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Engineering a Bamboo Bicycle

A Major Qualifying Project Report

Submitted to the Faculty of

Worcester Polytechnic Institute

In partial fulfillment of the requirements for the

Degree of Bachelor of Science in Mechanical Engineering

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30 April 2015

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Abstract

The primary objective of this Major Qualifying Project was to design and construct a bamboo bicycle that could be made available in developing nations and be assembled quickly with minimal training. In order to meet this objective, the project was decomposed into three main components: bicycle joint design, manufacturing fixture design, and safety and testing. The project team was divided into three corresponding groups, utilizing axiomatic design to break down each of the three components. The Joints Team created a system of gussets to transmit rider loads between bicycle frame members. The Jig Team designed a device that will enable an individual with minimal training to assemble a bamboo bicycle frame by maintaining component alignment during bicycle frame assembly. The Safety and Testing team designed bicycle frame tests to meet ASTM standards to ensure the safety of all potential riders. The team successfully manufactured a prototype bamboo bicycle using the Joints Team's system of gussets, the Jig Team's manufacturing fixture, and the bamboo selected by the Safety and Testing Team.

Acknowledgements

As a project team, we would like to thank Mason White and Majd Sbat at New England Wire Products, and John Pretto, Tim Dvorak, and Rob Trumbley at Goldenrod Corporation for their generous donations and assistance in manufacturing frame joint and jig components. We would also like to thank Kevin Arruda for helping us to manufacture other components in WPI's Higgins Laboratories and Washburn Shops, Michael Sweeney for 3-D printing help, Scott Osborn for assistance in welding jig assembly, and Russell Lang for helping with testing of components in WPI's Civil Engineering Laboratory. Also, special thanks to NRI for their assistance in selecting a composite material that would be suitable for our application. Finally, thank you to our advisors, Professor Christopher Brown and Professor Walter Towner for all of their assistance during the design and manufacturing processes.

Contents

Figures

Tables

1. Introduction

1.1 Overall Project

1.1.1 Objectives

The primary objective of this Major Qualifying Project was to design and construct a bamboo bicycle that could be made available in developing nations and be assembled quickly with minimal training.

1.1.2 Rationale

Bamboo bicycles are a less expensive and more environmentally conscious alternatives to typical aluminum, carbon fiber, and steel bicycles. In order to expand the market in developing nations, it is important to find a way to mass produce bamboo bicycles at the lowest possible cost. The design of the bicycle's joints strongly influences manufacturing time and cost. Joints on current bamboo bicycles are created by wrapping glass, carbon, or hemp fibers around the bamboo shoots and then applying a resin. This binding method requires large amounts of time and skilled labor. Providing a simpler method for manufacturing bamboo bicycles enables workers with minimal training to construct the frames. This can reduce the overall bicycle price by reducing labor costs. This would make it possible to sell bamboo bicycles in developing nations where transportation is essential, opening up new markets for commerce and providing opportunity for economic growth.

1.1.2.1 Use of Bamboo as a frame material

Bamboo has proven its worth as a construction material for millennia. It has been used in the construction structures ranging from peasant homes to imperial palaces. Bamboo is a grass, and fibrous in composition. The fibers grow anisotropically (unidirectionally), and are embedded in a lignin matrix. This makes bamboo a naturally occurring alternative to carbon fiber tubing that is used in modern performance bicycle frames. Adding to the flexural strength and rigidity of bamboo is the presence of walls that segment the fibrous tube of the bamboo stem. These "chambers" or "nodes" also add to the bamboo's resistance to damage due to impact. As a bicycle frame construction material, these segments can help to dampen road vibrations throughout the frame structure while still providing the stiffness required for proper handling and efficient power transfer (Egan 2011).

The average ultimate tensile strength of bamboo is between 300-350MPa and carries an average density of 0.4(g/cm^3). Unlike wood, bamboo has no rays or knots, allowing it to withstand more stress than comparable woods throughout the length of each stalk (Egan 2011). This strength is similar to that of aluminum, a material commonly used to make bicycles. Aluminum has an ultimate tensile strength of 310 MPa, but an average density of 2.7 (g/cm^3) (ASM Aerospace Specification Metals, Inc. 2015). Bamboo is an equally strong material, but much lighter than aluminum, making it ideal for bicycle frames.

1.1.3 State of the art

1.1.3.1 Previous MQPs

Three previous Major Qualifying Projects were conducted at Worcester Polytechnic Institute (WPI) to attempt to design a bamboo bicycle, in 2012, 2013, and 2014. In 2012, the project group created joints out of a polyethylene terephthalate (PETG) plastic. The plastic shell was vacuum formed, fitted around the bamboo rods, and then filled with epoxy. Ultimately, however, the plastic joints were not strong enough, and the frame failed during construction (Chan, et al. 2012). The 2013 project group created joints by molding 7725 fiberglass and aero epoxy ES6209 to the bamboo with aluminum 6061 molds, but this, too, failed to provide the necessary support to withstand the loads transmitted during riding (Gee, et al. 2013).

The 2014 group designed welded steel joints, featuring large gussets to spread the load, secured to the bamboo rods by hose clamps. This design was an attempt to create joints that were quickly and easily assembled. During frame testing, however, the bolts of the hose clamps failed to sustain the applied loads. (Andres, et al. 2014.) The gusset design from the 2014 project influenced our current design.

The testing procedure of the prototype bicycles has also evolved throughout previous projects. In 2012, the prototype bicycle was never tested because the frame failed during construction (Chan, et al. 2012). By 2014, the team developed testing methods for both the bamboo rods and the bicycle frame. Both bamboo rods and metal rods from an existing mountain bicycle were tested in a 3-point bending test. After the bamboo was tested, the constructed prototype bicycle frame was compression tested using the static loading compression machine in the WPI civil engineering labs (Andres, et al. 2014). While this testing provided important information about the bicycle’s strengths and weaknesses, it did not comply with ASTM bicycle frame testing methods.

1.1.3.2 Columbia University Bamboo Bike Project

Columbia University launched a bamboo bicycle project that was a primary source of inspiration for our project. Their project goal was to aid Africans in rural areas by stimulating a bicycle building industry to satisfy local needs. In particular, they focused their efforts on supplying bicycles for Ghana, where cycling is often the only mode of transportation, other than walking. Due to the nature of this project, the organization has limited themselves to finding cheaper alternatives for components, rather than modifying the assembly process in order to reduce costs. Locally grown bamboo is used for the frames, and individual bicycle parts are shipped from China and India. Because the bicycles require assembly upon arrival, this opens up the opportunity for creating a bicycle building industry, boosting the economy. These bicycles sell for $55 and are capable of carrying large loads. The bicycles produced in this program are less expensive than bicycles that are imported from China and India, and are of a higher quality (Columbia University 2011).

1.1.3.3 Commercially Produced Bamboo Bikes

Calfee Design is one of the pioneers in both carbon fiber and bamboo bicycle production, and is one of the foremost names in composite bicycle frame development. For the bamboo versions of Calfee Design's performance frames, bamboo is used in place of the conventional steel, titanium, aluminum, or carbon fiber tubing. The bamboo is heat-treated to remove moisture and eliminate a majority of insects or other pathogens that may cause decomposition of the bamboo. The bamboo is then coated in polyurethane that acts as a vapor seal and protective coating for the frame members. (Calfee Design 2015)

Initially, Calfee Design transferred their carbon fiber frame production technology to the bamboo bicycle concept by producing frames using wrapped carbon fiber lugs to connect all the frame members. This practice changed shortly after production as it was discovered that the swelling and contracting of the bamboo due to environmental conditions caused the carbon fiber lugs to delaminate from the bamboo frame members. Calfee Design then researched natural fibers to replace the carbon fiber matrix in order to combat the delamination issue by finding a material that would swell or contract with the bamboo. This led to the integration of oriented hemp fibers being used along with a plant-derived epoxy resin in lieu of the carbon fiber composite in order to ensure the longevity of the bicycle frame (Egan 2011).

Other companies, such as HERObike, sell bicycle frame kits and complete bicycles made using bamboo frame members. The bicycle frames utilize a wrapped composite lug system similar to that of Calfee Design with the exception that the composite materials are conventional carbon fiber roving and woven fiberglass. (HERObike 2015).

1.1.4 Approach

To approach the problem, the project was divided into three groups: joint design, manufacturing fixture (jig) design, and safety and testing. Each group decomposed their subject using Axiomatic Design, explained below, and used an iterative design process until final designs were reached for various aspects of the project. Once the designs were completed, all physical components were modeled in SolidWorks and then manufactured. Prototypes were assembled with the intent of being tested in accordance with ASTM standards.

1.1.4.1 Explanation of Axiomatic Design

Table 1. Axiomatic Design Definitions

Term	Definition
Axiom	Fundamental truth for which there are no counter examples
Customer Needs (CN)	Functional needs of the product, do not need to be independent
Functional Requirement (FR)	Independent requirements characterizing the functional needs of the product
Design Parameter (DP)	Key physical characteristic of the design that satisfy the a specific FR
Constraint	Limiting bounds on acceptable design solutions
Parent	FR or DP that has been further decomposed
Child	Decomposed level of the parent
Upper Level FR	FR0 and its children, FR1, FR2, FR3, etc.
Coupling	Design elements can no longer be adjusted or changed independently

All three project teams utilized Axiomatic Design (AD). Using AD, the team identified customer needs to help create functional requirements (FRs). Once the FRs were defined, design parameters (DPs) were developed which guided the design of the bicycle frame, jig, and testing procedures. Axiomatic design uses two core axioms in order to guide the design process, hence its name. Axiom 1 states that FRs must maintain independence, and Axiom 2 states that the information content of the design must be minimized (Suh 1990). In a decomposition, FRs and DPs are broken down into children that are collectively exhaustive with respect to the parent and mutually exclusive with respect to each other (i.e., CEME) (Brown 2015). This ensures that all information content is present and that there is little to no coupling in the design, meaning that a singular element or component can be altered without the need to redesign any other components or elements. The design must also fulfill the pre-determined customer needs (CNs) and comply with constraints.

1.2 Joints

1.2.1 Objectives

The objective of the Joints Team was to design a system of gussets to transmit rider loads between bicycle frame members.

1.2.2 Rationale - Modularity in Design

Modularity in the design of a bamboo bicycle frame is critical for a variety of reasons. Joints need to be adapted to the varying diameters of the bamboo rods used in frame construction. Adaptable joints also allow for the usage of a broad variety of external components such as wheels and crank sets. By keeping the system modular, custom frame geometries can also be produced to accommodate a variety of different rider sizes and riding styles.

1.2.3 State of the art

1.2.3.1 Wrapped Composite Lug Joints

In the field of carbon fiber bicycle frames, wrapped composite lugs are the predominant choice of construction. In wrapped composite lug frames, most of the frames joint structure comes from the careful wrapping of each individual joint with a pre-impregnated composite tape, usually utilizing a conventional autoclave-curing resin matrix with carbon fiber reinforcements.

1.2.3.2 Prefabricated, Gusseted Lug Joints

Calfee Design has pioneered construction methods utilizing pre-fabricated joint lug designs with integrated gusseting to help transmit loads between frame members. One of the main advantages of using prefabricated, gusseted lugs is that they can provide the necessary strength needed in a bicycle frame without the extra weight of the wrapped composite material required to achieve the desired frame rigidity (Calfee Design 2015).

1.2.4 Approach - Hybrid Wrapped Composite/Gusseted Joint Design

The team decomposed the design problem with axiomatic design. The resulting joint design combined the conventional wrapped composite lug joint with a prefabricated, gusseted lug design. By using these two systems together, the team hoped to achieve a significant weight reduction over previous frames, while also simplifying the assembly process of each frame. The gussets were modeled in SolidWorks, outsourced for manufacturing, and used in the production of a prototype bicycle frame.

1.3 Jig

1.3.1 Objective

The objective of the Jig Team was to design a device that enables an individual with minimal training to assemble a bamboo bicycle frame by maintaining component alignment during bicycle frame assembly.

1.3.2 Rationale

1.3.2.1 Modularity in Design

Modularity greatly increases the versatility of a design. It was determined that a modular jig was necessary both to accommodate multiple frame geometries and variance in bamboo geometry. This would remove the need to design and manufacture a new jig when scaling the bicycle frame for different size riders or changing the geometry to better suit the intended riding terrain.

1.3.2.2 Simplicity of Operation

Simple fixtures are easier to operate. By designing intuitive fixtures, training and manufacturing time can be reduced, lowering the final cost of a bamboo bicycle. Lower production time and cost can make bicycles accessible in parts of the world with insufficient public transportation or infrastructure, improving quality of life for residents through increased mobility and opportunities for economic growth.

1.3.3 State of The Art

Most commercially available and homebuilt jigs fixture the joints of the bamboo bicycle frame, relying on interfaces at the joints to maintain alignment of the bamboo. During background research there were no primary sources found discussing the design of bamboo bicycle jigs. However a pattern was observed from all sources, and example images found online. Most bamboo bicycle manufacturing jigs fall under two general categories: backing plate jigs and frame jigs.

1.3.3.1 Backing Plate Jigs

The most common form of jig for bamboo bicycles encountered during background research was the backing plate style jigs. Figures 1 and 2 show two examples of backing plate jigs. Both fixture the joints of the frame, with the joints themselves supporting and aligning the bamboo. There are other versions of backing plate jigs that fixture the bamboo, but they are less common. Backing plate jigs can use relatively small and simple fixtures since the distance from the plate to the components is typically small. Additionally, they can be oriented vertically or horizontally based on assembly preference. One drawback of a backing plate jig is that it limits access to the side of the bicycle frame closest to the backing plate.

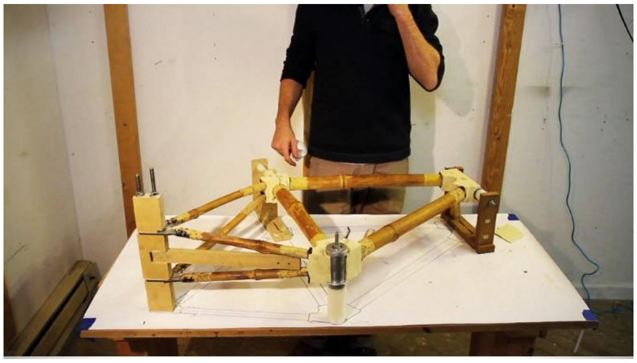


Figure 1. Backing Plate Jig, from http://forums.mtbr.com/frame-building/bamboo-bike-695716.html

Figure 2. Backing Plate Jig, from HEROBike

1.3.3.2 Frame Jigs

Frame Jigs are typically more complicated than backing plate jigs as they need longer supports for the fixtures. However, this extra complexity is offset by the ability to access the bicycle frame from all sides during manufacturing. Figures 3 and 4 show two examples of frame jigs. Figure 3 shows a metal frame jig that supports fixtures from the bottom. Figure 4 shows a wood jig that uses an exo-frame around the whole bicycle frame, and can be oriented in any direction for ease of assembly.

Figure 3. Frame Jig, from https://bamboobike.wordpress.com/other-peoples-projects/

Figure 4. Frame Jig, from http://www.instructables.com/id/How-I-built-a-carbon-bike-frame-at-home-and-a-bam/

1.3.4 Approach- State of the art difference

The team decomposed the design problem using axiomatic design. The resulting design of the bamboo bicycle frame jig will advance the state-of-the-art by combining the advantages of frame and backing plate jigs with the modularity and adjustability inherent in AD. The new jig design is an exo-frame jig, using t-slot 8020 extrusion as the frame to allow maximum adjustability of fixture positions. The legs of the exo-frame allow for the entire jig to be oriented multiple ways for ease of bicycle manufacturing. The fixtures also hold both the joints and bamboo rods to ensure component alignment. The final design is capable of being adjusted to handle a range of frame sizes and bamboo tolerances. The jig frame components and fixturing components were modeled in SolidWorks, outsourced for manufacturing, and a prototype jig was constructed.

1.4 Safety and Testing

1.4.1 Objectives

The objective of the Safety and Testing team was to ensure the safety of all potential riders by determining if the bicycle frame met ASTM standards for a condition two bicycle.

1.4.2 Rationale - Choosing ASTM standards

There are several well-established test standards available that the safety and testing group could refer to, such as ISO Standards (International Organization for Standardization) and ASTM standards (American Society for Testing and Materials). Since this particular bicycle was designed, produced, tested in America, the research that safety and testing group had done was based on the ASTM standards. These standards are well developed and globally accepted. The group also decided to base all tests around the ASTM standard for a condition two bicycle, which is described in detail in section 6.2.

1.4.3 State of the art - ASTM Testing Procedures for Frame

Based on ASTM standards, the safety and test group came up with testing methods to determine the mechanical properties of the bicycle frame. There are three components associated with a comprehensive bicycle frame test: the horizontal loading test, vertical loading test and critical impact test. The horizontal loading test is used to determine the frame performance against a horizontal force that acts on the bicycle frame.The vertical loading test is used to determine the frame's performance against a vertical force.The impact strength test is used to determine the overall strength of the bicycle frame.

1.4.4 Approach

Our team utilized axiomatic design to organize our testing procedure into an easy method that would result in the best chance to comply with ASTM standards. Following the functional requirements of our decomposition, we tested different types of bamboo to see which kind would have the highest mechanical properties to construct the frame. The frame would then be tested, once manufactured, in accordance with the ASTM standards for frame testing. Based on whether the frame met the standards, we could classify it as a condition two bicycle.

2. Decompositions

The following sections outline the decompositions for each of the three subgroups of the bamboo bicycle project. When creating the decomposition for the bamboo bicycle, customer needs and constraints were taken into account. Overall customer needs included:

- Frame must be made of bamboo
- Bicycle must be modular
- Simple to assemble for an individual with minimal training
- Bicycle must be easily assembled in an hour
- Meets ASTM safety standards for a condition two bicycle.

2.1 Joints Decomposition

#	[FR] Functional Requirements	[DP] Design Parameters
0	Transmit loads between bicycle components	System of joints
1	Transmit loads between bamboo components	System of bamboo connections
2	Transmit loads between joint and metal/purchased	System of joint to purchased component connections

Figure 5.

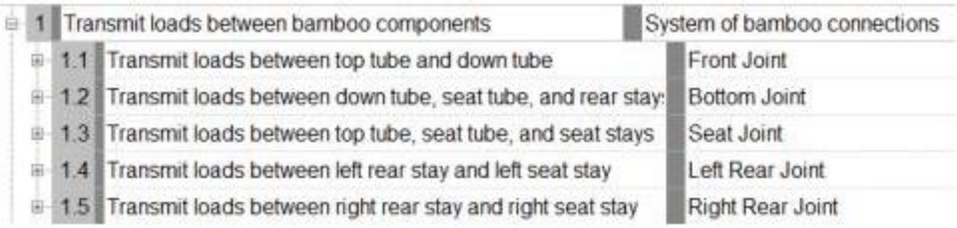
The overall goal for the bicycle was functional requirement zero (FR0): transmit loads between bicycle components, with the design parameter of creating a system of joints. The upper level FRs are visible in figure 5.Constraints for the joints deal mostly with the durability of the bicycle itself. Constraints include:

- Must be able to be manufactured at WPI's facilities or facilities located near Worcester, Massachusetts
- Must be able to be support the weight of a 300 lb person
- Must add no more than 20lb to the bicycle

After taking the constraints into account, the team broke down the analysis further into FR1: “transmit loads between bamboo components” and FR2: “transmit loads between joint and metal/purchased components”. The corresponding DPs are: “provide a system of connections between the bamboo” and “provide a system of joints to purchased components”.

2.1.1 Level I

2.1.1.1 Functional Requirement 1 - Transmit Loads between Bamboo Components



1	Transmit loads between bamboo components	System of bamboo connections
1.1	Transmit loads between top tube and down tube	Front Joint
1.2	Transmit loads between down tube, seat tube, and rear stay	Bottom Joint
1.3	Transmit loads between top tube, seat tube, and seat stays	Seat Joint
1.4	Transmit loads between left rear stay and left seat stay	Left Rear Joint
1.5	Transmit loads between right rear stay and right seat stay	Right Rear Joint

Figure 6.

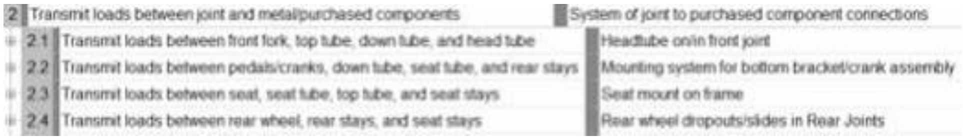
When analyzing FR1, the bamboo components were broken down into the five main frame members of the bicycle, namely the top tube, down tube, seat tube, rear stays, and seat stays. The team focused on each major junction of these bamboo frame members. By breaking down the frame into these clearly defined sections of the bicycle, the analysis becomes collectively exhaustive and mutually exclusive (CEME). Each section of the bicycle frame can be analyzed and decomposed independently in correspondence to Axiom 1, preventing coupling. A system of joints, namely the front, bottom, seat, left rear, and right rear joint, was created to connect the bamboo components in each section. Figure 6 above shows the decomposition of FR1 into the five main sections.

