concise with every FR and DP.
2) **Create the FRs:**
    - **a.** Start with the FR0. This is the most important FR as this states the goal for the entire project. Think carefully of the wording as what is written might not

actually be your project. For instance, if you are building a part, using the word "design" wouldn't be accurate as it does not indicate any physical product.

   b. Create the sub FRs. These are your basic goals to meet the overall objective. Do not get too detailed with these as they will be still broken down further.

   c. Create any further breakdowns of your sub FRs as needed. This is where it is good to put as much detail as possible. The further something can be broken down (within reason), the better it will be. Keep in mind that if one of your sub FRs has only one breakdown below it, it is better to either delete it or add more.

3) Create the DPs:

   a. For every FR, write up a corresponding DP stating how the FR will be met. These are usually short statements with only a few words. Remember to start each of these with a noun.

   b. If possible, try to think of multiple solutions to any FR problem, and list them all under the DP. When one of them is finalized the other can be deleted later.

4) Breaking up your Decomposition:

   a. If the current decomposition seems to be a bit lengthy, it would be advisable to make separate decompositions to better organize the ideas.

   b. Ideally, the separate decompositions would be an extension of the original decomposition. Therefore try to make each of the new FR0's the same as one of the first layer sub FRs in the original decomposition.

   c. Make sure to save each of the decompositions made as separate files even after making edits, in case something happens or an old idea needs to be tested out again there are records of everything.

5) Editing the wording:

   a. Close up the decomposition so only the FR0 and the first layer of sub FRs are shown. Look at the wording of the sub FRs and remember when combined, they all equal the original FR0. If not, make sure to spend time rewording the FRs. Each set of sub FRs should add up to the FR they branch off from.

   b. To solve this, try to make each of the verbs used in the sub FRs, synonyms to the verb used in the FR they branch from. Repeating the verb is acceptable.

Appendix C: SolidWorks Drawings of Molds

Head Tube

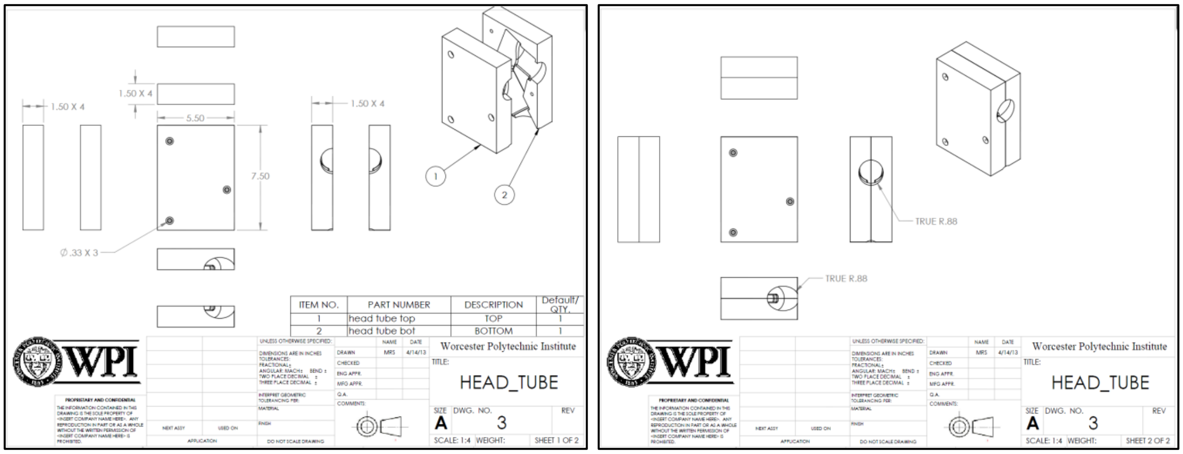


Figure 24: Head Tube Drawing

Bottom Bracket

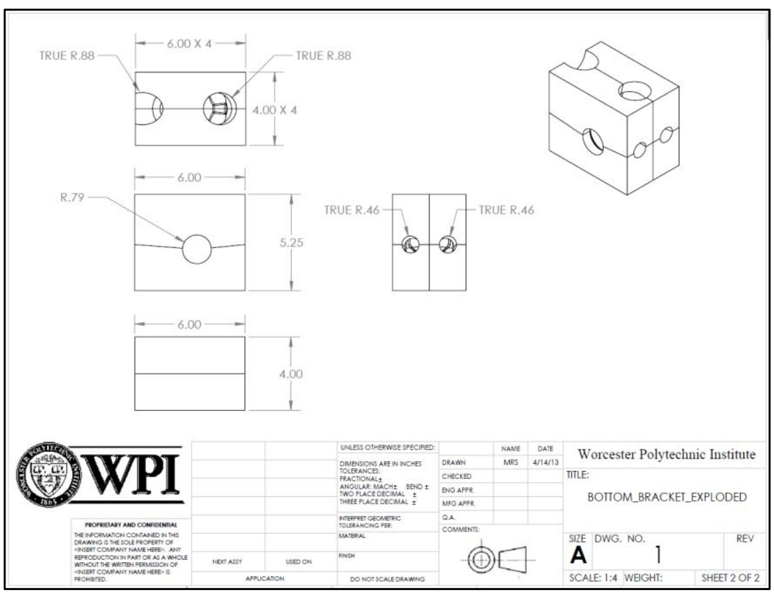


Figure 28: Seat Joint Drawing

Seat Joint

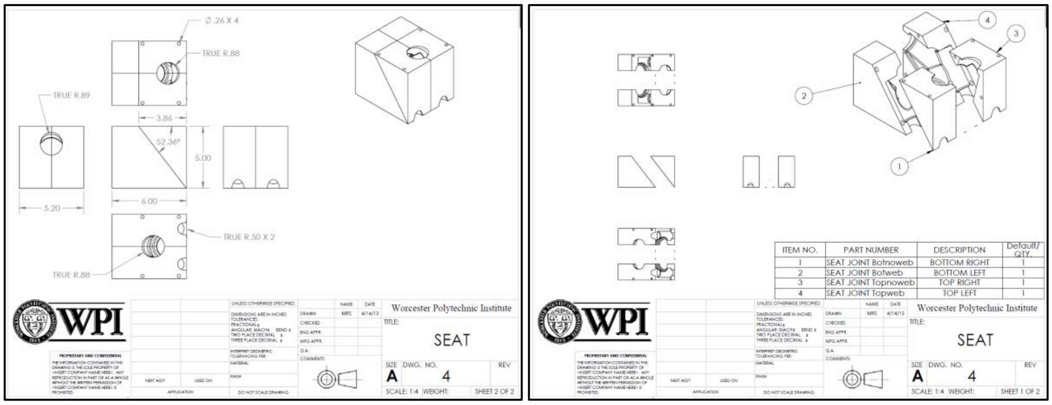


Figure 29: Seat Joint Drawing

Dropout

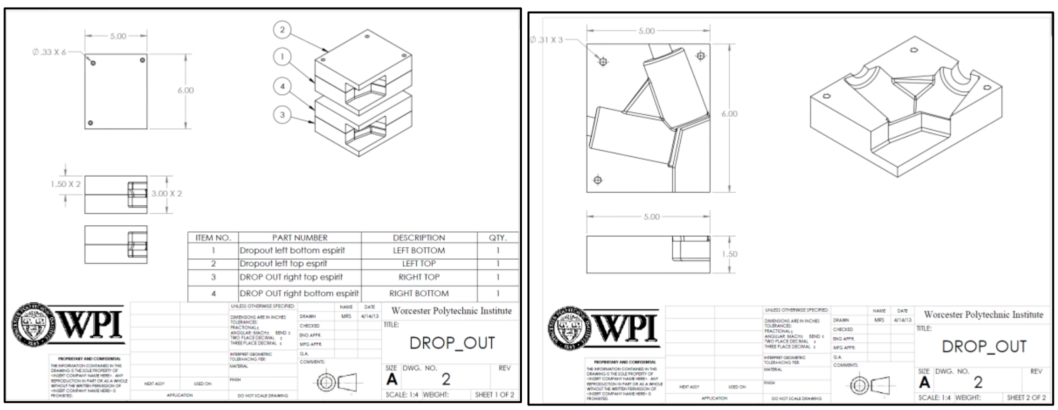


Figure 30: Dropout Drawing

Bicycle Assembly

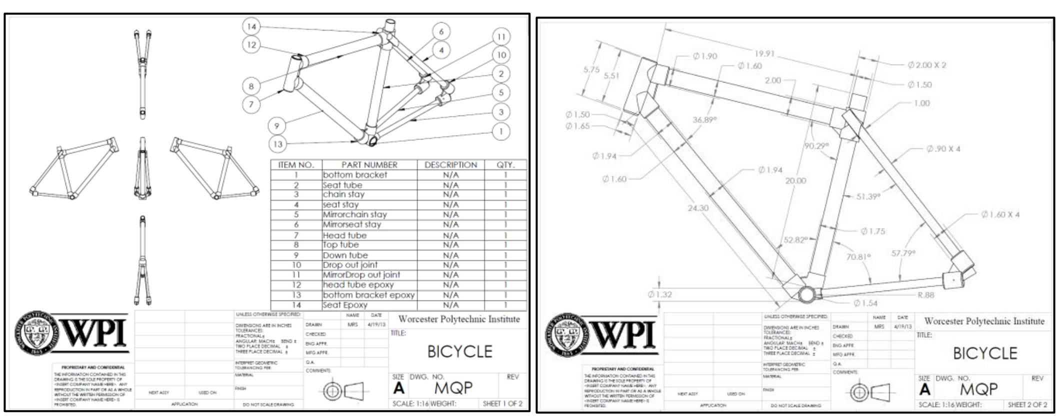


Figure 31: Bicycle Assembly

Appendix D: Joint Material Property Calculations

Table 4: Mold Volume

Mold	Volumes
Head tube	7.8578 in^3
Seat joint	14.29 in^3
Bottom bracket	3 in^3
Drop out	18 in^3

Elastic Modulus of West systems 105/206 and fiberglass are 7,846 Pa and 72 GPa respectively. To find the elastic modulus of a matrix containing 20% fiberglass and 80% epoxy the following calculation was performed.

$$E = E_{epoxy} * V_{epoxy} + E_{fiberglass} * V_{fiberglass}$$

E = (7846Pa * .8) + (72000000Pa * .2) = 14406276.8 Pa

This is the strength when the fiberglass is parallel to the stress.

$$E = \frac{E_{epoxy} * E_{fiberglass}}{E_{epoxy} * V_{epoxy} + E_{fiberglass} * V_{fiberglass}}$$

$$E = \frac{(7847\ Pa * 72000000Pa)}{(7846Pa * .8) + (72000000Pa * .2)} = 39217.90535 \text{ Pa}$$

This is when the stress acts perpendicular to the fibers. To preform our strength analysis we used this lower number to ensure safety.