1	Transmit loads between bamboo components	System of bamboo connections
1.1	Transmit loads between top tube and down tube	Front Joint
1.2	Transmit loads between down tube, seat tube, and rear stays	Bottom Joint
1.3	Transmit loads between top tube, seat tube, and seat stays	Seat Joint
1.3.1	Transmit loads from bamboo to joint	System for providing secure material interface between bamboo and joint
1.3.1.1	Transmit transverse loads from bamboo to joint	Aluminum Gussets
1.3.1.2	Transmit axial loads from bamboo to joint	Prepreg Wrap
1.3.2	Transmit loads throughout joint	Gussets between bamboo junctions
1.4	Transmit loads between left rear stay and left seat stay	Left Rear Joint
1.5	Transmit loads between right rear stay and right seat stay	Right Rear Joint

Figure 7.

In each section, FR1.x is decomposed into FR1.x.1, transmit loads from bamboo to joint, and FR1.x.2, transmit loads throughout joint, based on the DP of each region's FR. This section of the decomposition is shown above in figure 7.These transfers of loads are independent components of the overall system's dynamics. The DPs were created to minimize the information content in accordance with Axiom 2, which is why decomposition stopped for FR1.x.2 when the solution of gussets between bamboo junctions became obvious. FR1.x.1, with its DP: system for providing secure material interface between bamboo and joint, needed further decomposition until an obvious solution was reached. In each case, it was further decomposed into FR 1.x.1.1, transmit transverse loads from bamboo to joint with a DP of gussets, and FR 1.x.1.2, transmit axial loads from bamboo to joint with a DP of pre-impregnated wrap. Because the DPs for both FR1.x.1.1 and FR1.x.2 involve the use of gusseting, coupling occurs in the matrix. This is a result of the need for the gussets to transmit transverse loads from the bamboo to the joint and to transmit loads throughout the joint from one frame member to the others. Despite the fact that we have a coupled matrix, by giving the gussets multiple roles, both related to load transmission, we were able to reduce the amount of information in our design, satisfying axiom 2.

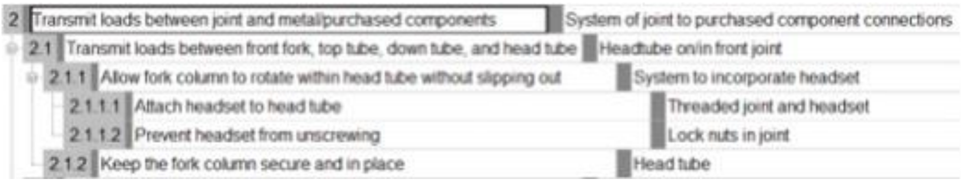
2.1.1.2 Functional Requirement 2 - Transmit Loads between Joint and Purchased/Manufactured Components



2	Transmit loads between joint and metal/purchased components	System of joint to purchased component connections
2.1	Transmit loads between front fork, top tube, down tube, and head tube	Headtube on/in front joint
2.2	Transmit loads between pedals/cranks, down tube, seat tube, and rear stays	Mounting system for bottom bracket/crank assembly
2.3	Transmit loads between seat, seat tube, top tube, and seat stays	Seat mount on frame
2.4	Transmit loads between rear wheel, rear stays, and seat stays	Rear wheel dropouts/slides in Rear Joints

Figure 8.

When analyzing FR2, the manufactured and purchased components were decomposed into the main components of the bicycle, including: the seat, wheels, and pedals. This section of the decomposition is shown in figure 8. Each interface was then analyzed independently, once again in correspondence with Axiom 1. The DP, a system of joints to purchased component interfaces was analyzed.



2	Transmit loads between joint and metal/purchased components	System of joint to purchased component connections
2.1	Transmit loads between front fork, top tube, down tube, and head tube	Headtube on/in front joint
2.1.1	Allow fork column to rotate within head tube without slipping out	System to incorporate headset
2.1.1.1	Attach headset to head tube	Threaded joint and headset
2.1.1.2	Prevent headset from unscrewing	Lock nuts in joint
2.1.2	Keep the fork column secure and in place	Head tube

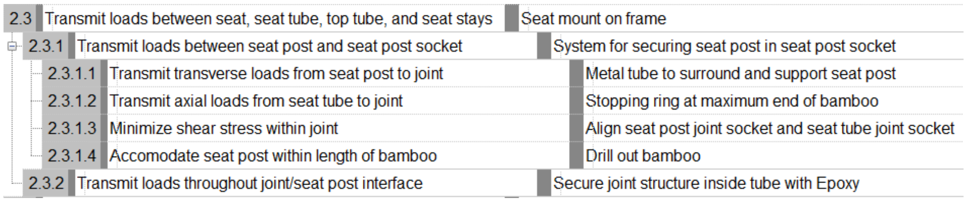
Figure 9.

The DP for FR2.1: "transmit loads between front fork, top tube, down tube, and head tube," is "a head tube with features to accommodate and retain a purchased headset." A headset is a bearing set used to support the front fork in the head tube of the bicycle. This is shown in figure 9.

2.2	Transmit loads between pedals/cranks, down tube, seat tube, and rear stays	Mounting system for bottom bracket/crank assembly
2.2.1	Transmit loads between bottom bracket and joint	Axle Shaft in/on joint
2.2.1.1	Secure bottom bracket within axle shaft	Threading inside shaft
2.2.1.2	Transmit transverse applied loads from bottom bracket on joint	Design with aluminum to withstand the applied loads
2.2.2	Transmit loads throughout joint/bottom bracket interface	Weld bottom bracket axle to the joint

Figure 10.

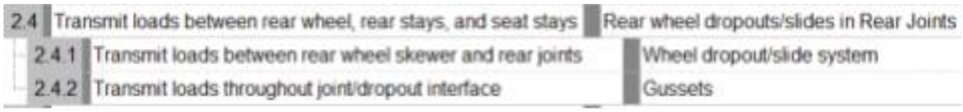
FR2.2: "transmit loads between pedals/cranks, down tube, seat tube, and rear stays," has the following DP: "a housing with threading in order to integrate the bottom bracket into the joint." This is shown in figure 10. In early iterations of the decomposition, gussets were going to be used in between the seat tube and each chain stay. When that design was further inspected, it was discovered that the gussets and chain were coupled with each other, as the gussets interfered with the chain's motion, violating axiom 1. With our current design, the bottom bracket joint, consisting of a "sling" holding the bottom bracket shell, down tube, and chain stays, and a gusset between the seat tube and down tube, is simpler than the design that came before it, complying with axiom 2.



2.3	Transmit loads between seat, seat tube, top tube, and seat stays	Seat mount on frame
2.3.1	Transmit loads between seat post and seat post socket	System for securing seat post in seat post socket
2.3.1.1	Transmit transverse loads from seat post to joint	Metal tube to surround and support seat post
2.3.1.2	Transmit axial loads from seat tube to joint	Stopping ring at maximum end of bamboo
2.3.1.3	Minimize shear stress within joint	Align seat post joint socket and seat tube joint socket
2.3.1.4	Accomodate seat post within length of bamboo	Drill out bamboo
2.3.2	Transmit loads throughout joint/seat post interface	Secure joint structure inside tube with Epoxy

Figure 11.

FR2.3: "transmit loads between seat, seat tube, top tube, and seat stays," was given the DP: "a seat post within a seat post socket" that was secured with epoxy and various alignments and joint structures. This design was chosen over a clamshell joint because the clamshell could not account for the shape of the bamboo, nor could it comply with our manufacturing constraint. This section of the decompositions is shown in figure 11.



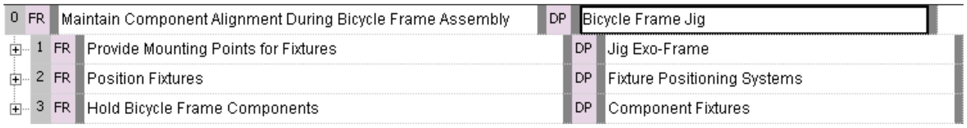
2.4	Transmit loads between rear wheel, rear stays, and seat stays	Rear wheel dropouts/slides in Rear Joints
2.4.1	Transmit loads between rear wheel skewer and rear joints	Wheel dropout/slide system
2.4.2	Transmit loads throughout joint/dropout interface	Gussets

Figure 12.

FR2.4: "transmit loads between rear wheel, chain stays, and seat stays," has the DP "rear wheel dropout/slides in Rear Joints. This is shown in figure 12. The rear joints of our system used integrated gusseting in the dropouts of the bicycle frame in order to distribute loads between the seat and chain stays on each side, as well as between the rear wheel and frame stays.

2.2 Jig Decomposition

2.2.1 Discuss FR0 and DP0



0	FR	Maintain Component Alignment During Bicycle Frame Assembly	DP	Bicycle Frame Jig
1	FR	Provide Mounting Points for Fixtures	DP	Jig Exo-Frame
2	FR	Position Fixtures	DP	Fixture Positioning Systems
3	FR	Hold Bicycle Frame Components	DP	Component Fixtures

Figure 13.

The highest level functional requirement is FR0: "maintain component alignment during bicycle frame assembly." This is to ensure that the components of the bicycle frame have the proper positioning and alignment during assembly. To accomplish this the jig team defined DP0 as "bicycle frame jig." The team decomposed parts of the jig further to fully determine what was necessary for the design in FRs 1-3. These FRs are shown in figure 13. For FR1, a mounting system for each of the fixtures was provided to hold the components of the bicycle frame. In order to do this, DP1 was defined as "jig exo-frame". This represents the frame that all jig fixtures will attach to. The exo-frame was further decomposed to find the mounting requirements for the fixtures that hold the bicycle components in alignment. This is defined by FR2: "position fixtures," which is satisfied by DP2: "fixture positioning systems." The fixture positioning systems are the components of the jig that attach to the exo-frame and hold the fixtures in their proper place. FR3 is to "hold the bicycle frame components" to ensure they are held in the proper alignment during assembly. This is accomplished by DP3: "component fixtures," which is further decomposed into child FRs for each fixture to hold the components of the bicycle frame.

2.2.2 Discussion of Child FRs and DPs

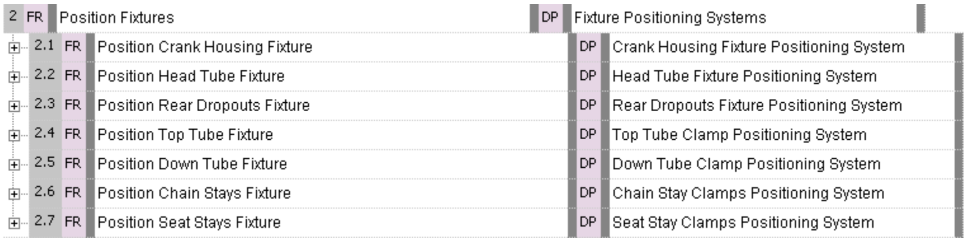
2.2.2.1 FR1 and DP1

1	FR	Provide Mounting Points for Fixtures	DP	Jig Exo-Frame
1.1	FR	Provide Mounting Points in the x-direction	DP	Jig Exo-Frame x-components
1.2	FR	Provide Mounting Points in the y-direction	DP	Jig Exo-Frame y-components
1.3	FR	Provide Stability along z-direction	DP	Jig Exo-Frame z-components

Figure 14.

FR1: "provide mounting points for fixtures" is decomposed into three children, FRs 1.1-1.3. This is shown in figure 14.The jig frame surrounds the bicycle frame in the x-axis and y-axis, so the first two children of FR1 are to provide mounting points in those directions for fixture support features. The third child of FR1 is to provide stability along the z-direction so that the jig is sturdy during assembly. The DPs for each child of FR1 are defined as the components of the exo-frame in a direction of 3D Cartesian space.

2.2.2.2 FR2 and DP2

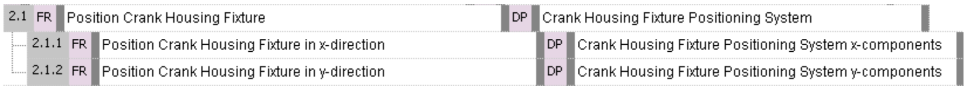


2	FR	Position Fixtures	DP	Fixture Positioning Systems
2.1	FR	Position Crank Housing Fixture	DP	Crank Housing Fixture Positioning System
2.2	FR	Position Head Tube Fixture	DP	Head Tube Fixture Positioning System
2.3	FR	Position Rear Dropouts Fixture	DP	Rear Dropouts Fixture Positioning System
2.4	FR	Position Top Tube Fixture	DP	Top Tube Clamp Positioning System
2.5	FR	Position Down Tube Fixture	DP	Down Tube Clamp Positioning System
2.6	FR	Position Chain Stays Fixture	DP	Chain Stay Clamps Positioning System
2.7	FR	Position Seat Stays Fixture	DP	Seat Stay Clamps Positioning System

Figure 15.

FR2: "position fixtures" is necessary to define the location of the component fixtures within the exo-frame. FR2 is broken down into children for each of the jig fixtures, where each child (FRs 2.1-2.7) is responsible for positioning an individual fixture within the jig. The DPs for each FR is a positioning system for the specific fixture. This is shown in figure 15.

2.2.2.2.1 Children of FR2 and DP2



2.1	FR	Position Crank Housing Fixture	DP	Crank Housing Fixture Positioning System
2.1.1	FR	Position Crank Housing Fixture in x-direction	DP	Crank Housing Fixture Positioning System x-components
2.1.2	FR	Position Crank Housing Fixture in y-direction	DP	Crank Housing Fixture Positioning System y-components

Figure 16.

Each of the children of FR2, FR 2.1-2.7, have the same two functional requirements as their children. These two FRs are to position the respective fixture in the x-direction and to position the respective fixture in the y-direction. The corresponding DPs are listed as the x and y components of the positioning system for that fixture. This is shown in figure 16.

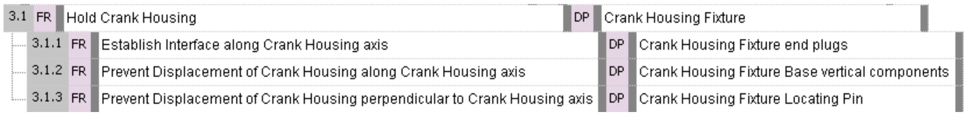
2.2.2.3 FR3 and DP3

3	FR	Hold Bicycle Frame Components	DP	Component Fixtures
3.1	FR	Hold Crank Housing	DP	Crank Housing Fixture
3.2	FR	Hold Head Tube	DP	Head Tube Fixture
3.3	FR	Hold Rear Dropouts	DP	Rear Dropouts Fixture
3.4	FR	Hold Bamboo Components	DP	Bamboo Clamp

Figure 17.

FR3: Hold Bicycle Frame Components, is satisfied by DP3: "component fixtures." Three of the joints in the bicycle frame are unique, and as such required individual children to address how each joint is aligned correctly within the jig. FR3.1 addresses the crank housing, FR3.2 addresses the head tube, and FR3.3 addresses the rear dropouts. The bamboo components of the bicycle are all aligned using separate fixtures, but because each bamboo component has similar geometry, the fixtures are defined by the same functional requirement, FR3.4. This is shown in figure 17.

2.2.2.3.1 FR3.1 and DP3.1

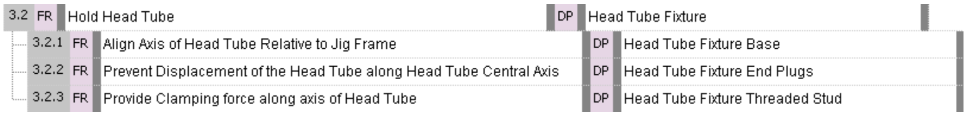


3.1	FR	Hold Crank Housing	DP	Crank Housing Fixture
3.1.1	FR	Establish Interface along Crank Housing axis	DP	Crank Housing Fixture end plugs
3.1.2	FR	Prevent Displacement of Crank Housing along Crank Housing axis	DP	Crank Housing Fixture Base vertical components
3.1.3	FR	Prevent Displacement of Crank Housing perpendicular to Crank Housing axis	DP	Crank Housing Fixture Locating Pin

Figure 18.

FR3.1: "hold crank housing" is broken down into three children FRs to accomplish DP3.1. FR3.1.1 establishes an interface along the crank housing axis in the form of the two end plugs. FR3.1.2 is satisfied by DP3.1.2, preventing displacement along the crank housing axis by the vertical components of the crank housing fixture base. FR3.1.3 is satisfied by DP3.1.3, preventing displacement perpendicular to the crank housing axis by the locating pin going through the fixture base and end plugs. This is shown in figure 18.

2.2.2.3.2 FR3.2 and DP3.2



3.2	FR	Hold Head Tube	DP	Head Tube Fixture
3.2.1	FR	Align Axis of Head Tube Relative to Jig Frame	DP	Head Tube Fixture Base
3.2.2	FR	Prevent Displacement of the Head Tube along Head Tube Central Axis	DP	Head Tube Fixture End Plugs
3.2.3	FR	Provide Clamping force along axis of Head Tube	DP	Head Tube Fixture Threaded Stud

Figure 19.

FR3.2: "hold head tube" is broken down into four children FRs to accomplish DP3.2. FR3.2.1 is satisfied by DP3.2.2, aligning the central axis of the head tube by the head tube fixture base. FR3.2.2 is satisfied by DP3.2.2, preventing displacement of the head tube along its central axis by the top and bottom head tube plugs. FR3.2.3 is satisfied by DP3.2.3, providing a clamping force along the central axis by the threaded stud through the plugs and head tube fixture base. This is shown in figure 19.

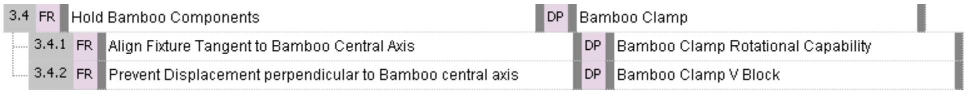
2.2.2.3.3 FR3.3 and DP3.3

3.3	FR	Hold Rear Dropouts	DP	Rear Dropouts Fixture
3.3.1	FR	Maintain Distance between Dropouts	DP	Rear Dropout Fixture Alignment Fork
3.3.2	FR	Provide Clamping Force along shared Dropout axis	DP	Quick Release Self-Centering Skewer

Figure 20.

FR3.3: "hold read dropouts" has two components that work together to meet DP3.3: "rear dropout fixture." FR3.3.1 is satisfied by DP3.3.1, maintaining the correct distance between the dropouts by way of the rear dropout alignment fork. FR3.3.2 is satisfied by DP3.3.2, using a self centering quick release skewer to provide a clamping force on the rear dropouts along the shared axis. This is shown in figure 20.

2.2.2.3.4 FR3.4 and DP3.4



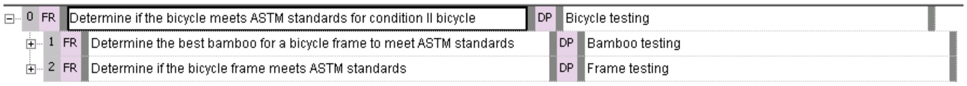
3.4	FR	Hold Bamboo Components	DP	Bamboo Clamp
3.4.1	FR	Align Fixture Tangent to Bamboo Central Axis	DP	Bamboo Clamp Rotational Capability
3.4.2	FR	Prevent Displacement perpendicular to Bamboo central axis	DP	Bamboo Clamp V Block

Figure 21.

FR 3.4: "hold bamboo components" is broken down into two children. FR3.4.1 addresses aligning the bamboo fixture with the central axis of the bamboo by DP3.4.1, providing rotational capability in the xy-plane. FR3.4.2 addresses maintaining the position of the bamboo by DP3.4.2 preventing displacement with a v-block. This is shown in figure 21.

2.3 Safety and Testing Decomposition

2.3.1 Level 1

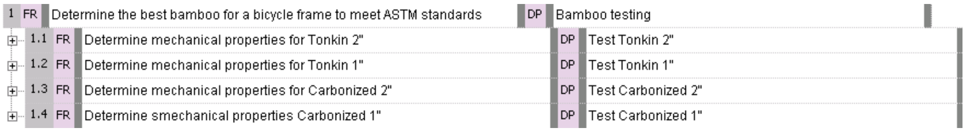


		FR		DP
0	FR	Determine if the bicycle meets ASTM standards for condition II bicycle	DP	Bicycle testing
1	FR	Determine the best bamboo for a bicycle frame to meet ASTM standards	DP	Bamboo testing
2	FR	Determine if the bicycle frame meets ASTM standards	DP	Frame testing

Figure 22.

The highest level requirement defined by the safety and testing group was to determine if the bicycle would be safe for potential riders. In order for it to be deemed safe it is required to meet the American Society for Testing and Materials (ASTM) standard tests. FR0 determines if the bicycle meets ASTM standards for a condition two bicycle. The corresponding DP is bicycle testing; which involves any testing that could be used to meet the required standards. FR0 is decomposed into two main requirements. FR1 was intended as a means to confirm we are using the best performing bamboo in the construction of the bicycle frame. FR2 was the requirement to meet the ASTM standards by completing the frame testing. This is shown in figure 22.

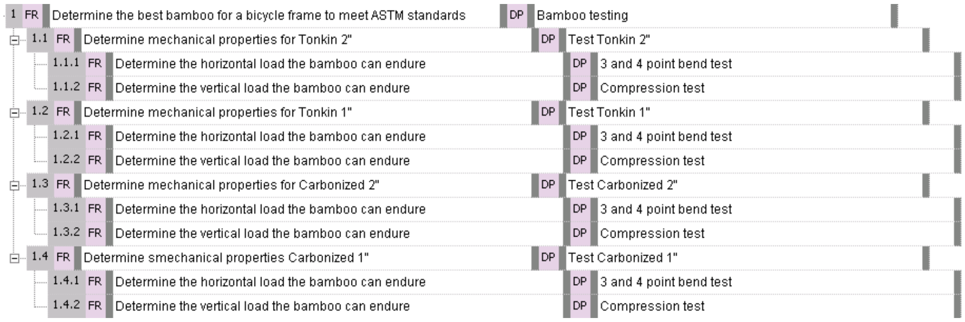
2.3.2 Functional Requirement 1



		FR		DP
1	FR	Determine the best bamboo for a bicycle frame to meet ASTM standards	DP	Bamboo testing
1.1	FR	Determine mechanical properties for Tonkin 2"	DP	Test Tonkin 2"
1.2	FR	Determine mechanical properties for Tonkin 1"	DP	Test Tonkin 1"
1.3	FR	Determine mechanical properties for Carbonized 2"	DP	Test Carbonized 2"
1.4	FR	Determine smechanical properties Carbonized 1"	DP	Test Carbonized 1"

Figure 23.

FR1: Determine the best bamboo for a bicycle frame to meet ASTM standards. In order for the bicycle to comply with ASTM standards and be safe to ride, the bamboo with the strongest mechanical properties needed to be chosen. In order to meet this requirement and fulfill DP1, the bamboo needs to be tested. FR1 was decomposed into four children FRs, taking into consideration the four types of bamboo tested. This is shown in figure 23. The full decomposition is shown in figure 24.



		FR		DP
1	FR	Determine the best bamboo for a bicycle frame to meet ASTM standards	DP	Bamboo testing
1.1	FR	Determine mechanical properties for Tonkin 2"	DP	Test Tonkin 2"
1.1.1	FR	Determine the horizontal load the bamboo can endure	DP	3 and 4 point bend test
1.1.2	FR	Determine the vertical load the bamboo can endure	DP	Compression test
1.2	FR	Determine mechanical properties for Tonkin 1"	DP	Test Tonkin 1"
1.2.1	FR	Determine the horizontal load the bamboo can endure	DP	3 and 4 point bend test
1.2.2	FR	Determine the vertical load the bamboo can endure	DP	Compression test
1.3	FR	Determine mechanical properties for Carbonized 2"	DP	Test Carbonized 2"
1.3.1	FR	Determine the horizontal load the bamboo can endure	DP	3 and 4 point bend test
1.3.2	FR	Determine the vertical load the bamboo can endure	DP	Compression test
1.4	FR	Determine smechanical properties Carbonized 1"	DP	Test Carbonized 1"
1.4.1	FR	Determine the horizontal load the bamboo can endure	DP	3 and 4 point bend test
1.4.2	FR	Determine the vertical load the bamboo can endure	DP	Compression test

Figure 24.

2.3.2.1 Discuss FR 1.1 and DP 1.1

FR 1.1 Determine the mechanical properties for Tonkin 2". The requirement is decomposed into two children FR's to accomplish DP 1.1. FR 1.1.1 is satisfied by DP 1.1.1, determining the horizontal load the bamboo can endure by a 3 and 4-point bend test. FR 1.1.2 is satisfied by DP 1.1.2, determining the vertical load the bamboo can endure by a compression test.

2.3.2.2 Discuss FR 1.2 and DP 1.2

FR 1.2 Determine the mechanical properties for Tonkin 1". The requirement is decomposed into two children FR's to accomplish DP 1.2. FR 1.2.1 is satisfied by DP 1.2.1, determining the horizontal load the bamboo can endure by a 3 and 4-point bend test. FR 1.2.2 is satisfied by DP 1.2.2, determining the vertical load the bamboo can endure by a compression test.

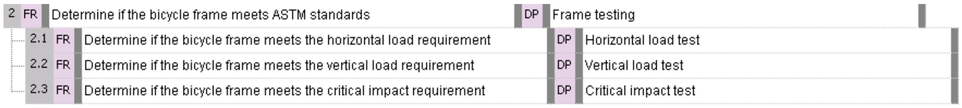
2.3.2.3 Discuss FR 1.3 and DP 1.3

FR 1.3 Determine the mechanical properties for Carbonized 2".The requirement is decomposed into two children FR's to accomplish DP 1.2. FR 1.3.1 is satisfied by DP 1.3.1, determining the horizontal load the bamboo can endure by a 3-point and 4-point bend test. FR 1.3.2 is satisfied by DP 1.3.2, determining the vertical load the bamboo can endure by a compression test.

2.3.2.4 Discuss FR 1.4 and DP 1.4

FR 1.4 Determine the mechanical properties for Carbonized 1". The requirement is decomposed into two children FR's to accomplish DP 1.4. FR 1.4.1 is satisfied by DP 1.4.1, determining the horizontal load the bamboo can endure by a 3 and 4-point bend test. FR 1.4.2 is satisfied by DP 1.4.2, determining the vertical load the bamboo can endure by a compression test.

2.3.3 Functional Requirement 2



2	FR	Determine if the bicycle frame meets ASTM standards	DP	Frame testing
2.1	FR	Determine if the bicycle frame meets the horizontal load requirement	DP	Horizontal load test
2.2	FR	Determine if the bicycle frame meets the vertical load requirement	DP	Vertical load test
2.3	FR	Determine if the bicycle frame meets the critical impact requirement	DP	Critical impact test

Figure 25.

FR 2: Determine if the bicycle frame meets ASTM standards. In order to determine if the bicycle does comply with ASTM standards and fulfill DP1, the bicycle frame needs to be tested. FR 2 was decomposed into three children FRs to satisfy the three different requirements. This is shown in figure 25.

2.3.3.1 Discuss FR 2.1 and DP 2.1

FR 2.1 Determine if the bicycle meets the horizontal load requirement. This requirement aligned with DP 2.1, using the ASTM horizontal load test to fulfill FR 2.1.

2.3.3.2 Discuss FR 2.2 and DP 2.2

FR 2.2 Determine if the bicycle meets the vertical load requirement. This requirement aligned with DP 2.2, using the ASTM horizontal load test to fulfill FR 2.2.

2.3.3.3 Discuss FR 2.3 and DP 2.3

FR 2.3 Determine if the bicycle meets the critical impact requirement. This requirement aligned with DP 2.3, using the ASTM horizontal load test to fulfill FR 2.3.

3. Implementation of Axiomatic Design

Using the axiomatic design decompositions the team was able to create designs that met the different functional requirements of the project. The designs were modeled in SolidWorks to provide an accurate representation of how they would meet these requirements.

3.1 Joints

The following sections discuss the transition from axiomatic design to SolidWorks models. Models were created for each joint and were sent to New England Wire and Goldenrod Corporation so the parts could be manufactured.

3.1.1 Level 0 and 1 Functional Requirements

According to the Joints design decomposition discussed in section 2, the top level Functional Requirement of the design is to transmit loads between bicycle components. The Design Parameter chosen to satisfy this requirement is a system of joints. Decomposing this, the system of joints in our design has to fulfill two functional requirements: Transmit loads between bamboo components, and transmit loads from the joints to purchased stock bicycle components. In order to fulfill these requirements, five different joints have been identified, and each joint has been decomposed separately.

3.1.2 Level 2+ Functional Requirements

3.1.2.1 Front Joint

The front joint was designed to transmit loads between the top tube, down tube, and front fork, and consists of two different pieces. In order to keep the fork column secure and in place, (FR2.1.2,) a metal head tube was designed. To transmit loads from the bamboo to the joint and throughout the joint, (FR1.1, FR1.1.1.1, and FR2.1,) a gusset is placed connecting the top tube, the head tube, and the down tube. The bamboo-contacting arms of the gusset are extended in order to give more area for the pre-impregnated wrap to grip satisfying FR1.1.1.2. The head tube is welded to the gusset to join the head tube to the rest of the joint. The CAD design of the Front Joint can be seen in figure 26.

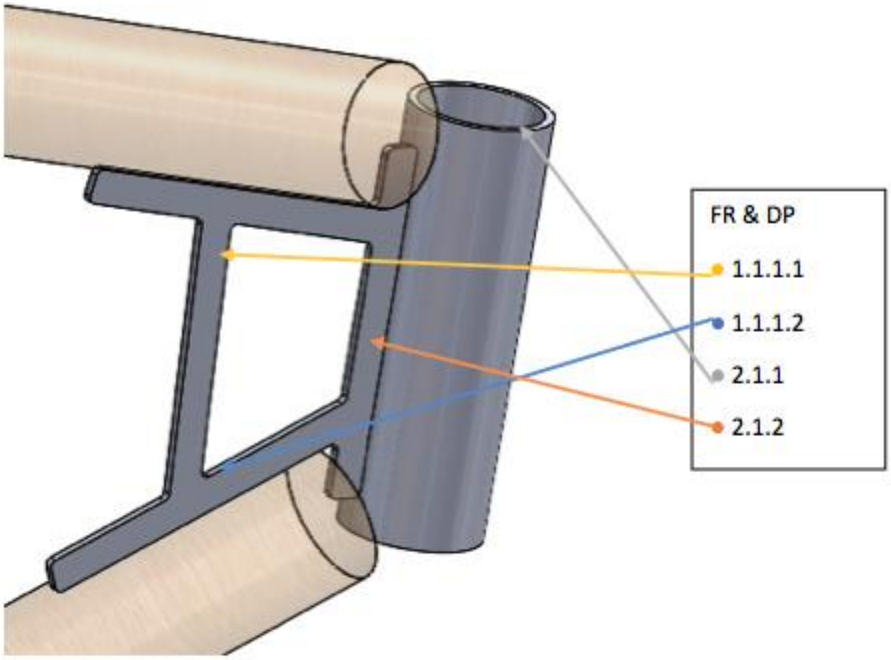


Figure 26.Front Joint

3.1.2.2 Seat Joint

The seat joint is designed to transmit loads between the seat tube, top tube, seat stays, and seat post, and consists of five different pieces. In order to transmit loads from the bamboo to the joint and throughout the joint, (FR1.3.2 and FR1.3.1.1) a series of four triangular aluminum gussets has been created. One is located between the top tube and the seat tube, two between the seat tube and each seat stay, and one smaller gusset between the two seat stays. The bamboo-contacting sides of the gussets are extended in order to give more area for the pre-impregnated wrap to grip, (FR1.3.1.2) except for the small wedge between the stays due to the constraints of its small size. To join the seat post to the bicycle (FR 2.3.1.1 and FR 2.3.1.2) , a shaft with a collar was designed, to be secured with epoxy in the end of the bored-out bamboo seat tube. The seat post would be placed into the shaft and secured with a standard seat post clamp. The ring on the pipe would press against the end of the seat tube and transfer the axial load of the seat post into the bamboo. The CAD design of the seat joint is shown below, in figure 27.

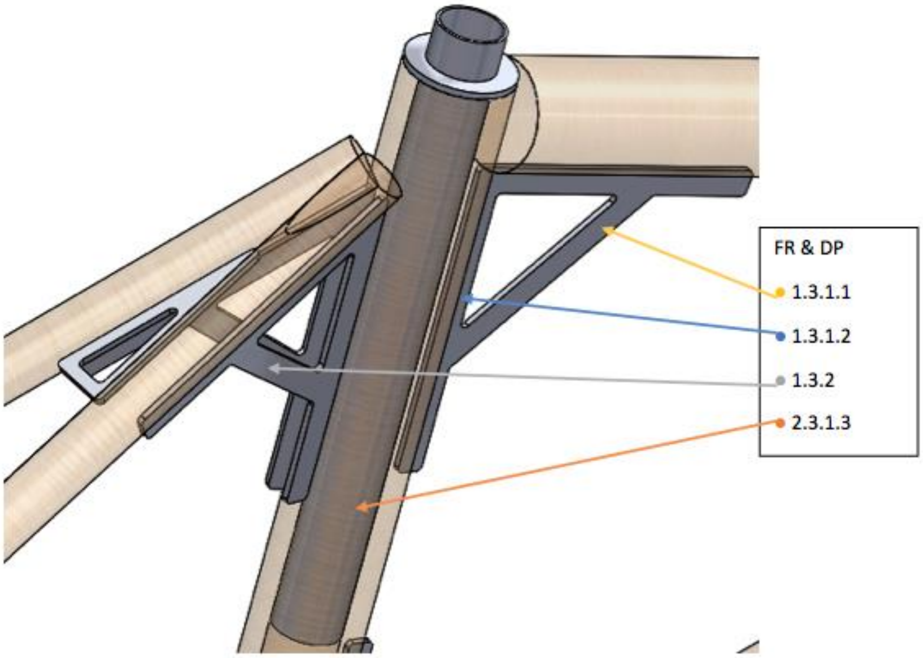


Figure 27.Seat Joint

Due to manufacturing constraints, the seat post holder was redesigned to be made out of a single piece of stock, rather than a pipe and a ring welded together. In the updated design, the ring was physically attached to the pipe. The design of the seat post receiver placed a constraint on manufacturing that the bamboo be cut just under the node to allow the seat post receiver to fit without needing to bore out a node. This eliminates the need for FR2.3.1.4 entirely. The redesigned seat tube holder can be seen below, in figure 28.

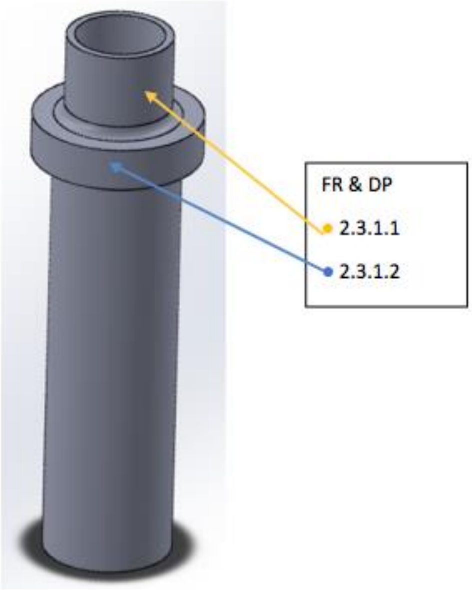


Figure 28. Seat Post Receiver

3.1.2.3 Bottom Joint

The bottom joint is designed to transmit loads between the seat tube, down tube, seat stays, and seat post, and consists of three different pieces. In order to transmit loads from the bamboo to the joint and throughout the joint, (FR1.2.2 and FR1.2.1.1) a triangular aluminum gusset is placed between the down tube and the seat tube, with the same design as the triangular gussets in the seat joint. A steel "saddle" has been created to transfer the loads between the seat stays and the down tube. This saddle itself consists of three parts, welded together: one steel tube section, cut open to accommodate the bottom bracket axle, one steel cutout to press against the down tube, and one steel cutout to press against the stays. (This satisfies FR2.2.2.) This design allows for the manufacture of a complicated shape required for the bottom bracket to stay in place without requiring a press to manufacture the needed parts. Using a press would have been too costly and time consuming for this project. Lastly, in order to transfer loads between the bottom bracket and the joint, (FR2.2.1) an axle shaft for the bottom bracket was created and welded into the saddle. The CAD model of the Bottom Joint is shown below, in figure 29.

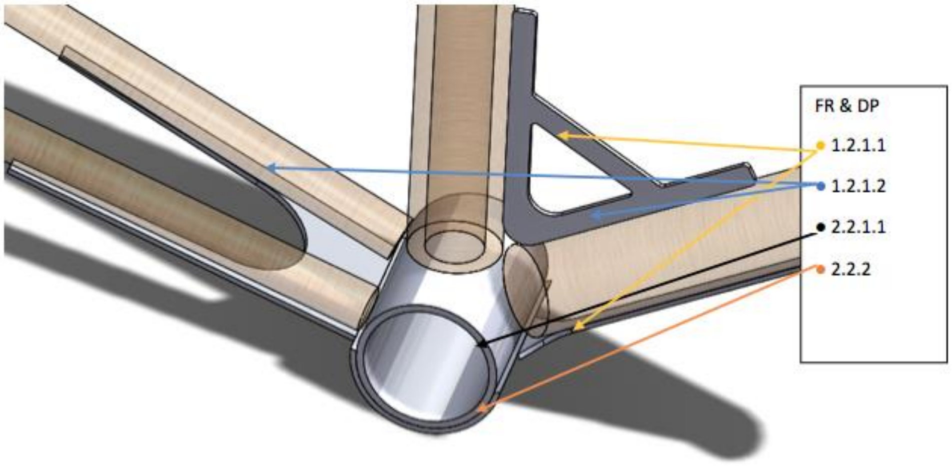


Figure 29. Bottom Joint

3.1.2.4 Left and Right Rear Joints

The left and right rear joints are designed to transmit loads between the seat stays and the down stays, and the rear wheel (FR1.4.1, FR1.5.1, and FR2.4), and consist of two mirror-symmetrical pieces. In order to transmit loads from the rear wheel to the joint, (FR2.4.1,) each joint contains a rear dropout slot. Gussets are used to transfer loads from the stays to the bamboo, (FR1.4.11 and FR1.5.11,) and a bend ensures that all components are properly aligned. Gusset size is kept minimal to avoid interference with the wheel and drivetrain. The CAD model of the left and right rear joints can be seen in figure 30.

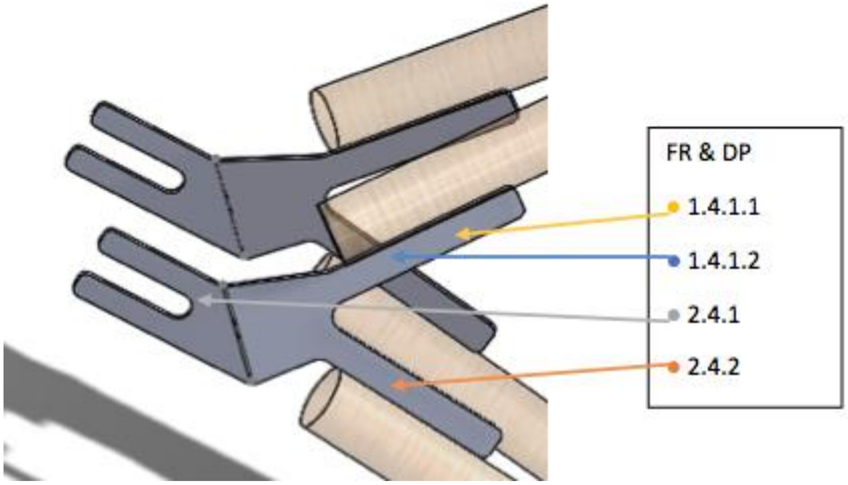


Figure 30. Left and Right Rear Joints

3.1.3 Joint CAD Modeling Process

In the CAD design of the bicycle joints, in order to comply with Suh's second axiom and minimize information content, the geometry of all the parts is based off a single file that specifies the junction point of each joint and the axes of all bamboo rods, shown in Figure 31. This ensures that all the parts fit together consistently while allowing for adjustments to be made to the frame geometry without modifying each part separately. All parts are made with simple extrudes, cuts, and revolves.

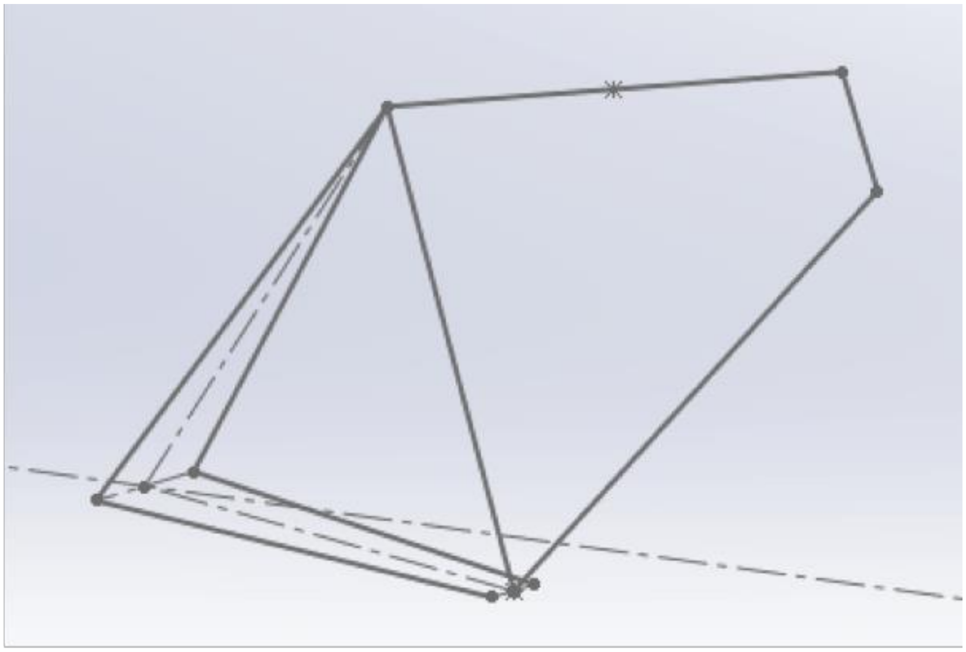


Figure 31.