Appendix E: Full Decomposition

#	[FR] Functional Requirements	[DP] Design Parameters
0	FR Provide a sturdy mode of transportation for third world countries.	DP Bamboo bike
1	FR Sustain up to 300lb without breaking	DP Strong frame that can withstand "y" N of force
1.1	FR Use strong joint structures	DP Molds (see mold decomp)
1.2	FR Build the front half of the frame so it sustains the most of the force	DP Stronger bamboo attached to the front wheel
1.3	FR Build a frame that distributes stress throughout the frame.	DP Diamond frame: truss consisting of two triangl
1.4	FR Use a strong frame material	DP Frame made of bamboo, a cheap strong
2	FR Present optimal joint geometry	DP Joint geometry
3	FR Use mechanism to hold the bike frame in position	DP Jig
3.1	FR Position standard bike parts in molds	DP Mold geometry
3.1.1	FR Position head tube	DP Head tube mold
3.1.2	FR Position dropouts	DP Dropout mold
3.1.3	FR Position bottom bracket tube	DP Bottom bracket mold
3.2	FR Position bamboo along y-z plane	DP Brackets
3.3	FR Position bamboo along x axis	DP Standard bike parts
3.3.1	FR Position top tube in frame geometry	DP Head tube and seat tube
3.3.2	FR Position down tube in fram geometry	DP Head tube and bottom bracket tube
3.3.3	FR Position seat tube in frame geometry	DP Seat tube and bottom bracket tube
3.3.4	FR Position seat stays in frame geometry	DP Seat tube and dropouts
3.3.5	FR Position chain stays in frame geometry	DP Bottom bracket tube and dropouts
4	FR Prepare bamboo for manufacturing	DP Bamboo manufacturing method
4.1	FR Prepare bamboo tubes	DP Tube preparation method
4.1.1	FR Cut tubes	DP Saw
4.1.2	FR Roughen edges	DP Calipers, knife
4.1.3	FR Fill ends	DP Foam, anything available
4.1.4	FR Check	DP Check system

Figure 32: Main Decomposition

	DP0: Bamboo bike	DP1: Strong frame that can wi	DP1.1: Molds (see mold de	DP1.2: Stronger bamboo a	DP1.3: Diamond frame: tru	DP1.4: Frame made of bar	DP2: Joint geometry	DP3: Jig	DP3.1: Mold geometry	DP3.1.1: Head tube mo	DP3.1.2: Dropout mold	DP3.1.3: Bottom brack	DP3.2: Brackets	DP3.3: Standard bike parts	DP3.3.1: Head tube an	DP3.3.2: Head tube an	DP3.3.3: Seat tube and	DP3.3.4: Seat tube and	DP3.3.5: Bottom brack	DP4: Bamboo manufacturing r	DP4.1: Tube preparation n	DP4.1.1: Saw	DP4.1.2: Calipers, knife	DP4.1.3: Foam, anythin	DP4.1.4: Check system
FR0: Provide a sturdy mode of tra	X																								
FR1: Sustain up to 300lb with		X					O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
FR1.1: Use strong joint st			X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
FR1.2: Build the front half			O	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
FR1.3: Build a frame that			O	O	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
FR1.4: Use a strong fram			O	O	O	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
FR2: Present optimal joint ge		O	O	O	O	O	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
FR3: Use mechanism to hold		O	O	O	O	O	O	X												O	O	O	O	O	O
FR3.1: Position standard		O	O	O	O	O	O		X				O	O	O	O	O	O	O	O	O	O	O	O	O
FR3.1.1: Position head		O	O	O	O	O	O			X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
FR3.1.2: Position drop		O	O	O	O	O	O			O	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O
FR3.1.3: Position botto		O	O	O	O	O	O			O	O	X	O	O	O	O	O	O	O	O	O	O	O	O	O
FR3.2: Position bamboo		O	O	O	O	O	O		O	O	O	O	X	O	O	O	O	O	O	O	O	O	O	O	O
FR3.3: Position bamboo		O	O	O	O	O	O		O	O	O	O	O	X						O	O	O	O	O	O
FR3.3.1: Position top t		O	O	O	O	O	O		O	O	O	O	O		X	O	O	O	O	O	O	O	O	O	O
FR3.3.2: Position dow		O	O	O	O	O	O		O	O	O	O	O		O	X	O	O	O	O	O	O	O	O	O
FR3.3.3: Position seat		O	O	O	O	O	O		O	O	O	O	O		O	O	X	O	O	O	O	O	O	O	O
FR3.3.4: Position seat		O	O	O	O	O	O		O	O	O	O	O		O	O	O	X	O	O	O	O	O	O	O
FR3.3.5: Position chai		O	O	O	O	O	O		O	O	O	O	O		O	O	O	O	X	O	O	O	O	O	O
FR4: Prepare bamboo for ma		O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	X					
FR4.1: Prepare bamboo t		O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O		X				
FR4.1.1: Cut tubes		O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O			X	O	O	O
FR4.1.2: Roughen edg		O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O			O	X	O	O
FR4.1.3: Fill ends		O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O			O	O	X	O
FR4.1.4: Check		O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O			O	O	O	X