The completed parts are mated together in a single assembly, again using the basic frame geometry file as a "skeleton" to reference the location of every part. Doing this allows us to once again minimize information content, in accordance with Axiom 2. This process also allows for easier modification of the design in order to change the frame geometry of the entire frame. All one has to do is modify the original frame geometry part file and each part will be adjusted accordingly. The final CAD design of the joints, with added cosmetic lengths of bamboo, is shown in Figure 32.

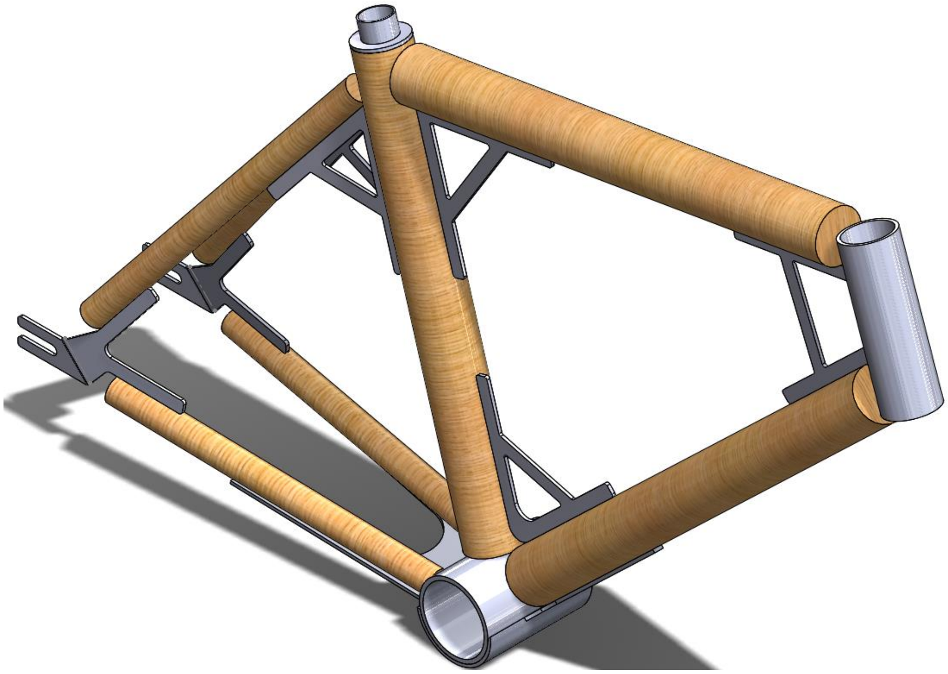


Figure 32.

3.2 Jig

The following sections discuss the transition from axiomatic design to SolidWorks models. Models were created for each part and were sent to New England Wire so the parts could be manufactured.

3.2.1 Level 0 Functional Requirement Integration

The top level functional requirement is to maintain the alignment of the bicycle components during assembly. The system designed is an external frame with fixtures extending inward to hold the bicycle components.

3.2.2 Level 1 Functional Requirement Integration

3.2.2.1 T Slot Framing

The 1st level functional requirement is to provide mounting points for the fixtures. The external frame is assembled from lengths of 1.5" 8020 aluminum T slot extrusions. The fixtures attach using end fed fasteners, allowing the position of every fixture to be adjustable. The final layout of the external frame is shown in figure 33. FR1.1 is met by the top and bottom T slot extrusions that are parallel to the x-axis. FR1.2 is met by the right and left T slot extrusions that are parallel to the y-axis. FR1.3 is met by the T slot extrusions at the four corners of the jig that are parallel to the z-axis.

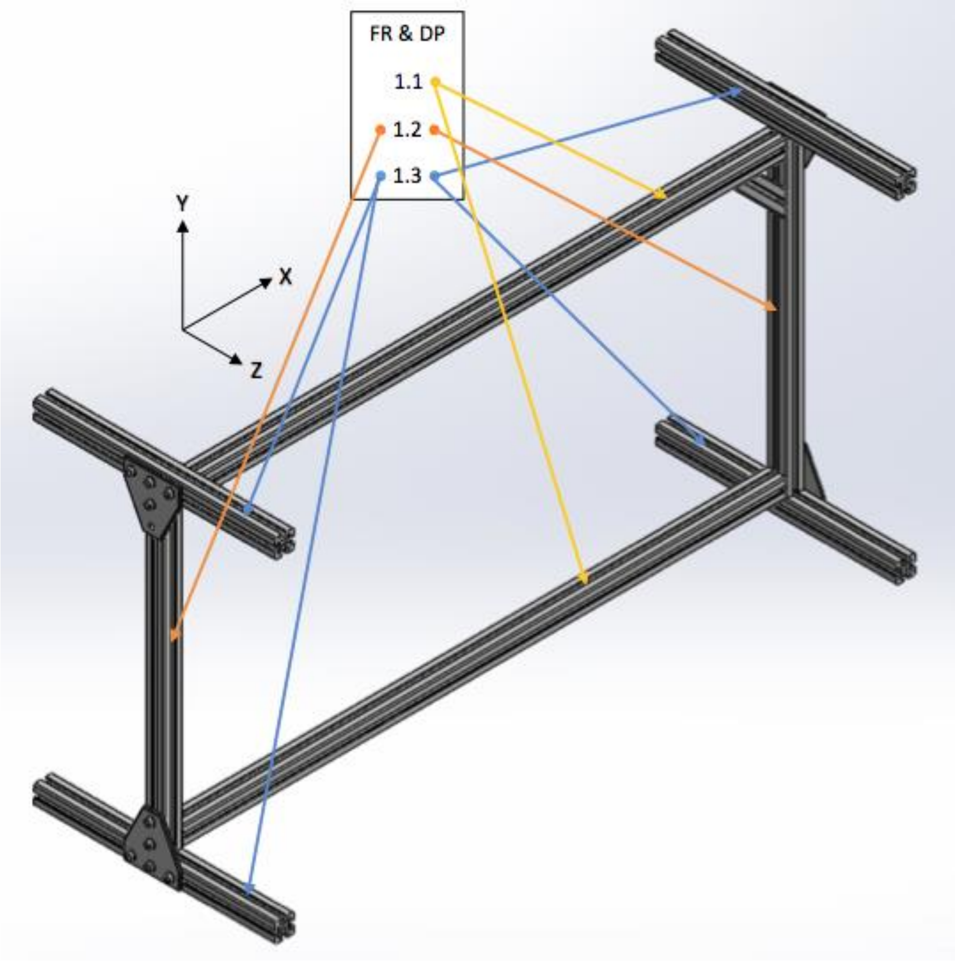


Figure 33.

3.2.3 Level 2 Functional Requirement Integration

The 2nd level functional requirements are to position the fixtures for each component of the bicycle frame. The components positioned in the jig are:

- Crank Housing
- Head Tube

- Rear Dropouts
- Bamboo components
- Top Tube
- Down Tube
- Chain Stays
- Seat Stays

3.2.3.1 Crank Housing Fixture Positioning

The crank housing fixture is positioned in space from the exo-frame by a u-bracket that is held in place by two T slot screws that can be loosened to adjust the position. Tightening these screws fixes the position of the crank housing fixture to meet FR2.1.1. The holes in the vertical components of the fixture determine the position of the crank housing in the y-direction, meeting FR2.1.2. This positioner is shown below in figure 34.

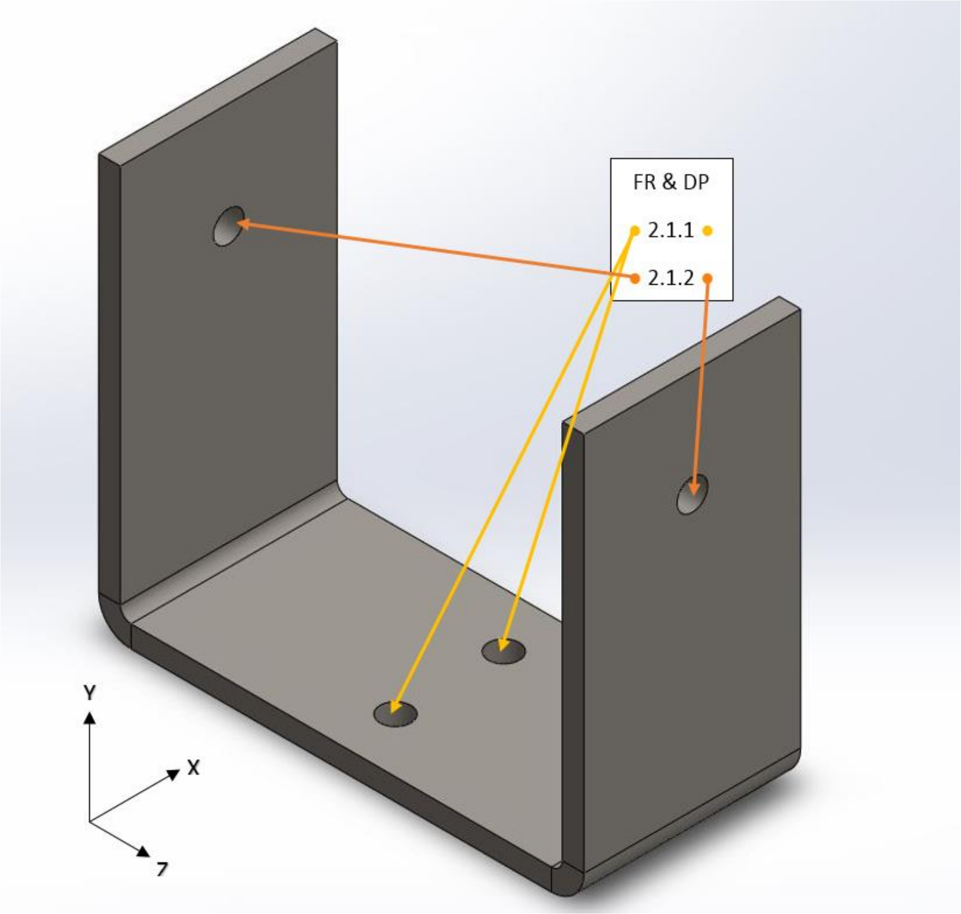


Figure 34.

3.2.3.2 Head Tube Fixture Positioning

The head tube fixture is positioned in space from the exo-frame by a bar of aluminum with an angle cut into it to get the proper angle of the head tube. It is held in place by two L-brackets and a pin through both. The L-brackets are attached to the left T slot extrusion of the jig exo-frame by two T slot screws. These screws can be loosened to adjust the position on the 8020 frame and tightened to fix the position, which functionally meets FR2.2.2. This positioner is shown below in figure 35.

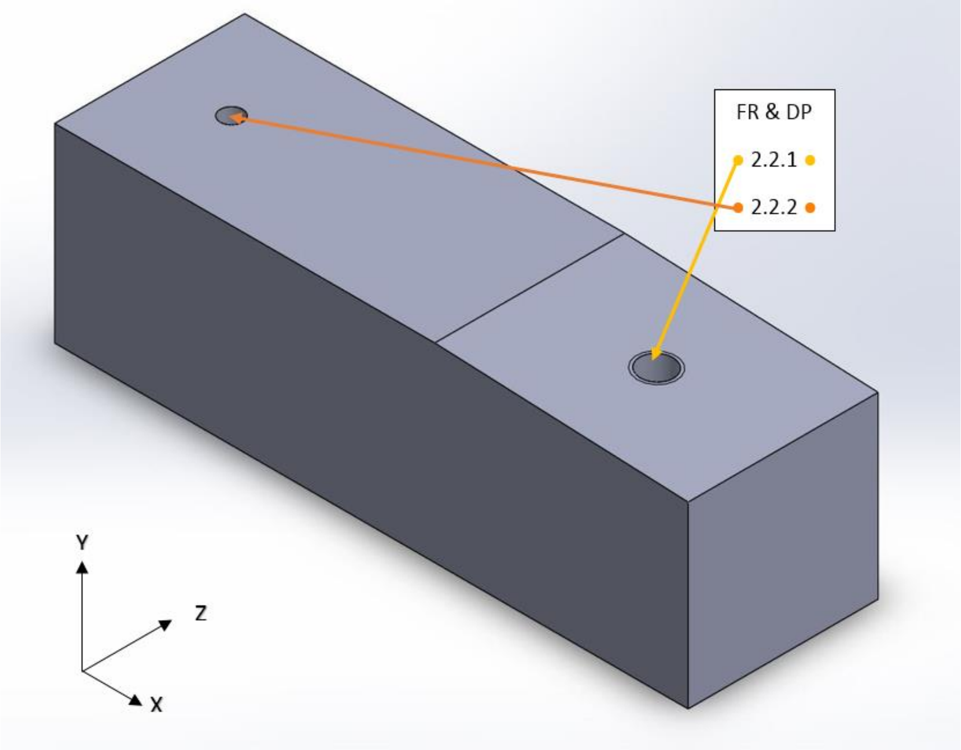


Figure 35.

3.2.3.3 Rear Dropouts Fixture Positioning

The rear dropouts fixture is positioned in space from the exo-frame by a bar of aluminum mounted to the right vertical T slot extrusion. FR 2.3.1 is determined by the fixed length of the aluminum bar, which is not adjustable. The aluminum bar is held in place by two L-brackets and a pin through both. The L-brackets are attached to the right T slot extrusion of the jig exo-frame by two T slot screws. These screws can be loosened to adjust the position on the 8020 frame and tightened to fix the position, which functionally meets FR2.3.2. This positioner is shown below in figure 36.

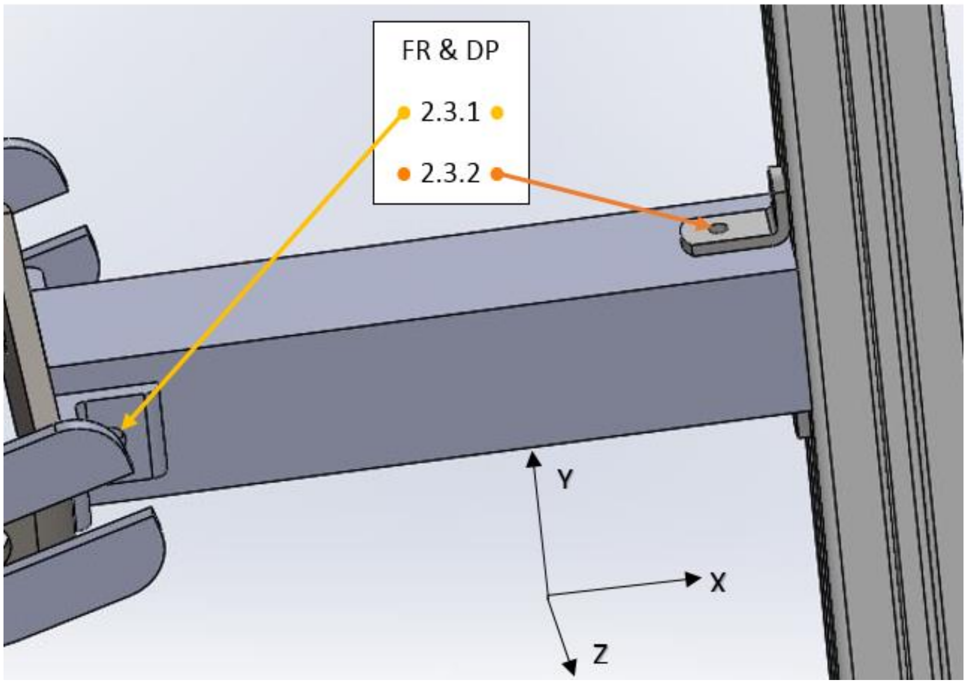


Figure 36.

3.2.3.4 Bamboo Components Fixture Positioning

3.2.3.4.1 Top Tube Fixture Positioning

The top tube bamboo fixture is positioned by a U-bracket that connects to the top T slot extrusion of the jig exo-frame by two T-slot screws that can be loosened to adjust the position. Tightening these screws fixes the position of the crank housing fixture to meet FR2.4.1. The top tube fixture is located by a 1/4 inch bolt through the slots in the vertical components of the U-bracket which can be loosened to adjust the position. tightening the wingnut on the bolt fixes the position of the fixture in the y-direction and meets FR2.4.2. This positioner is shown below in figure 37.

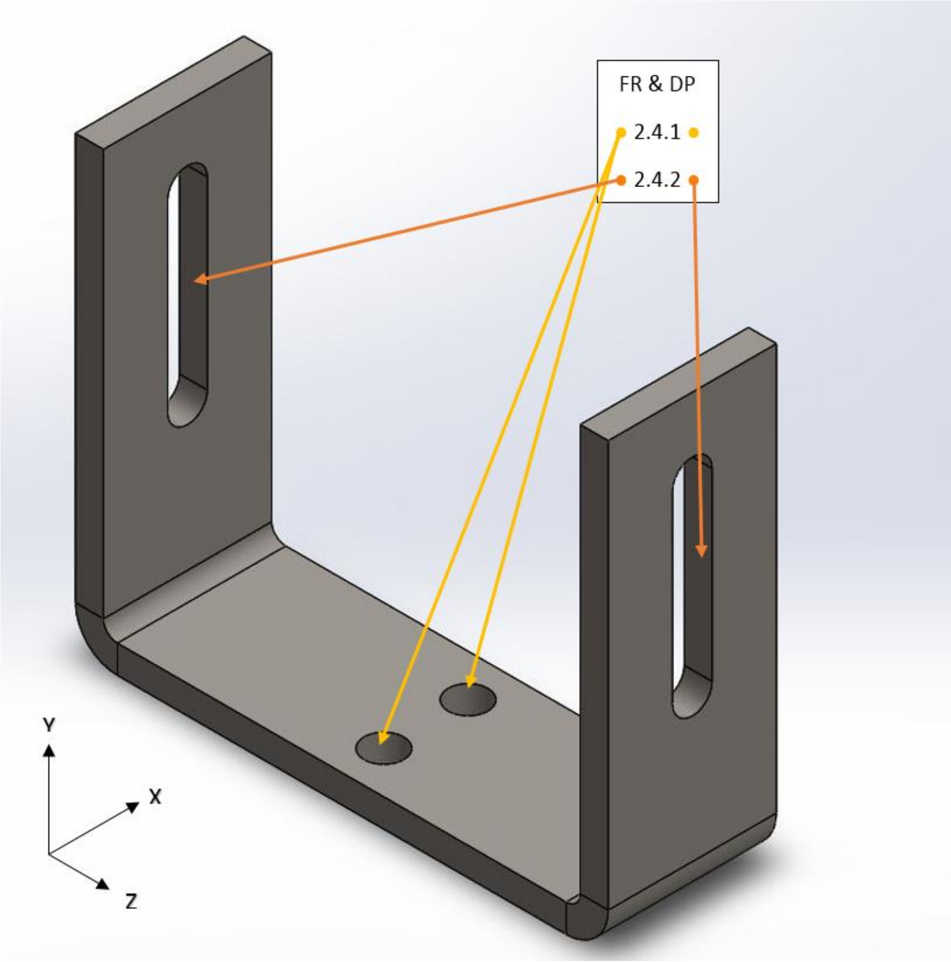


Figure 37.

3.2.3.4.2 Down Tube Fixture Positioning

The down tube fixture is positioned by a telescoping tube support mounted on the bottom T slot extrusion of the jig exo-frame. The telescoping tube is attached to the 8020 frame using two L-brackets and T-slot screws that can be loosened to adjust the position along the x-axis. Tightening these screws fixes the position of the down tube fixture mount and meets FR2.5.1. The vertical position of the down tube fixture is adjustable by loosening the wingnut on a 1/4 inch bolt through the slot in the larger telescoping tube and the hole in the smaller tube. Tightening the wingnut fixes the position in the y-direction and meets FR2.5.2. This positioner is shown below in figure 38.

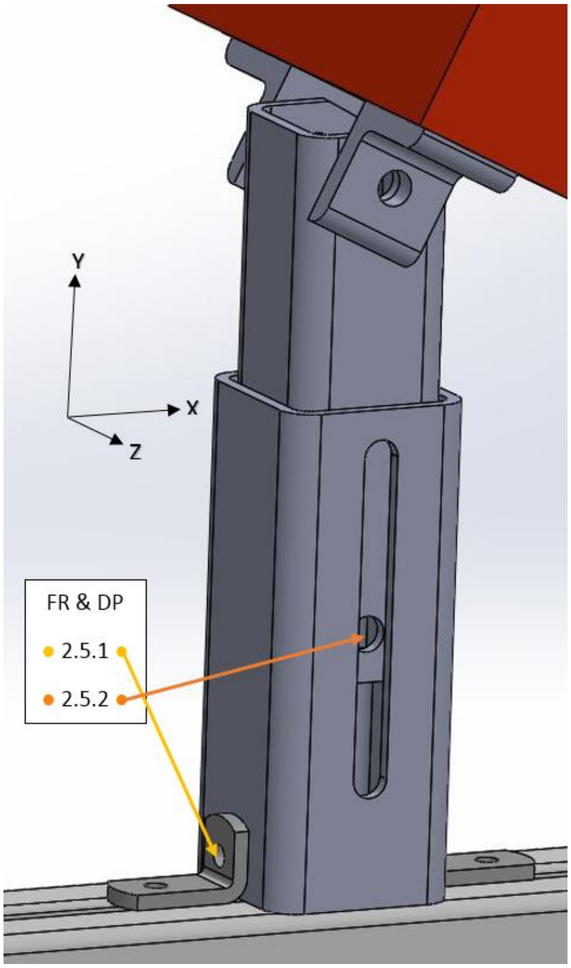


Figure 38.