Figure 33: Main Decomposition Matrix

#	[FR] Functional Requirements	[DP] Design Parameters
0	FR Provide stability to all bike components during manufacturing	DP Jig
1	FR Steady bike component outline	DP Jig components all held in place
1.1	FR Steady head tube	DP Head tube mold
1.2	FR Steady bottom bracket tube	DP Bottom bracket mold
1.3	FR Steady dropouts	DP Dropout molds
2	FR Sustain bike tube placements	DP Tube holding method (clamps)
2.1	FR Sustain top tube	DP Top tube holder
2.2	FR Sustain down tube	DP Down tube holder
2.3	FR Suatain head tube	DP Head tube holder
2.4	FR Sustain seat tube	DP Seat tube holder
2.5	FR Sustain chain stays	DP Chain stay holder
2.6	FR Sustain bottom bracket	DP Bottom bracket mold
2.7	FR Sustain dropouts	DP Threaded rod
3	FR Keep tubes in mold	DP Screws
3.1	FR Keep top tube centered	DP Top tube self centering device
3.2	FR Keep down tube centered	DP Down tube self centering device
3.3	FR keep head tube centered	DP Head tube self centering device
3.4	FR Keep seat stays centered	DP Seat stays self centering device
3.5	FR Keep chain stays centered	DP Chain stays self centering device
3.6	FR Keep bottom bracket centered	DP Bottom bracket self centering device
3.7	FR Keep dropouts centered	DP Dropout self centering device
4	FR Maintain mold positions	DP Jig brackets
4.1	FR Maintain seat joint positions	DP Bracket holding lower mold
4.2	FR Maintain dropout joint positions	DP Bracket holding lower mold
4.3	FR Maintain bottom joint position	DP Bracket holding lower mold
4.4	FR Maintain front joint position	DP Bracket holding lower mold

Figure 34: Jig Decomposition

	DP0: Jig	DP1: Jig components all held	DP1.1: Head tube mold	DP1.2: Bottom bracket mo	DP1.3: Dropout molds	DP2: Tube holding method (cl	DP2.1: Top tube holder	DP2.2: Down tube holder	DP2.3: Head tube holder	DP2.4: Seat tube holder	DP2.5: Chain stay holder	DP2.6: Bottom bracket mo	DP2.7: Threaded rod	DP3: Screws	DP3.1: Top tube self cente	DP3.2: Down tube self cen	DP3.3: Head tube self cen	DP3.4: Seat stays self cen	DP3.5: Chain stays self ce	DP3.6: Bottom bracket self	DP3.7: Dropout self center	DP4: Jig brackets	DP4.1: Bracket holding low	DP4.2: Bracket holding low	DP4.3: Bracket holding low	DP4.4: Bracket holding low
FR0: Provide stability to all bike c	X																									
FR1: Steady bike component		X				O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
FR1.1: Steady head tube			X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
FR1.2: Steady bottom brac			O	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
FR1.3: Steady dropouts			O	O	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
FR2: Sustain bike tube place		O	O	O	O	X								O	O	O	O	O	O	O	O	O	O	O	O	O
FR2.1: Sustain top tube		O	O	O	O		X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
FR2.2: Sustain down tube		O	O	O	O		O	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
FR2.3: Suatain head tube		O	O	O	O		O	O	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
FR2.4: Sustain seat tube		O	O	O	O		O	O	O	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
FR2.5: Sustain chain stay		O	O	O	O		O	O	O	O	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
FR2.6: Sustain bottom bra		O	O	O	O		O	O	O	O	O	X	O	O	O	O	O	O	O	O	O	O	O	O	O	O
FR2.7: Sustain dropouts		O	O	O	O		O	O	O	O	O	O	X	O	O	O	O	O	O	O	O	O	O	O	O	O
FR3: Keep tubes in mold		O	O	O	O	O	O	O	O	O	O	O	O	X								O	O	O	O	O
FR3.1: Keep top tube cent		O	O	O	O	O	O	O	O	O	O	O	O		X	O	O	O	O	O	O	O	O	O	O	O
FR3.2: Keep down tube ce		O	O	O	O	O	O	O	O	O	O	O	O		O	X	O	O	O	O	O	O	O	O	O	O
FR3.3: keep head tube ce		O	O	O	O	O	O	O	O	O	O	O	O		O	O	X	O	O	O	O	O	O	O	O	O
FR3.4: Keep seat stays ce		O	O	O	O	O	O	O	O	O	O	O	O		O	O	O	X	O	O	O	O	O	O	O	O
FR3.5: Keep chain stays c		O	O	O	O	O	O	O	O	O	O	O	O		O	O	O	O	X	O	O	O	O	O	O	O
FR3.6: Keep bottom brack		O	O	O	O	O	O	O	O	O	O	O	O		O	O	O	O	O	X	O	O	O	O	O	O
FR3.7: Keep dropouts cen		O	O	O	O	O	O	O	O	O	O	O	O		O	O	O	O	O	O	X	O	O	O	O	O
FR4: Maintain mold positions		O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	X				
FR4.1: Maintain seat joint		O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O		X	O	O	O
FR4.2: Maintain dropout jo		O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O		O	X	O	O
FR4.3: Maintain bottom jo		O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O		O	O	X	O
FR4.4: Maintain front joint		O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O		O	O	O	X