3.2.3.4.3 Chain Stays Fixture Positioning

The chain stays fixture is positioned by a telescoping tube support mounted on the bottom T slot extrusion of the jig exo-frame. The telescoping tube is attached to the 8020 frame using two L-brackets and T-slot screws that can be loosened to adjust the position along the x-axis. Tightening these screws fixes the position of the down tube fixture mount and meets FR2.6.1. The vertical position of the down tube fixture is adjustable by loosening the wingnut on a 1/4 inch bolt through the slot in the larger telescoping tube and the hole in the smaller tube. Tightening the wingnut fixes the position in the y-direction and meets FR2.6.2. This positioner is shown below in figure 39.

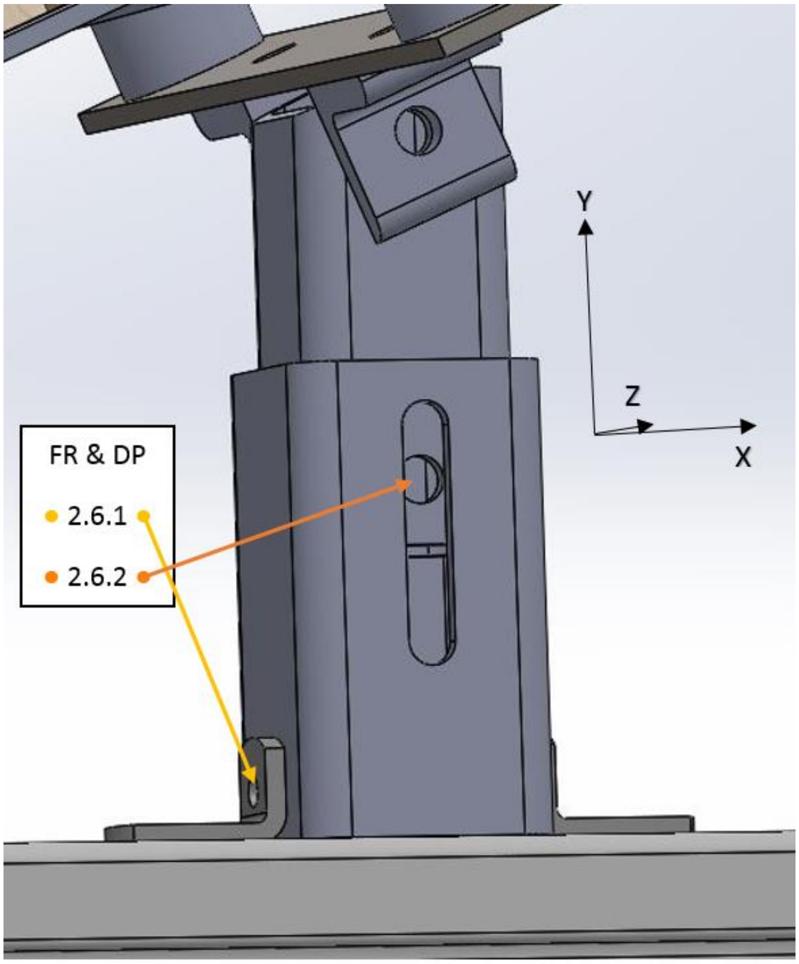


Figure 39.

3.2.3.4.4 Seat Stays Fixture Positioning

The seat stays fixture is positioned by a telescoping tube support mounted on the bottom T slot extrusion of the jig exo-frame. The telescoping tube is attached to the 8020 frame using two L-brackets and T-slot screws that can be loosened to adjust the position along the x-axis. Tightening these screws fixes the position of the down tube fixture mount and meets FR2.7.1. The vertical position of the down tube fixture is adjustable by loosening the wingnut on a 1/4 inch bolt through the slot in the larger telescoping tube and the hole in the smaller tube. Tightening the wingnut fixes the position in the y-direction and meets FR2.7.2. This positioner is shown below in figure 40.

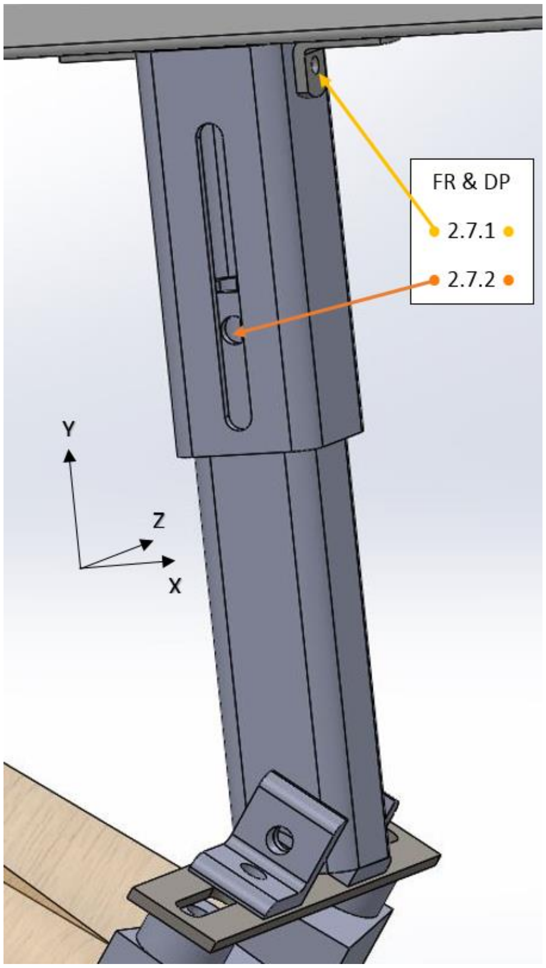


Figure 40.

3.2.4 Level 3 Functional Requirement Integration

The third level functional requirements are to hold the bicycle frame components. This is done by various fixtures for the different parts of the frame.

3.2.4.1 Crank Housing Fixture

The crank housing is held via plugs on either side that are located by a 5/16 inch bolt through the U-frame. FR3.1.1 is met by the Delrin end plugs establishing an interface with the crank housing along its central axis. The vertical components of the crank housing U-frame prevent any displacement of the crank housing along its central axis, fulfilling FR3.1.2. The 5/16 inch bolt through the U-frame and end plugs prevents any displacement perpendicular to the crank housing axis to achieve FR3.1.3. This fixture can be viewed in figure 41 below.

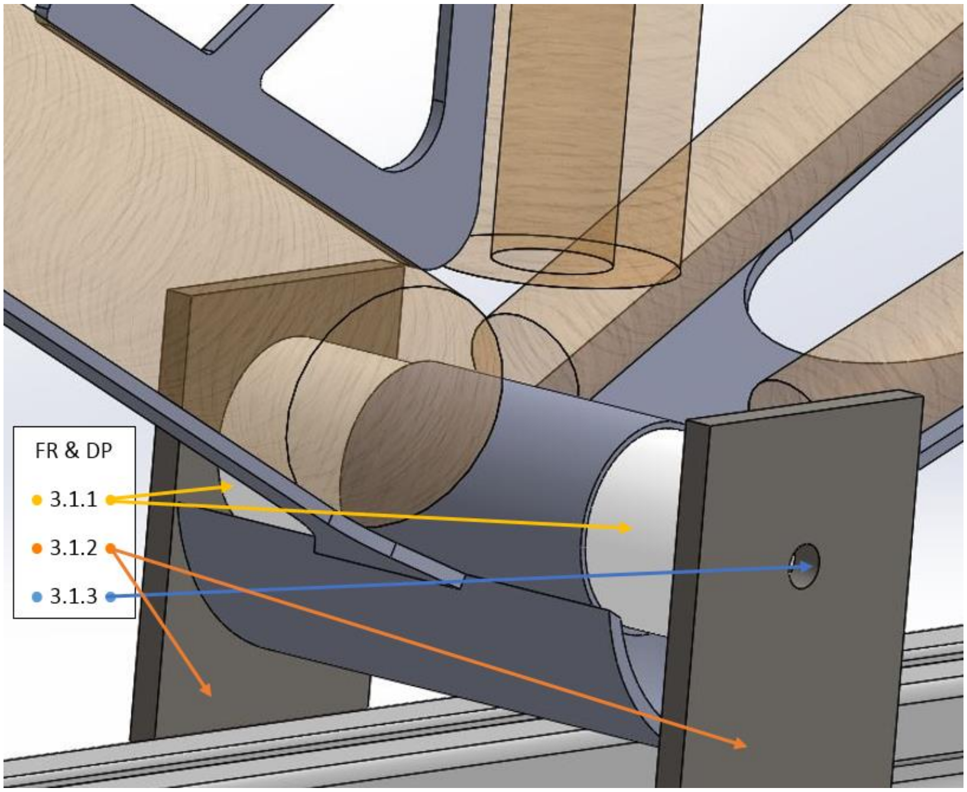


Figure 41.

3.2.4.2 Head Tube Fixture

The head tube is held in place by a threaded stud through plugs at either end and the head tube fixture positioner. FR3.2.1 is that the head tube is the correct angle relative to the jig frame, and is accomplished by the angled surface at the end of the head tube fixture positioner. The Delrin end plugs prevent displacement of the head tube perpendicular to its central axis, achieving FR 3.2.2. The threaded stud provides a clamping force on the head tube and prevents any displacement along the central access to meet FR 3.2.3. This fixture is shown in figure 42.

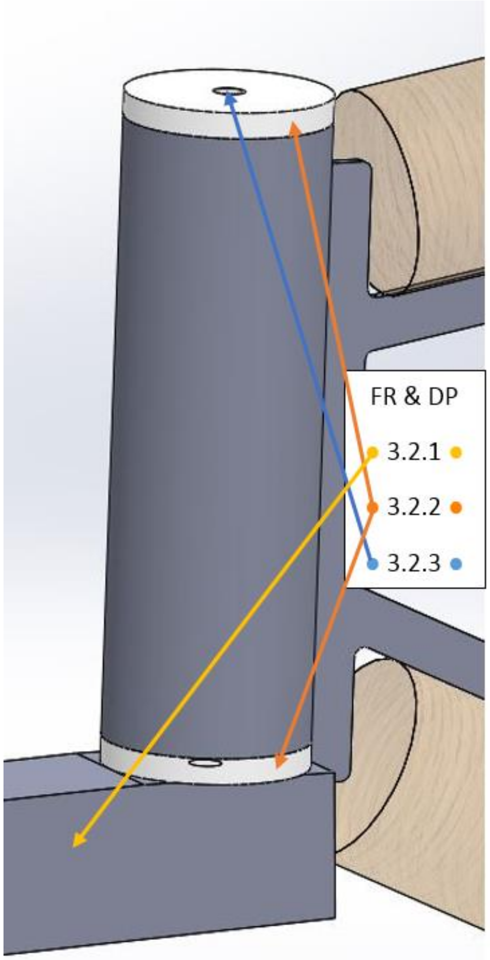


Figure 42.

3.2.4.3 Rear Dropouts Fixture

The rear dropouts are held in place using a quick release skewer located by a U frame spaced to match the dimensions of the rear wheel. The U-frame maintains the correct distance between the dropouts, meeting FR3.3.1. A quick release skewer provides a clamping force on the rear dropouts and prevents displacement, meeting FR3.3.2. This fixture is shown in figure 43 (skewer not shown).

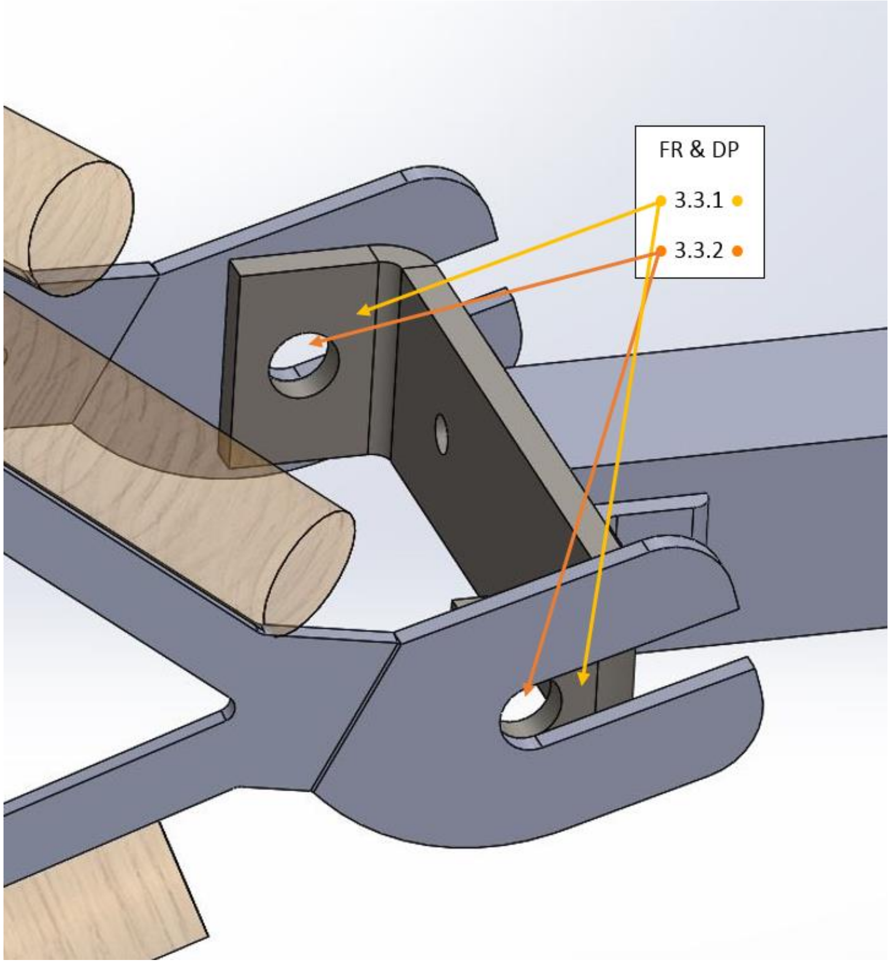


Figure 43.

3.2.4.4 Bamboo Components Fixtures

3.2.4.4.1 Top Tube Fixture

The top tube is aligned by a v-block that is held to a u-bracket by a skewer. Loosening the wingnut allows the v-block to rotate and achieve tangency with the bamboo rod, meeting FR 3.4.2. Displacement of the bamboo rod perpendicular to its central axis is prevented by the v-block clamp to fulfill FR3.4.2. This fixture is below in figure 44.

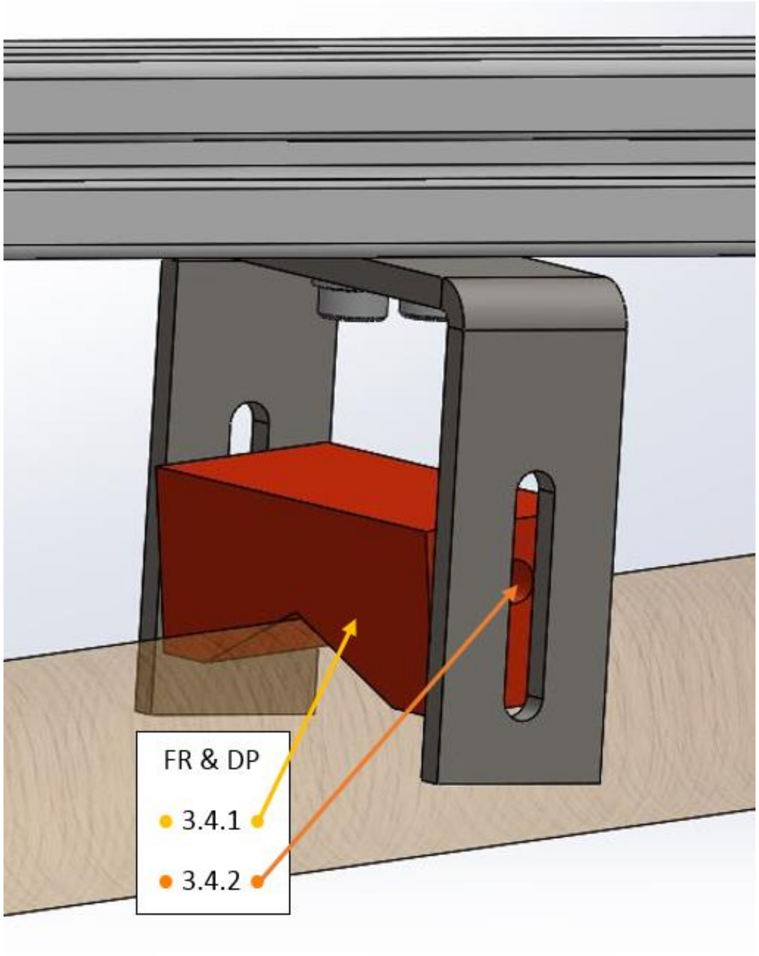


Figure 44.

3.2.4.4.2 Down Tube Fixture

The down tube aligned is aligned by a v-block held by two L-brackets. Loosening the nut holding the L-brackets to the telescoping tube allows the v-block to rotate and achieve tangency with the bamboo rod, meeting FR 3.4.2. Displacement of the bamboo rod perpendicular to its central axis is prevented by the v-block clamp to fulfill FR3.4.1. This fixture is in figure 45 below.

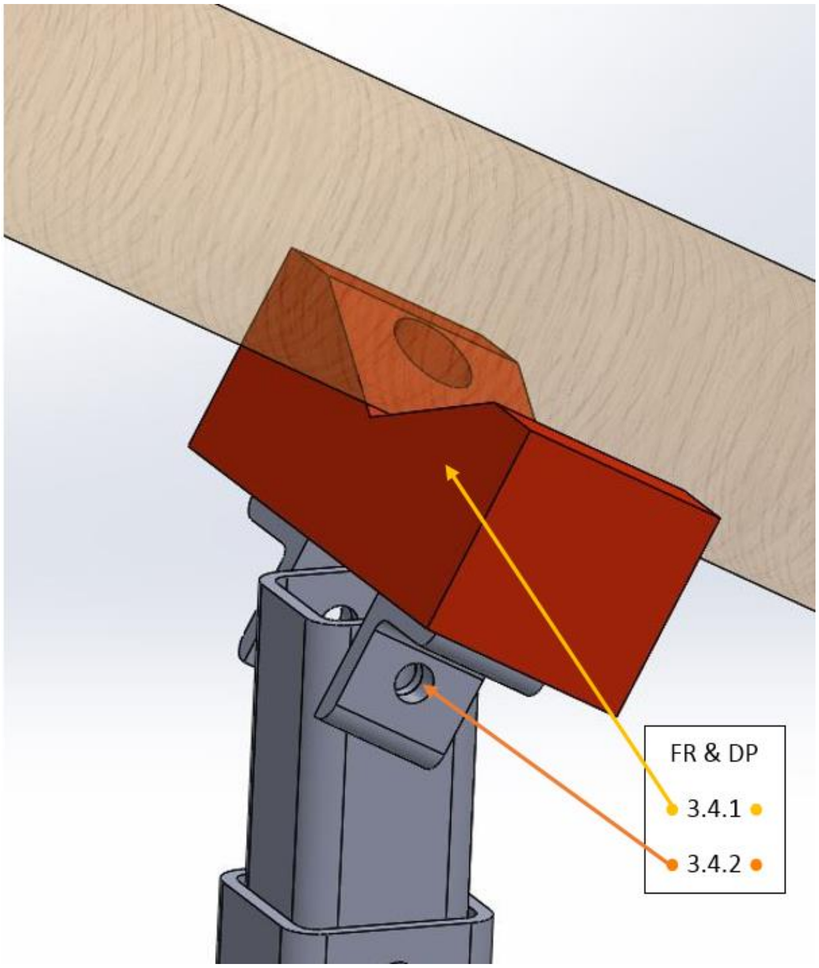


Figure 45.

3.2.4.4.3 Chain Stays Fixture

The chain stays are held in place by two smaller v-blocks pinned in slots to the plate. Displacement of the two bamboo rods perpendicular to their central axis is prevented by the two v-block clamps to fulfill FR3.4.1. The chain stays fixture is able to rotate both from the connecting point with the telescoping tube support and the connection between the fixture mount plate and the v-blocks. These two rotational freedoms permit the v-blocks to maintain tangency with both bamboo rods, fulfilling FR3.4.2. They are shown below in figure 46.

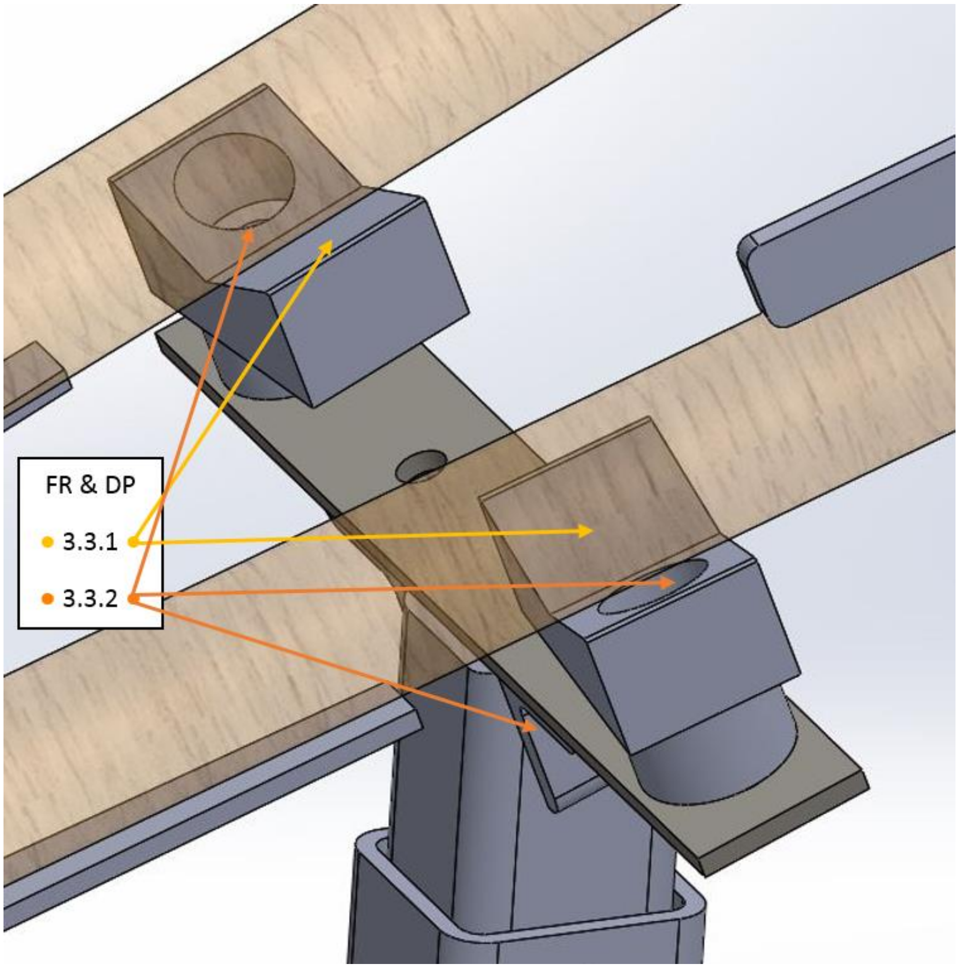


Figure 46.

3.2.4.4.4 Seat Stays Fixture

The seat stays are held in place by two smaller v-blocks pinned in slots to the plate. Displacement of the two bamboo rods perpendicular to their central axis is prevented by the two v-block clamps to fulfill FR3.4.1. The seat stays fixture is able to rotate both from the connecting point with the telescoping tube support and the connection between the fixture mount plate and the v-blocks. These two rotational freedoms permit the v-blocks to maintain tangency with both bamboo rods, fulfilling FR3.4.2. They are shown below in figure 47.

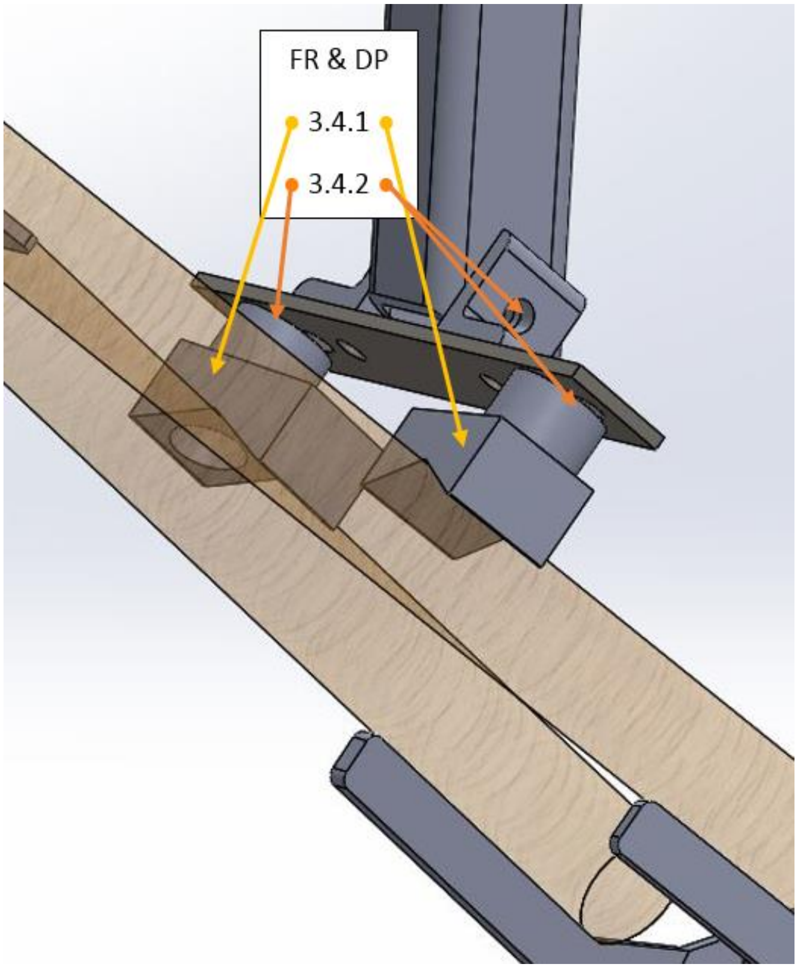


Figure 47.

4. Design Iteration

Throughout the design process, several iterations of the joints and manufacturing fixture were imagined. The designs evolved to minimize the manufacturing time and number of components, minimize cost, and simplify in-house prototype manufacturing. This included simplifying joint structures from multi-element milled assemblies to flat-plate gussets and assemblies, and opting for a simple, single v-block bamboo centering system in the prototype jig fixture, rather than spring-loaded clamping systems. These simplified elements are capable of serving the same functions as their multi-component counterparts, thereby minimizing information content when possible and adhering to Axiom 2. Some design iterations were modeled in SolidWorks and are shown in the following sections.

4.1 Joint Design Iteration

The design of the system of joints underwent an evolution from milled, multi-component joints, into relatively simple flat components that could either be directly incorporated into the bicycle frame, or modified by either being bent or welded to other components before incorporation, shown in figure 48 below. Each joint was designed with two functional requirements in mind, which were transmitting loads between bamboo frame members, and transmitting loads between the joint itself and the external components such as the wheels and front fork (See Section 2.1.1).

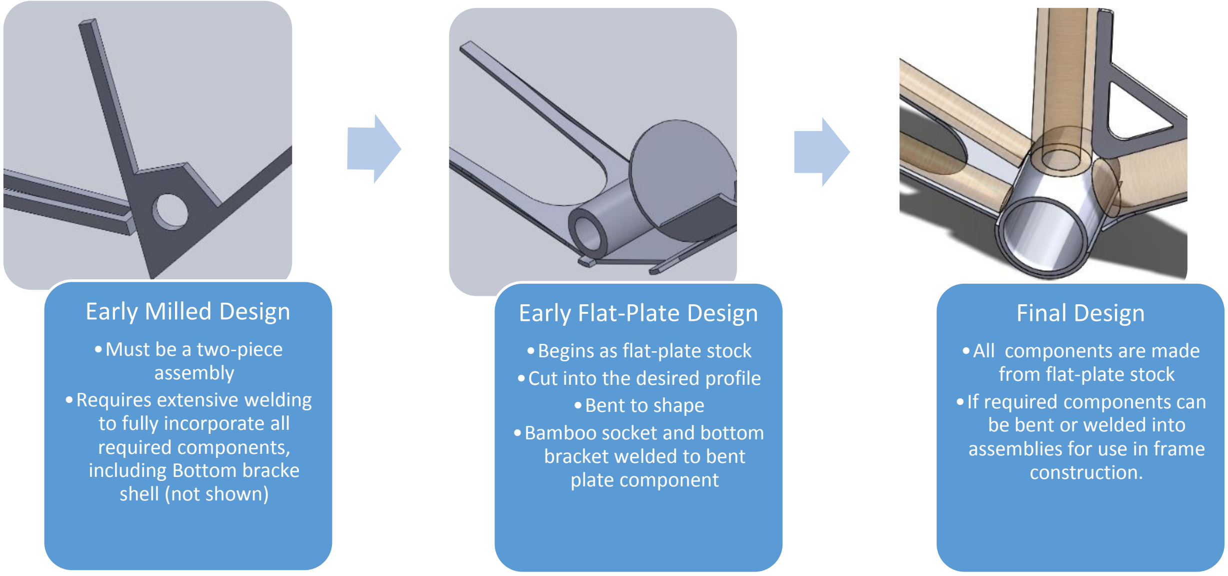


Figure 48. Evolution of the Bottom Bracket Joint

The initial designs used milled components to transmit loads between bamboo members and between the frame and purchased components. This would provide bracing against motion in all directions, both axially and torsionally. The system was similar to the 2012 project design where two halves of a mold were attached to the bamboo frame members and injected with a resin. To improve upon the 2012 system, a stronger composite such as fiberglass, or a metal would be used to form the mold halves, instead of PETG. The complexity of this system, however, did not align with the axiomatic design decomposition.

The gussets and joint components were designed to be attached with a vacuum-formed, heat curing fiberglass composite. This design was eliminated due to the need for complex bends in the joints and the difficulty of creating a vacuum seal in order to form the fiberglass around the metal gussets. In addition to these complications, it was not possible using facilities at WPI to heat the entire frame to the temperature required to cure the composite resin. A large oven or autoclave would be required to enclose the entire bicycle frame during curing. Bamboo rods would also start to lose strength if they were heated to the necessary temperature for the designated amount of time as they would dry and potentially split. The final design utilizes a pre-impregnated composite wrap, called SynthoGlass, that uses a water activated urethane resin and cures within 30 minutes. By using a pre-impregnated composite, we could accomplish optimal and consistent resin-to-fiber ratios, and also minimize curing time for construction of our frame system.

Another joint design change was to accommodate different and less expensive types of prefabricated bicycle components based on meeting our design constraints regarding cost and simple part sourcing, as well as adaptability. An example of this is the early design iterations for the bottom bracket joint. They were designed for use with a press-fit bottom bracket, which is slightly easier to accommodate in the joint design, but is significantly more expensive and difficult to source than its widely available threaded counterpart.

4.2 Jig Design Iteration

Over the course of the project, the team made several changes to the design of the bicycle frame jig to increase the adjustability of the frame and to make it easier to manufacture. In the first iteration, the exo-frame was made of straight bar stock aluminum providing the mounting points for the fixtures in order to meet FR1 of the Jig decomposition. This is shown below in figure 49a. Later iterations use aluminum 8020 extrusions, which allow the fixtures to be mounted without machining and be easily repositioned via the t-slot fasteners. The final exo-frame is shown in figure 49b.

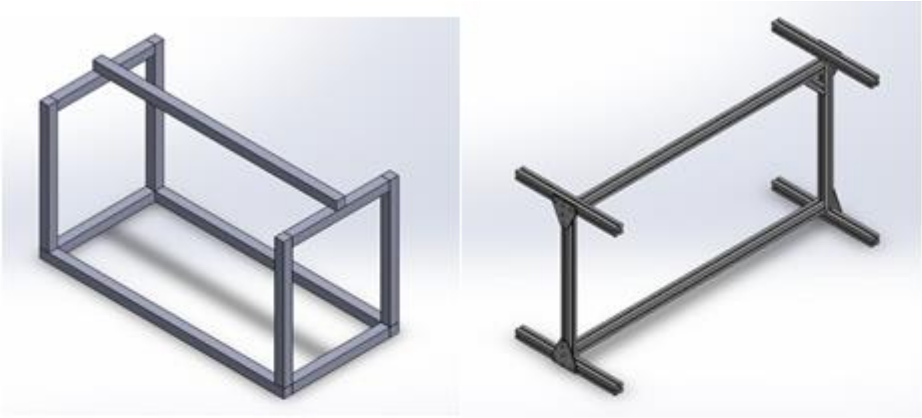


Figure 49. a) Jig made from straight bar stock aluminum b) Jig made from aluminum 8020 extrusions

The team also experimented with several different exo-frame configurations. Originally the team created a box-like design with bars for placing each of the fixtures in the z-direction called for by FR1.3. This design is below in figure 50a. Later iterations use a planar exo-frame with supports to meet the design constraints of minimizing material and reducing interference of the frame during bicycle manufacturing. The four support bars maintain the ability to orient the jig in multiple positions during bicycle manufacturing. These changes are shown in figure 50b.

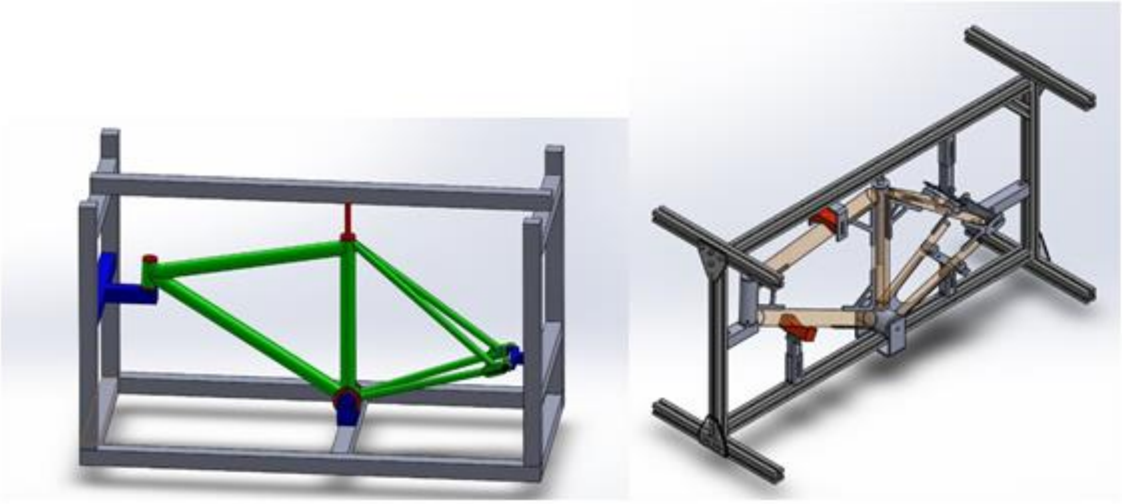


Figure 50. a) Box-style Jig b)Planar exo-frame Jig

The team originally designed the fixtures that held the bamboo pieces as self-centering clamps, in order to meet the jig FR3.4, with two v-blocks in a u-bracket, pushed together by springs. This is visible in figure 51a. However, in order to reduce manufacturing time, the design was modified to single v-block fixtures, shown in figure 51b. This still enables the fixtures to center bamboo pieces of varying geometry and shape. The down tube, chain stays, and seat stays fixtures are mounted on telescoping tubing, allowing the jig to be adjusted based on frame geometry. The v-blocks for the rear stay fixtures are mounted in channels machined in the flat plate, allowing the v-block positions to be individually adjustable. This design is simple to manufacture and is highly modular.

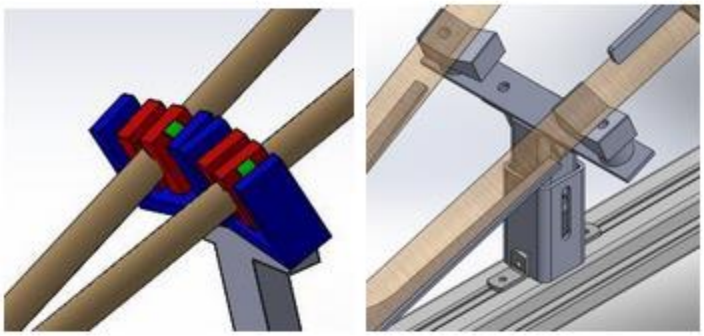


Figure 51. a) Self-Centering Clamps b) Single V-Block Fixtures

Early iterations of the top tube fixture were mounted on a telescoping tube similar to the other bamboo fixtures. After design changes to the seat post, there was no longer room to put telescoping tubing between the exo-frame and the v-block that positions the top tube. In order to compensate the team changed the design to use a u-bracket with slots to hold the v-block. The slots maintained the height adjustability and added the ability to rotate the v-block without additional components to meet FR3.4. The initial and final design iterations are shown in figure 52a and b.

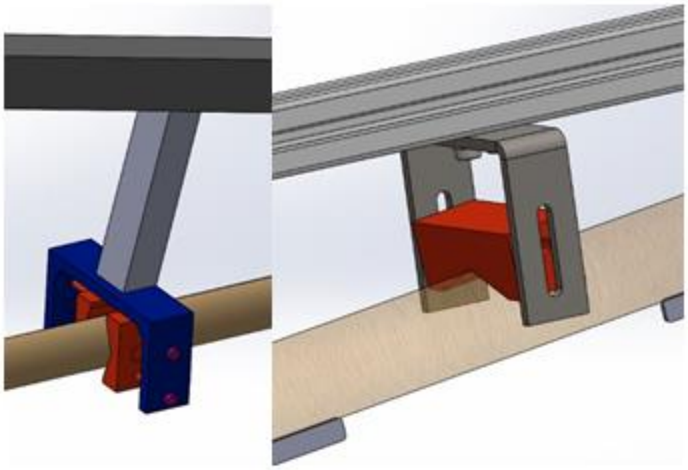


Figure 52. a)Self-Centering Clamps b)Single V-Block Fixtures

The plugs designed to hold the different head tube, crank housing and seat tube of the bicycle frame were modified during manufacturing. The diameters of the head tube and crank housing plugs were altered to meet the tolerances of their respective joints. Additionally, the team determined the FR of holding the seat tube was not necessary for the jig because this was met by the joints themselves. Once this FR was removed from the decomposition, the seat tube plug (DP) was removed from the final design. The jig design with and without the seat tube plug are shown in figures 53a and b below.

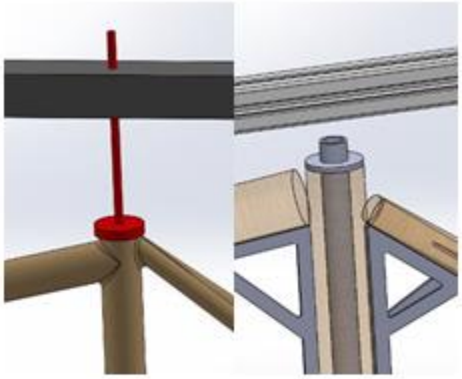


Figure 53. a)Jig with seat tube plug b)Jig without seat tube plug

5. Prototype production

In order to construct a prototype manufacturing fixture and bicycle, the SolidWorks designs featured in the previous section were manufactured by several companies and assembled in Washburn Shops. Stock bicycle components, such as the wheels, headset, front fork, and pedals were ordered from various suppliers. Some aluminum and steel components for the joints and jig were laser cut by New England Wire Products and turned by the Goldenrod Corporation. All other manufactured components were made in either Higgins Laboratories or Washburn Shops. The manufacturing fixture was assembled and used to construct the bicycle frame. After frame construction, Barney's Bicycle, a local bicycle shop, assisted in the assembly process. All final components were added to the bicycle on campus.

5.1 Joints

Prototype production involved the manufacturing of all gussets and frame joints, the manufacture of the frame itself utilizing these joints, and the incorporation of purchased components in order to build the frame into a full bicycle. We did not use a separate axiomatic design decomposition to guide the manufacturing process of our prototype. We operated under the presumption that our decomposition regarding the design of our joints was sufficient in guiding our decisions regarding methods of joint construction in order to effectively transmit loads between frame members and between the frame and other attached components. Any discussion regarding observations and recommendations for future builds will be discussed in Section 8.1.

5.1.1 Gussets and Frame Member Joints

Before the frame could be assembled, the gussets had to be manufactured. The SolidWorks designs of flat-plate gussets and other bent components were sent to New England Wire Products, a manufacturing company located in Fitchburg, MA, to be laser cut out of 1/8 inch steel plate. This involved creating drawings of each individual gusset or flat-plate component required for assembly of our frame. These drawings were then used to guide the CNC laser cutter at New England Wire Products in order to produce all of our flat-plate componentry.

One of our other manufactured components, the head tube, was turned from a steel tube on a lathe at WPI's Higgins Laboratories. The head tube had two bearing fits cut in order to meet the necessary specifications for headset integration. (The headset is the bearing set that supports the front fork in the head tube.) Using specifications from Cane Creek (the manufacturer of our chosen headset), we were able to turn bearing fits into our head tube in order to properly integrate the headset that we purchased. The head tube was then welded to the front gusset in order to complete the front joint of our system.

The bottom bracket joint was also created in house by welding laser-cut, flat-plate components to a section of steel pipe. A welding jig was designed and constructed to facilitate the fixturing of these components while they were welded together The jig itself was constructed out of plywood and was used to hold the components in place during welding and is shown in figure 54 below.