Figure 35: Jig Decomposition Matrix

#	[FR] Functional Requirements	[DP] Design Parameters
0 FR	Build a strong joint structure	DP Wet-layup Process
1 FR	Form a casing around joints to provide strength	DP Process to use Aluminummolds
2 FR	Add a layer on top of bamboo before putting in mold to provide strength	DP Process to apply Fiberglass (7725 Fiberglass Cloth)
2.1 FR	Soak fiberglass so it adheres to both the bamboo and the mold	DP Process to apply epoxy onto fiberglass
2.2 FR	Add strength to all areas of the bamboo	DP Process to evenly apply fiberglass on all areas on the
3 FR	Set mold pieces in place while the epoxy hardens.	DP Process to screw molds together to minimize movement.
4 FR	Create a controlled flow for the epoxy when applying	DP Process to inject epoxy through holes in mold
4.1 FR	Create method to ensure complete flow of epoxy	DP Process to inject epoxy until it comes out of overflow holes
4.2 FR	Keep the epoxy in the mold while it hardens	DP Process to apply clay sealant on gaps
5 FR	Holding mechanism to keep joint molds in place during manufacturing	DP Jig

Figure 36: Wet-Layup Decomposition

	DP0: Wet-layup Process	DP1: Process to use Aluminur	DP2: Process to apply Fibergl	DP2.1: Process to apply e	DP2.2: Process to evenly a	DP3: Process to screw molds	DP4: Process to inject epoxy t	DP4.1: Process to inject ep	DP4.2: Process to apply cl	DP5: Jig
FR0: Build a strong joint structure	X									
FR1: Form a casing around jo		X	O	O	O	O	O	O	O	O
FR2: Add a layer on top of bar		O	X			O	O	O	O	O
FR2.1: Soak fiberglass so		O		X	O	O	O	O	O	O
FR2.2: Add strength to all		O		O	X	O	O	O	O	O
FR3: Set mold pieces in plac		O	O	O	O	X	O	O	O	O
FR4: Create a controlled flow		O	O	O	O	O	X			O
FR4.1: Create method to e		O	O	O	O	O		X	O	O
FR4.2: Keep the epoxy in t		O	O	O	O	O		O	X	O
FR5: Holding mechanism to l		O	O	O	O	O	O	O	O	X

Figure 37: Wet-Layup Decomposition Matrix

#	[FR] Functional Requirements	[DP] Design Parameters
0	Optimize joint geometry	joint geometry
1	mold head tube	head tube joint
1.1	optimize length	FEA to determine minimum length needed to transfer load
1.2	optimize thickness around tube	FEA to determine minimum thickness needed to transfer load
1.3	optimize amount of composite between tubes	FEA to determine minimum material needed to transfer load
1.4	machinable edges/corners	fillets
1.5	optimize mold manufacturability	manufacturing limitations
1.5.1	secure reinforcing materials in mold	kevlar/carbon fiber reinforcements
1.5.1.1	optimize mold strength	reinforcing web
1.5.2	secure liquids in the mold	rubber seals/duct tape
1.5.3	prevent liquid from flowing into bamboo	foam, tape
1.6	optimize bike manufacturability	bike manufacturing constraints
1.6.1	demold easily	non-stick inner mold surface
2	mold seat post	seat post joint
2.1	optimize length	FEA to determine minimum length needed to transfer load
2.2	optimize thickness around tube	FEA to determine minimum thickness needed to transfer load
2.3	optimize amount of composite between tubes	FEA to determine minimum material needed to transfer load
2.4	machinable edges/corners	fillets
2.5	optimize mold manufacturability	manufacturing limitations
2.5.1	secure reinforcing materials in mold	kevlar/carbon fiber reinforcements
2.5.2	secure liquids in the mold	rubber seals/duct tape
2.5.3	prevent liquid from flowing into bamboo	foam, tape
2.6	optimize bike manufacturability	bike manufacturing constraints
2.6.1	demold easily	non-stick inner mold surface
3	mold bottom bracket	bottom bracket joint
3.1	optimize length	FEA to determine minimum length needed to transfer load
3.2	optimize thickness around tube	FEA to determine minimum thickness needed to transfer load
3.3	optimize amount of composite between tubes	FEA to determine minimum material needed to transfer load
3.4	machinable edges/corners	fillets
3.5	optimize mold manufacturability	manufacturing limitations
3.5.1	secure reinforcing materials in mold	kevlar/carbon fiber reinforcements
3.5.2	secure liquids in the mold	rubber seals/duct tape
3.5.3	prevent liquid from flowing into bamboo	foam, tape
3.6	optimize bike manufacturability	bike manufacturing constraints
3.6.1	demold easily	non-stick inner mold surface
4	mold dropout	dropout joint
4.1	optimize length	FEA to determine minimum length needed to transfer load
4.2	optimize thickness around tube	FEA to determine minimum thickness needed to transfer load
4.3	optimize amount of composite between tubes	FEA to determine minimum material needed to transfer load
4.4	machinable edges/corners	fillets
4.5	optimize mold manufacturability	manufacturing limitations
4.5.1	secure reinforcing materials in mold	kevlar/carbon fiber reinforcements
4.5.1.1	optimize mold strength	reinforcing web
4.5.2	secure liquids in the mold	rubber seals/duct tape
4.5.3	prevent liquid from flowing into bamboo	foam, tape
4.6	optimize bike manufacturability	bike manufacturing constraints
4.6.1	demold easily	non-stick inner mold surface

Figure 38: Mold Decomposition

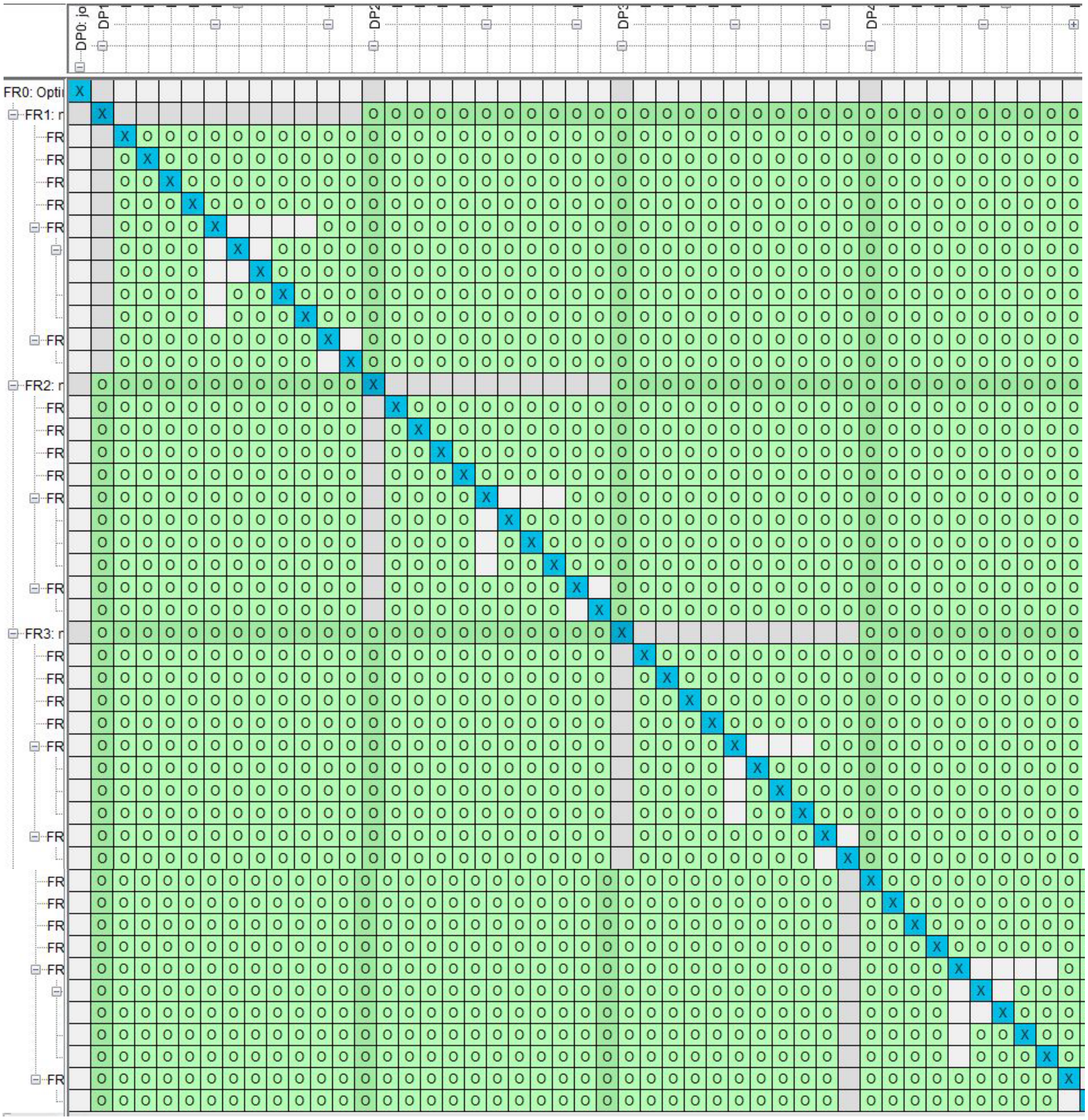


Figure 39: Figure 39: Mold Decomposition Matrix

Appendix F: Instron Head tube Results

Below are the results of the two Instron tests. Head tube one had one layer of fiberglass and head tube two had two layers.