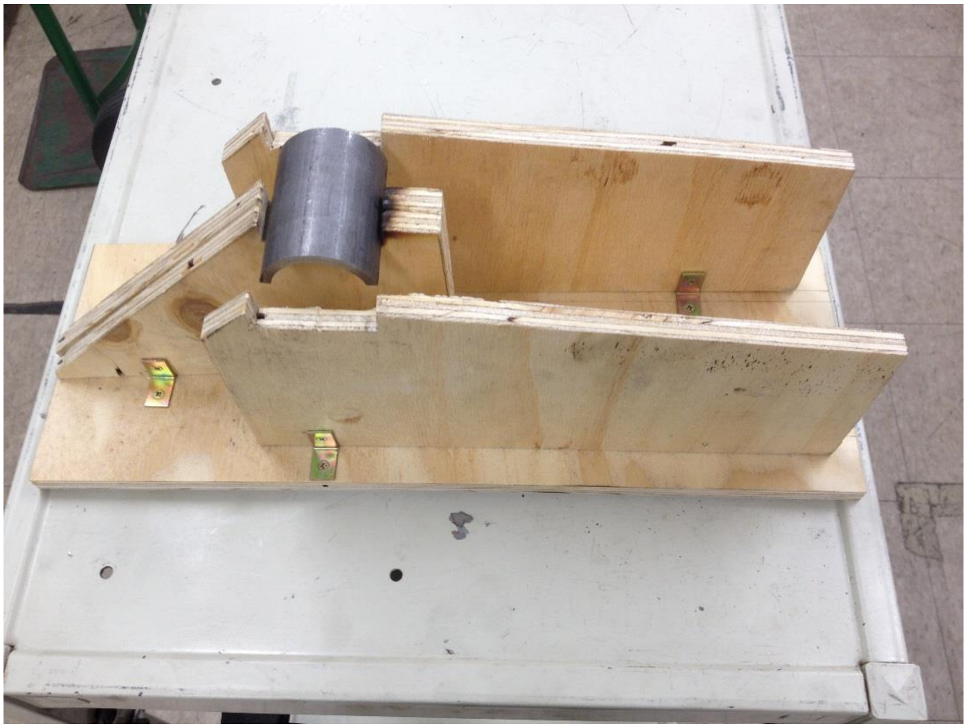


Figure 54.Bottom Bracket Welding Jig

The bottom bracket joint was then constructed by welding two flat-plates pieces to a half-section of steel pipe. During manufacturing, a modification was made to this joint, making a cut in-house to provide clearance for the crank arm and drive sprocket.

The final manufactured component, the seat post receiver, was turned out of aluminum by the Goldenrod Corporation in Beacon Falls, Connecticut. Technical drawings were made from our SolidWorks model of the component in order to facilitate the manufacture of this component, and were sent to the engineering department at the Goldenrod Corporation for production. Upon receiving the part, a small slot was cut into the top of the component to facilitate clamping of the seat post for the purpose of seat height adjustment on the bicycle.

5.1.2 Frame Production

Bamboo rods, cut to the required length, were held by the manufacturing fixture. The fixture centered the bamboo rods to maintain the designated frame geometry and frame member alignment (see section 5.2 for more information). The joint components of the frame were put in place by hand, and cable ties were used as temporary fasteners to hold the frame members and gussets together.

Figure 55.Assembly of the bicycle frame

Once the frame and components were held together and in place, the pre-impregnated wrap was used to permanently fix the joints to the bamboo frame members. SynthoGlass, the selected wrap, is a water-curing fiberglass composite with a urethane resin matrix. When the wrap is exposed to water it is activated, giving a five minute working time. Due to the short working time, the joints had to be wrapped one at a time.

As the joints were wrapped, the cable ties were removed to ensure that the wrap was flush against the bamboo and gusset. This increased the integrity of the connection between the gussets and the bamboo and improved the aesthetics of the bicycle. To further improve bonding, a compression wrap was applied over the pre-impregnated wrap. The resin cured fully in 30 minutes. The frame was left to rest in the jig overnight as a precaution to ensure proper curing before it was removed from the fixture.

During frame construction, a small gusset between the two seat stays was omitted from the frame. The reason for doing so was a design flaw that did not allow the team to properly wrap and integrate the gusset into the frame structure.

5.1.3 External Component Interfaces

The completed frame was taken to Barney's Bicycle in Worcester in order for the headset, front fork, and stem to be professionally installed. The headset was pressed into the head tube using special tooling, and the front fork's steering tube was cut to the proper length using specialized equipment, and spacers and our purchased stem were added to complete the front fork assembly. The remaining components were installed on the bicycle using hand tools on campus. These components are listed in the table below, along with where they were sourced from and where they were installed. Coaster brakes, also known as "pedal brakes", were chosen over hand brakes for this bicycle in order to comply with Axiom 2 and minimize information content; Hand-operated brakes would require mounting bosses that would add to the complexity of our design.

Table 2. Prefabricated Parts Sources

Part	Source	Place of Installation
Seat	Bike Nashbar	WPI
Seat post	Bike Nashbar	WPI

Seat Clamp	Bike Nashbar	WPI
Crank Set	Bike Nashbar	WPI
Bottom Bracket	Bike Nashbar	WPI
Chain	Bike Nashbar	WPI
Wheel Set	Coasties	WPI
Front Fork	Bike Nashbar	Barney's Bicycle
Stem	Bike Nashbar	Barney's Bicycle
Headset	Performance Bike	Barney's Bicycle
Handlebars	Performance Bike	WPI
Handlebar Grips	Bike Nashbar	WPI
Tires	Bike Nashbar	WPI
Tubes	Bike Nashbar	WPI
Pedals	Bike Nashbar	WPI

5.2 Jig Production

Prototype production consisted of manufacturing fixtures and supports to be used with the exo-frame to complete the jig. Axiomatic Design was not used for designing the process of assembling the jig, as the fixtures designed using AD were not coupled and could be assembled and installed concurrently.

5.2.1 Frame Skeleton

The 8020 Aluminum frame components were ordered from Air Inc., a fluid power distributor located in Franklin, MA. The aluminum extrusions came cut to specified lengths and machined for the specialty anchor fasteners, also ordered from Air Inc. The various components of the jig frame skeleton were assembled using only a hex key.

5.2.2 Telescoping Supports

The down tube, chain stays, and seat stays fixtures are located far enough inward from the jig frame skeleton that they warranted individual support features. Sections of 1.5 and 1.25 inch square aluminum telescoping tubing were ordered from Alcobra Metals, Inc., a machining supply company located in Spokane, WA. The sections were cut to the specified lengths, and then holes and slots were drilled and milled into the material. The 1.5 inch sections were attached to the jig frame skeleton using L-brackets and 1/4 inch nuts and bolts. The 1.25 inch sections were slotted into the 1.5 inch sections and fastened using 1/4 inch bolts and wingnuts.

5.2.3 Fixture Mounts

The following sections discuss the mounting systems for the fixture mounts on the jig. This includes telescoping supports and u-brackets.

5.2.3.1 Crank Housing Fixture Mount

The crank housing fixture mount was produced by New England Wire Products, a manufacturing company located in Weston, MA. The part was laser cut out of mild steel and bent to our specifications. The crank housing fixture mount is attached to the jig frame skeleton using t-slot fasteners that are tightened by a hex key.

5.2.3.2 Head Tube Fixture Mount

The head tube fixture mount was machined in house out of 1.5in aluminum bar stock. It was attached to the jig frame skeleton using L-brackets and a number 10 bolt and nut.

5.2.3.3 Rear Dropouts Fixture Mount

The rear dropouts fixture mount was machined in house out of the same 1.5 inch square aluminum tube stock as the bottom section of the telescoping supports. It was attached to the jig frame skeleton using L-brackets and t-slot fasteners, and tightened using a hex key

5.2.3.4 Top Tube Fixture Mount

The top tube fixture mount was produced by New England Wire Products, where it was laser cut out of mild steel and bent to our specifications. the top tube fixture mount is attached to the jig frame skeleton using t-slot fasteners that are tightened by a hex key.

5.2.3.5 Chain Stays V-block Mounting Plate

The chain stays v-block mounting plate was laser cut by New England Wire Products from 1/8 inch flat steel plate and attached to the chain stays telescoping support using L-brackets and 1/4 inch fasteners.

5.2.3.6 Seat Stays Fixture Mounting Plate

The seat stays v-block mounting plate was laser cut by New England Wire Products from 1/8 inch flat steel plate and attached to the seat stays telescoping support using L-brackets and 1/4 inch fasteners.

5.2.4 Fixtures

The following sections discuss the fixtures on the jig used to hold components of the bicycle frame, including bamboo frame members and joints, during prototype manufacturing.

5.2.4.1 Crank Housing Fixture

The crank housing end plugs were machined in house from Delrin acetal homopolymer, and are located by a 5/16 inch bolt purchased from the Home Depot that interfaces with the crank housing fixture mount.

5.2.4.2 Head Tube Fixture

The head tube end plugs were machined in house from Delrin acetal homopolymer, and are located by a 1/4 inch bolt purchased from the Home Depot that interfaces with the crank housing fixture mount.

5.2.4.3 Rear Dropouts Fixture

The rear dropout alignment fork was produced by New England Wire Products, where it was laser cut out of mild steel and bent to our specifications. The alignment fork was attached to the rear dropout fixture mount using L-brackets and 1/4 inch fasteners. The alignment fork locates a quick release skewer, purchased from Bike Nashbar, that clamps the rear dropouts into place.

5.2.4.4 Top Tube Fixture

The top tube V-block was produced using additive manufacturing out of ABS plastic in house using a 3D printer owned by Michael Sweeney. The hole through the sides was drilled and tapped to interface with the top tube fixture mount using a 5/16 inch bolt and located centrally by washers.

5.2.4.5 Down Tube Fixture

The down tube V-block was produced using additive manufacturing out of ABS plastic in house using a 3D printer owned by Michael Sweeney. The V-block was attached to the down tube telescoping support using L-brackets and 1/4 inch fasteners.

5.2.4.6 Chain Stays Fixture

The chain stays V-blocks were produced using additive manufacturing out of ABS plastic in house using a 3D printer owned by Michael Sweeney. The V-blocks were attached to the chain stays v-block mounting plate using 1/4 inch fasteners.

5.2.4.7 Seat Stays Fixture

The seat stays V-blocks were produced using additive manufacturing out of ABS plastic in house using a 3D printer owned by Michael Sweeney. The V-blocks were attached to the seat stays v-block mounting plate using 1/4 inch fasteners.

6. Testing

The testing plans and procedures for both the bamboo rods and the full bicycle frame are outlined in this section. Data from the completed tests and data analysis can be found in the following section.

6.1 Bamboo Testing

One of the main objectives of the Safety and Testing Team was to discover the type of bamboo best suited for a bicycle frame. Based off previous projects, two types of bamboo were purchased for testing. The first was Tonkin, which had been chosen in previous years. The other was Carbonized bamboo that was researched by the team and had not previously been tested. The objective of the testing was to find a bamboo that performed better than Tonkin. These tests were completed in WPI's Civil Engineering Lab. The following tables show the dimensions of the bamboo rods used in each test. The dimensions were used to calibrate the static loading compression machine that was used to complete the tests and to calculate the stress acting on bamboo rods during testing.

Table 3. Cracked Bamboo Dimensions

Cracked Bamboo Dimensions					
Bamboo	Length (in)	Wall Thickness (in)	Diameter (in)	Node Diameter 1 (in)	Node Diameter 2 (in)
Tonkin 1" ***3-Point***	12	0.124	1.05	1.66	
Tonkin 1" ***4-Point***	12	0.114	0.871	0.959	
Carbonized 1" ***3-Point***	12	0.451	0.797	0.916	0.877
Carbonized 1" ***4-Point***	12	0.1067	0.844	0.948	0.967
Carbonized 2" ***3-Point***	12	0.239	2.01	2.152	
Carbonized 2" ***4-Point***	12	0.218	1.976	2.184	2.19
Tonkin 2" ***3-Point***	12	0.186	1.99	2.152	
Tonkin 2" ***4-Point***	12	0.183	2.02	2.29	

Table 3shows the dimensions of the cracked bamboo rods used in the three and four point bend tests. The data shows the natural variation in wall thickness, diameter, and node diameter.

Table 4. Non-Cracked Bamboo Dimensions

Non-Cracked Bamboo Dimensions					

Bamboo	Length (in)	Wall Thickness (in)	Diameter (in)	Node Diameter 1 (in)	Node Diameter 2 (in)
Tonkin 1" ***3-Point***	12	0.112	0.787	0.961	
Tonkin 1" ***4-Point***	12	0.115	0.714	0.967	
Carbonized 1" ***3-Point***	12	0.126	0.75	0.849	0.876
Carbonized 1" ***4-Point***	12	0.118	0.719	0.875	
Carbonized 2" ***3-Point***	12	0.264	1.931		
Carbonized 2" ***4-Point***	12	0.203	1.94	2.116	
Tonkin 2" ***3-Point***	12	0.183	1.63	1.828	
Tonkin 2" ***4-Point***	12	0.19	1.76	1.972	1.802

Table 4 shows the dimensions of the good condition bamboo rods used in the three and four point bend tests.

Table 5. Non-Cracked Bamboo Dimensions for Compression Testing

Non-Cracked Bamboo Dimensions					
Bamboo	Length (in)	Wall Thickness (in)	Diameter (in)	Node Diameter 1 (in)	Node Diameter 2 (in)
Tonkin 1" ***Compression***	6	0.194	0.97	1.112	
Carbonized 1" ***Compression***	6	0.173	0.867	0.96	
Carbonized 2" ***Compression***	6	0.17	1.91	1.984	
Tonkin 2" ***Compression***	6	0.165	1.59	1.78	

Table 5shows the dimensions of the good condition bamboo rods used in the compression test.

6.1.1 Three point bend test overview

The three point bend test was performed to evaluate the strength of the bamboo. To complete this test, a static loading compression machine was used. A 12" piece of bamboo was placed on top of two half cylinders with the load centered above the sample. These cylinders acted as the outer two points, with the press at the center of the bamboo acting as the third. Figure 56 below shows the location of the three points during the test.

Figure 56.

The press was lowered down to the center of the bamboo and aligned properly. The machine gradually increased the downward force on the bamboo at a steady rate until the bamboo reached the point of fracture. This test was performed on both types of bamboo, Tonkin and Carbonized, with 1 and 2 inch diameters to obtain the most accurate and complete results possible.

Figure 57 shows the different cross sections of the different types of bamboo tested. The test was also performed on bamboo that had cracked during shipping. This allowed the team to determine any differences in the load tolerance of the cracked bamboo and whether it would be suitable for frame construction.

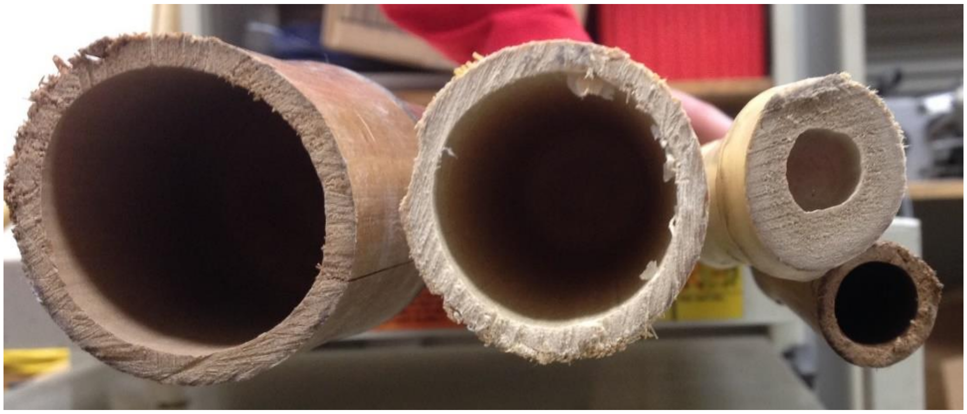


Figure 57.

6.1.1.1 Procedure

The team followed a precise procedure to maintain consistent results for the different types of bamboo that were tested. All the samples were cut to the same length and had similar nodal placement. Since the node is responsible for most of the structural integrity, the node was placed off-center so the load would not be located at the weakest point of the sample.

The specific length and average diameter were entered into the machine to keep the numerous tests organized. Otherwise, it would have been impossible to keep track of the separate test results. The piece was placed within the machine in its proper orientation with the compressive force located on the center. The force increased until the sample reached its point of fracture. The sample was then removed from the machine once the force was reduced.

6.1.1.2 Discussion

As previously mentioned, one critical issue that was encountered was the state of the bamboo. Due to the imperfections and numerous cracks, the team decided to test both the cracked and non-cracked bamboo. These tests would show the impact of small surface cracks on structural integrity of the rod. Figure 58 below shows the variety of surface cracks on bamboo rods.

Figure 58.

This data was also important because it shows the long-term integrity of the bamboo frame. The surface cracks could have been caused by changes in temperature and humidity during shipping. The company the bamboo was purchased from has a disclaimer on their website that mentions the possibility of cracking during shipping due to weather conditions. These factors would also affect bicycles that become weathered with exposure to sun, wind, rain, and seasonal changes. The tests show the behavior of the bamboo after it weakened with exposure to weathering (Sunset Bamboo 2014). The defects and imperfections in the rods were important because it is very possible for them to be present in a completed bicycle frame. When testing the non-cracked bamboo, the team placed the sample so that any imperfections would not be located directly next to the three points of contact to maintain consistent results. For cracked bamboo, the rod was not oriented in a specific manner due to the numerous cracks present on the rod.

Due to the way bamboo is grown and processed, it was nearly impossible to find a piece that would have a consistent diameter throughout the rod. The differences in diameter were also altered by the location of the node. The node in some instances caused the diameter to be almost 0.2 inches bigger than other surrounding diameters. All bamboo lengths were cut to produce a sample that would have one node off-center so the data from different samples could be directly compared. The dimensions of all the samples used during testing are located above in section 6.1.

6.1.2 Four Point bend Test Overview

The four point bend test was completed to evaluate the bamboo's strength with another point of contact along the sample. The static loading compression machine was used for this test. A 12" piece of bamboo was placed on top of two half cylinders with the load centered above the sample. A system of metal bars to was developed to provide an additional point of contact and create proper load placement. The system included two identical bars placed perpendicularly to the bamboo that acted as points of contact. An additional bar was placed on top of these, parallel to the bamboo rod and perpendicular to the two metal bars. It distributed the load evenly between the two points of contact on the bamboo. The bars were placed on the sample 3 inches from both ends. This can be seen below in figure 59.

The press was lowered down to the center of the bamboo and aligned properly. The machine gradually increased the downward force on the bamboo at a steady rate until the bamboo reached the point of fracture. This test was performed on both types of bamboo, Tonkin and Carbonized, with 1 and 2 inch diameters to obtain the most accurate and complete results possible.The four point bend test was done in addition to the three point test to provide a more accurate evaluation of the bamboo. Like the three point test, the four point test was also performed on bamboo that had cracked during shipping.

Figure 59.

6.1.2.1 Procedure

The four point test followed a similar procedure to section 6.1.1.3 in order to maintain consistent results for all types of bamboo. All the samples were cut to the same length and had similar nodal placement. Again, the node was placed off-center in the compression machine. Two team members fitted the system of metal bars above the bamboo, and the press was properly aligned.

The load was applied on the center of the top bar and was evenly dispersed to the points of contact on the sample. The force increased until the sample reached its point of fracture. The sample and metal bar system were removed from the machine once the force was reduced.

6.1.2.1 Discussion

When creating the metal bar system in order to perform the test, several design challenges were encountered. The bamboo would begin to slip in the compression machine when the bamboo and metal bars were being aligned. This caused the bamboo to roll, which relocated the imperfections in the rod. In order to keep the data consistent, the team had to develop a way to maintain the bamboo's orientation within the machine. Steel spacers were used on either side of the bamboo rod to fix it in place. The spacers are visible above in Figure 59.

On top of the bamboo, two metal bars were placed perpendicular to the sample at the measured distances of 3 inches and 9 inches. Above the perpendicular bars was another bar, placed parallel to the sample to disperse the load equally to both locations. This effectively maintained the position of the bamboo throughout the test.

Nodal placement for the four point test was more complex than the three point test. The force concentrations were located at two points of contact during the test and the weak point remained at the center of the rod. To maintain consistent testing procedures between the three point and four point tests, nodes could not be placed directly under the points of contact or in the center of the rod. Nodes also could not be placed at the end of the sample, because of the great reduction in structural integrity. As a result, the node was positioned between the center and one point of contact from the cylinder underneath. This is highlighted in figure 60 below.

Figure 60.

6.1.3 Compression Test Overview

The compression test was performed to determine the vertical load the bamboo could endure. This test was also performed using the static loading compression machine. A piece of bamboo was placed vertically on the platform of the machine. The press was located above the piece of bamboo and was fitted with a flat surface.

The press was then lowered, aligned, and gradually increased at a constant rate until the bamboo either splintered, fractured or was crushed. The compression test was administered on both types of bamboo, Tonkin and Carbonized, with both 1 and 2 inch diameters. Each sample was cut to a length three times its diameter, per instruction of the lab advisor. The results provided the stress acting on the bamboo and the maximum load the sample could tolerate.