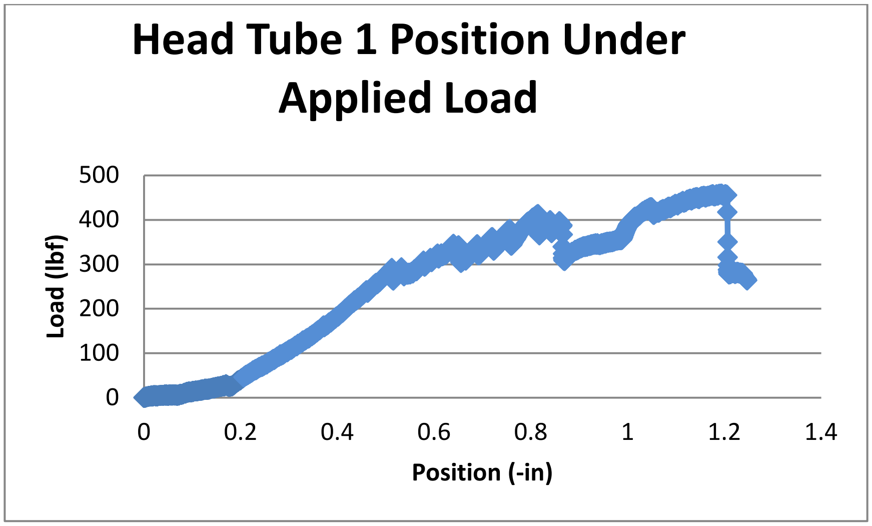


Figure 40: Intron Test 1

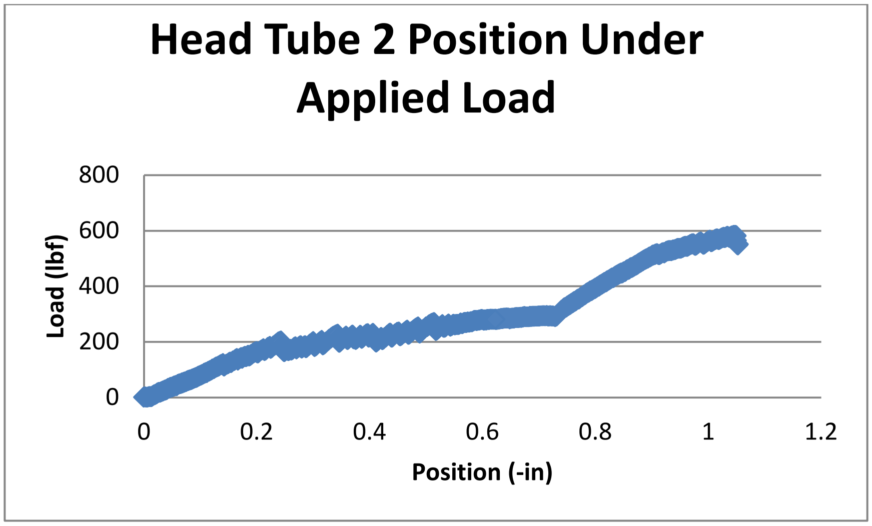
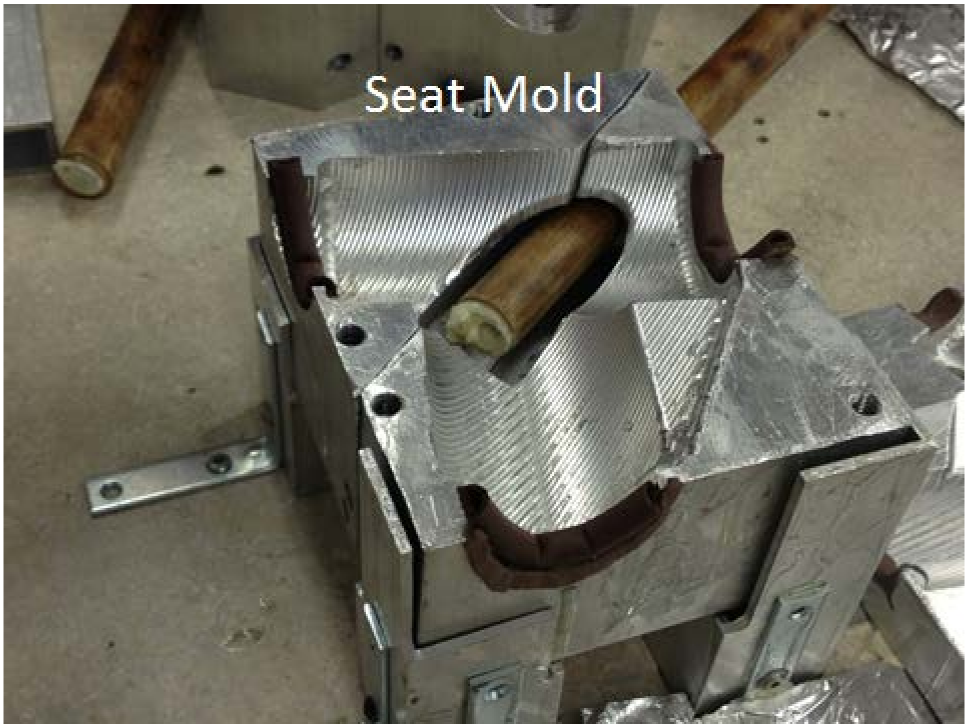


Figure 41: Instron Test 2

The max weights held, before major failure, by the two were 458 lbf and 583 lbf respectively.

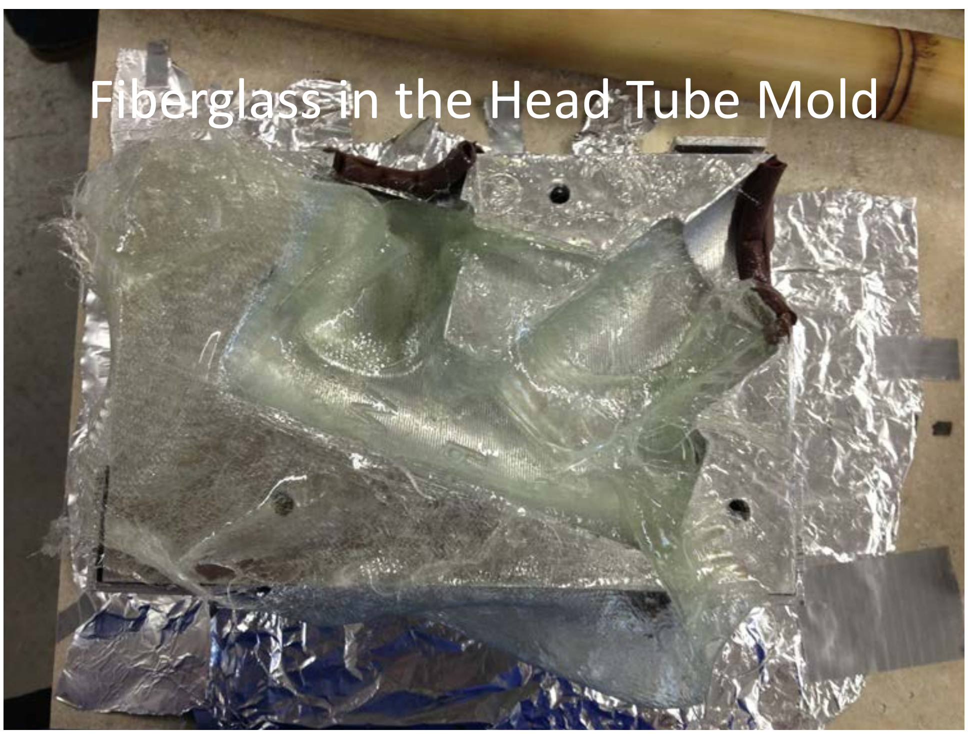
Appendix G: Molding Process Pictures




Head Tube Mold


Right Dropout Mold


Fiberglass in Epoxy


Fiberglass in the Head Tube Mold


Fiberglass In The Right Dropout Mold


Fiberglass in the Bottom Bracket Mold


Securing the Right Dropout Mold


Securing the Bottom Bracket Mold

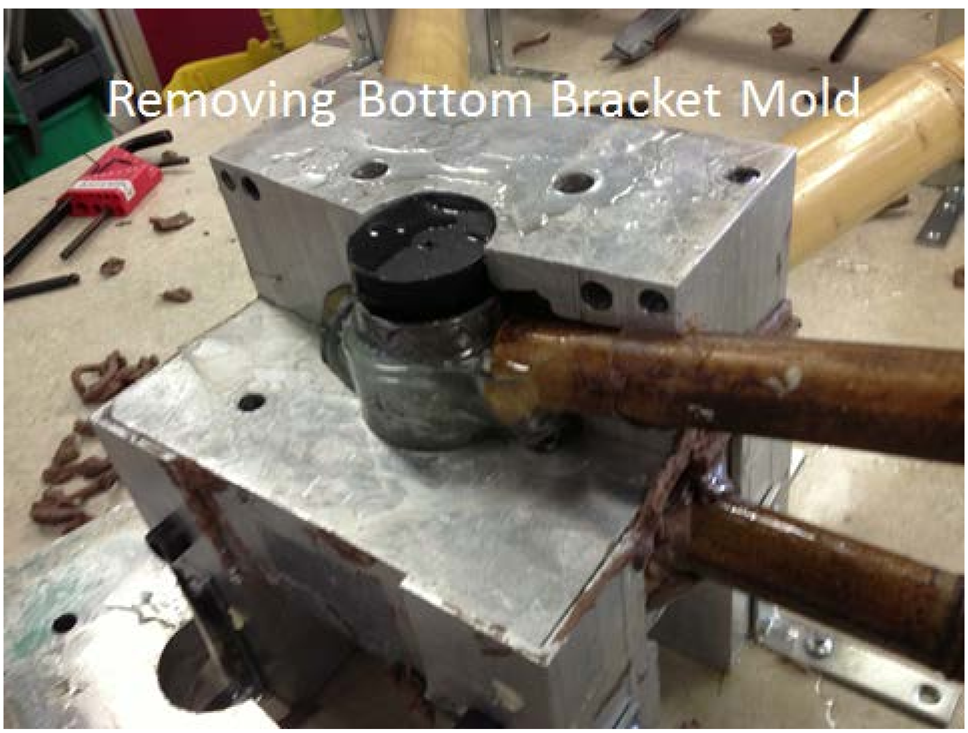

Securing the Seat Mold


Right & Left Dropout Molds


Injecting Epoxy


Jig with all Molds


Completed Head Tube Mold


Removing Bottom Bracket Mold


Removing Dropout Molds


Taking Drop Out Molds Apart


Removing Seat Mold


Additional Fiberglass to Provide Strength


Additional Fiberglass to provide strength


Testing


Side View


Isometric View