Unlike the previous tests, compression testing was not completed for the cracked bamboo. The cracked bamboo was inconsistent due to the varying sizes of the cracks, as well as the location of the cracks in relation to the nodes. Data collected would have been inconsistent and would not have allowed the team to draw accurate conclusions. Figure 61 below shows the effects of the compression test on the Carbonized sample.

Figure 61.

6.1.3.1 Procedure

All samples were cut to a length three times their diameter. The average diameter and exact length were entered into the machine for organizational purposes similar to the previous tests. The sample was loaded vertically into the machine and the press was lowered and aligned properly. The machine gradually increased the downward force on the bamboo at a steady rate until the bamboo reached the point of fracture or splintering. The sample was removed from the machine once the force was reduced.

6.1.3.2 Discussion

For the compression test, it was important to have the node located in the center of the sample. Imperfections in node placement did not present as much of a challenge for this test, but an effort was made to ensure consistency between tests. In Figure 62 the node placement for the compression test is visible.

Figure 62.

Another challenge the team encountered was cutting the samples to create a level edge. It is important for the flat plate of the press to lay flat against the cross section of the bamboo. The tools available made it difficult to obtain an even surface for testing. To overcome this, an electric belt sander was used to level the ends of the bamboo rods after cutting.

6.2 Frame Testing

The following section provides information about the full bicycle frame testing procedures in order to comply with ASTM standards. The testing was researched but not completed due to time constraints on the project. More information about future testing can be found in the Discussion, section 8.3.

6.2.1 ASTM Standards

ASTM standards were used to ensure that the bicycle frame is safe for riders. The standards have multiple classifications for different classes of bicycles with several requirements for each classification. The group decided upon a condition two bicycle, described below in section 6.2.1.1 with specific critical impact, horizontal and vertical load requirements to meet the standard.

6.2.1.1 ASTM Conditions for bicycles

ASTM standards describe the different classes of bicycles. Based on testing results, a bicycle can be classified into one of six different categories. These categories establish how much weight the frame can handle, the speed it can sustain safely, the height of jumps or bumps the frame can tolerate, as well as the bicycle's intended use.

Condition 0- The first classification is for children's bicycles. The users of the bicycle must be under 80 pounds or under the age of three. They are primarily intended for training with the supervision of an adult.

Condition 1- A condition 1 bicycle is categorized as suitable for adults riding on paved surfaces with the tires remaining on the ground.

Condition 2- This bicycle can be utilized both for off-road and on-road riding. This bicycle can endure jumps up to 6 inches off the ground.

Condition 3- A condition 3 bicycle is intended for riders that are doing more difficult off-road riding on a more treacherous terrain. This bicycle also has the structural integrity to withstand jumps up to two feet.

Condition 4- This category of bicycle has the capability of traveling off-road at speeds of up to 25 MPH and can tolerate jumps of a maximum of four feet. A bicycle fitting this standard is normally used for intense off-road riding.

Condition 5- The last condition is for the most extreme off-road riding possible. This type of bicycle is able to exceed speeds of the condition 4 standard, as well as the maximum jump height.

In accordance with the team's decomposition, a condition two bicycle frame was selected. A bicycle of this rating is ideal because it is very modular. It would be able to traverse the uneven and poorly paved roads in cities and unpaved roads in rural areas. It is also less expensive and easier to manufacture than bicycles with higher safety ratings.

6.2.1.2 ASTM Standards for Frame

There were three requirements for a condition two bicycle. The horizontal load requirement is 50,000 cycles with a cyclic load of 800 Newton's tensile and 600 Newton’s compressive. The vertical load requirements is similar with 50,000 cycles of a cyclic compressive load between 120-1,200 Newton’s. The critical impact requirement is different from the previous requirements and entails withstanding a drop height of 180 millimeters.

These frame tests were not completed for the bamboo bicycle frame due to delays in the production of the frame and a lack of machinery at WPI to perform tests properly. In order to do the proper testing, the frame would need to be outsourced to a frame testing company. There are no local companies that had the proper machinery or were willing to conduct these tests.

6.2.2 Horizontal Loading Test

The horizontal loading test is used to determine the frame's performance against a horizontal force. The rear axle attachment point of the bicycle frame is fixed on a mount point. A cyclic load is then applied horizontally on the front axle attachment point. The fixture can be seen in figure 63 below. During a single, complete cycle, the load would move forward and backward once. The number of completed cycles and the horizontal load magnitude are recorded until the frame’s failure, to classify the type of the bicycle.

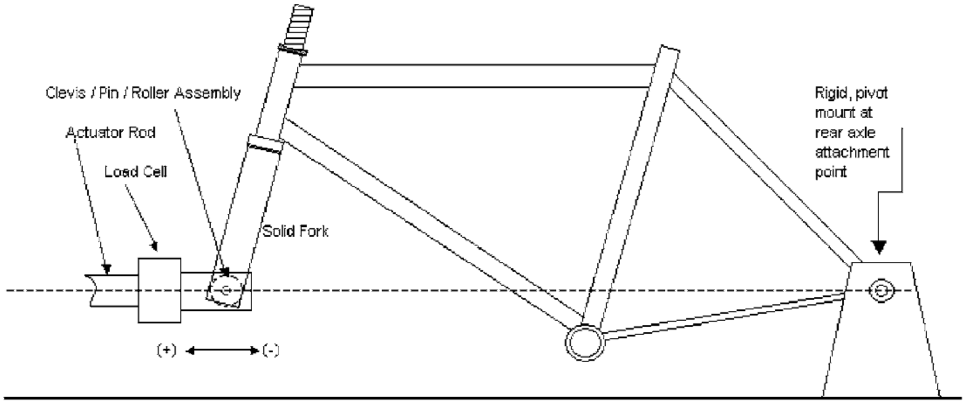


Figure 63.

6.2.3 Vertical Loading Test

The vertical loading test is used to determine the frame’s performance against a vertical force. Similar to the horizontal loading test, the rear axle attachment point of the frame is fixed to a mount point, and a free roller is attached to the front axle attachment point. The fixture can be seen below in figure 64. A vertical cyclic load is applied at the seat’s axle. The load moved along the z-axis. During a single, complete cycle, the load moved upward and downward once. The number of completed cycles and load magnitude is recorded until the frame's failure, to classify the type of bicycle.

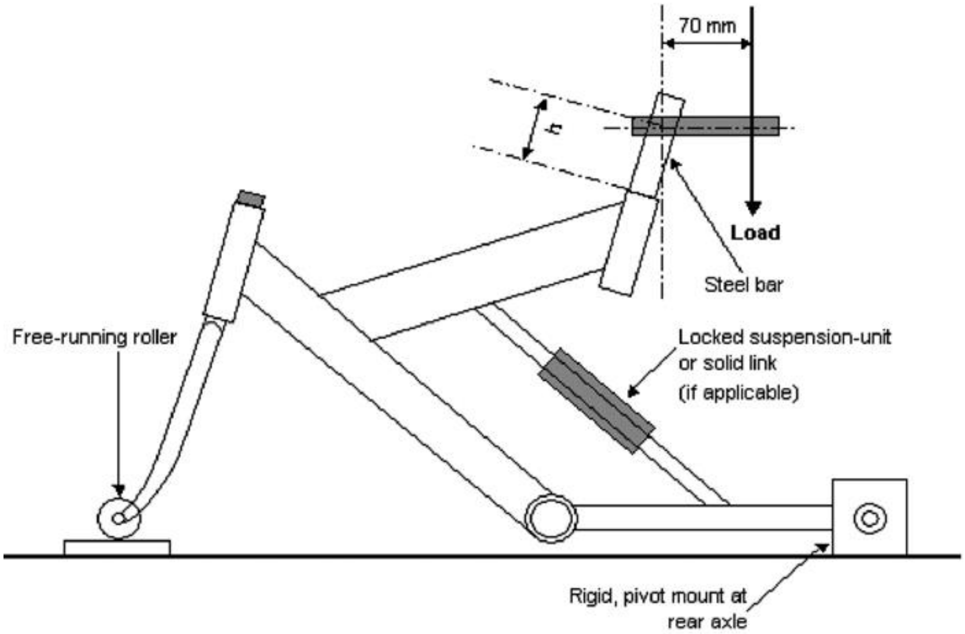


Figure 64.

6.2.4 Critical Impact Strength Test

The critical impact test is used to determine the overall strength of the bicycle frame. During the test, the bicycle frame is placed vertically, and the rear axle attachment point is fixed to a mount point. Once again, a roller is attached to the front axle attachment point. The fixture can be seen below in figure 65. A load is applied above the roller and then released. There is a permanent deflection set for the frame. The magnitude of the deflection set and the size of the load are measured to determine the classification of the bicycle.

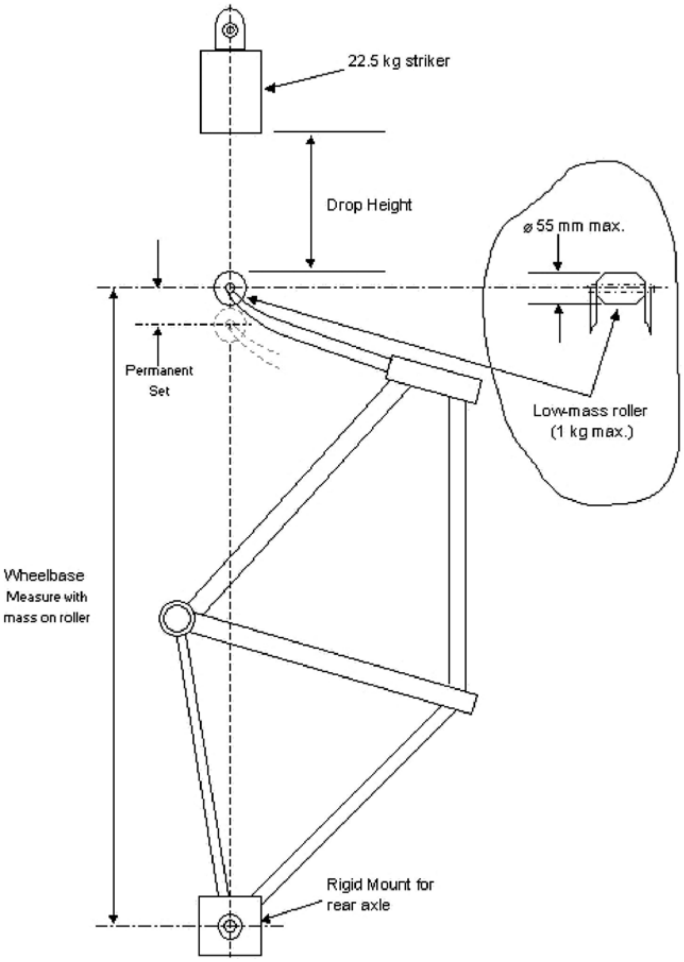


Figure 65.

7. Data Analysis and Iteration

The following section includes testing results collected from the three point bend test, the four point bend test, and the compression test for Tonkin and Carbonized bamboo, with both 1 and 2 inch diameters. Data is included for both good condition and cracked bamboo.

7.1 Table of results

Table 6. Bamboo Test Results

Test Results			
	3-Point Test (lbf)	4-Point Test (lbf)	Compression Test (lbf)
Tonkin 1"			

Non-Cracked	305	324	7059
Cracked	130	30	NA
Carbonized 1"			
Non-Cracked	159	108	4042
Cracked	121	162	NA
Carbonized 2"			
Non-Cracked	281	266	3768
Cracked	157	410	NA
Tonkin 2"			
Non-Cracked	433	518	7766
Cracked	282	188	NA
2014 MQP Steel Bicycle Tubing	919	NA	9791

This table shows the results of all three tests completed on each type of bamboo, cracked and non-cracked. The data is analyzed in section 7.3.

7.2 Graphs of results

The following graphs were generated from data for each test completed. The information represented in these graphs is analyzed in the following section, 7.3.

7.2.1 Graphs of 3 Point Bend Test

The following two graphs display the results from the 3-point bend test of the non-cracked bamboo and the cracked bamboo.

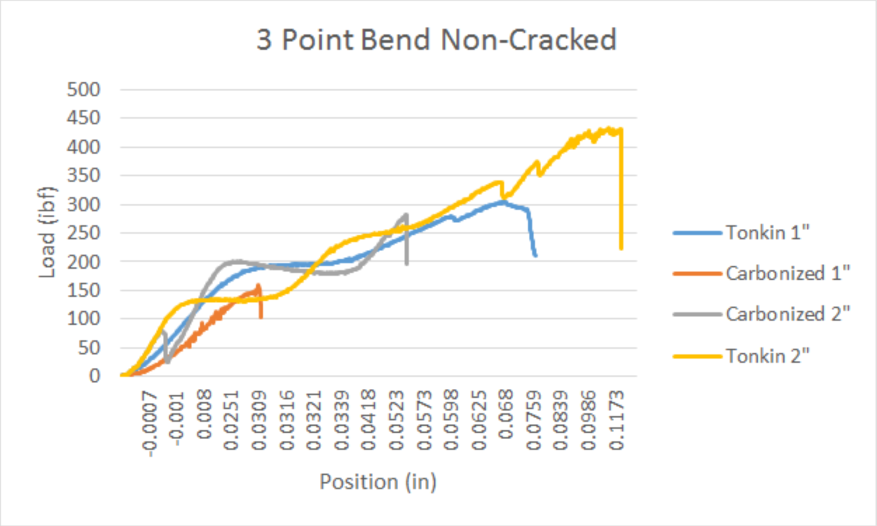


Figure 66.

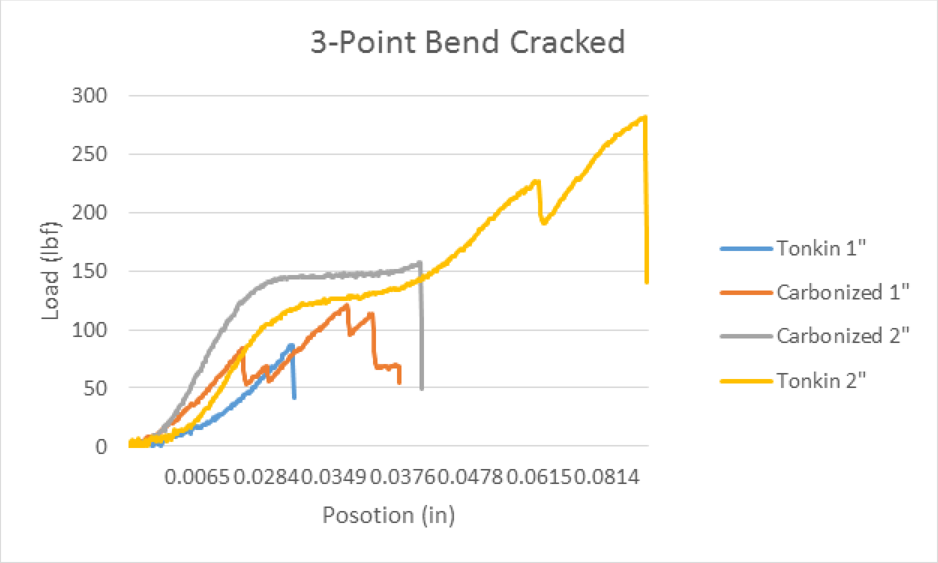


Figure 67.

7.2.2 Graphs of 4 Point Bend Test

The following two graphs display the results from the 4-point bend test of the non-cracked bamboo and the cracked bamboo.

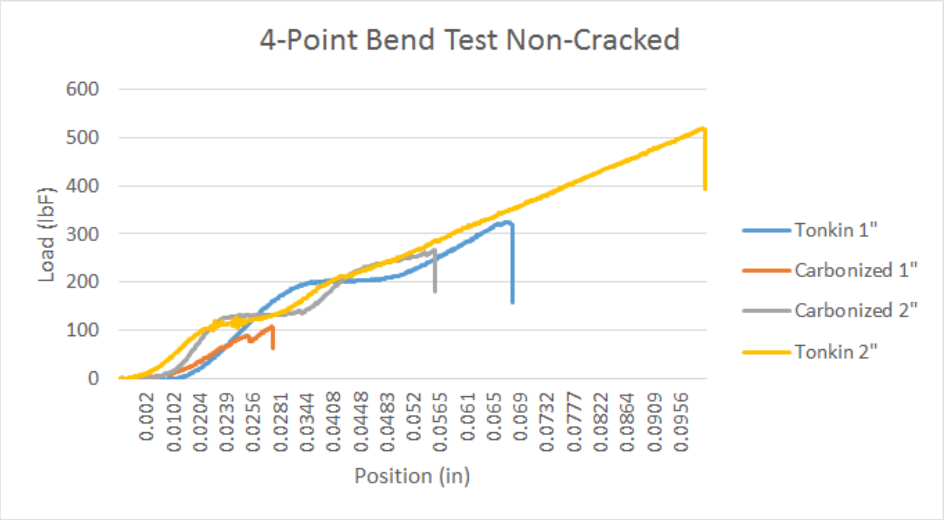


Figure 68.

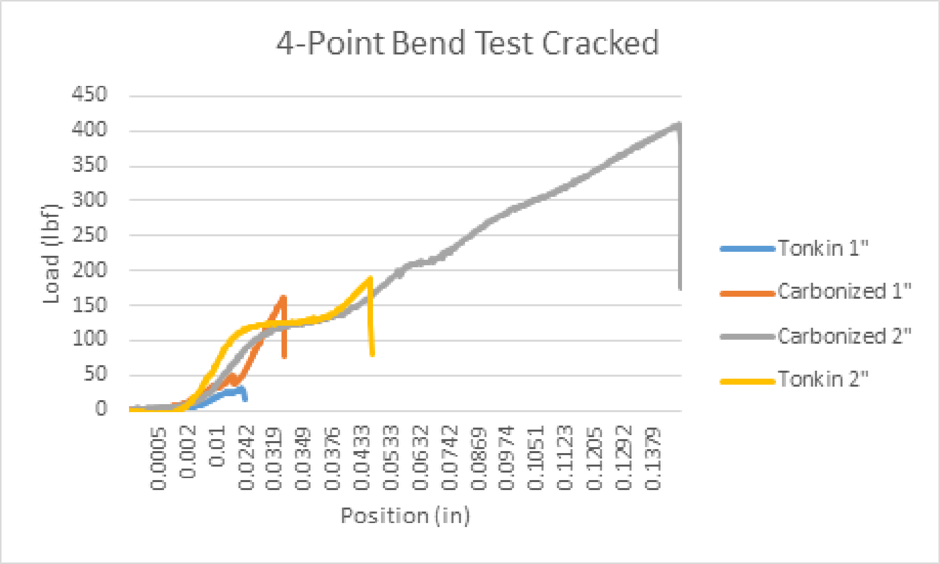


Figure 69.

7.2.3 Graphs of Compression Test

The following graph displays the results from the compression test of the non-cracked bamboo.

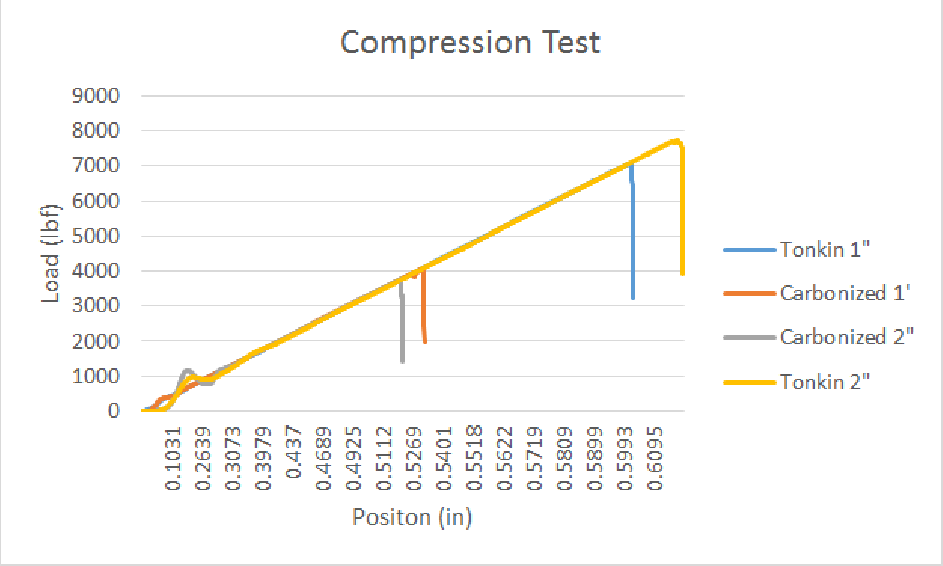


Figure 70.

7.3 Analysis of Bamboo Results

The compression test, the 3-point bending test and 4-point bending test were all performed on the bamboo to ensure that the results of the tests were accurate with the true strength of the bamboo. As mentioned in prior sections, cracked bamboo was tested in addition to un-cracked bamboo. The 2014 Bamboo Bicycle MQP had performed a 3-point bend test and a compression test on steel tubes from a current road bicycle. The steel had experienced a peak load of 919 lbf in the 3-point bend test and 9,791 lbf in the compression test (Andres et al. 2014). The team was able to use these results as a benchmark for our test results. As expected, the cracked bamboo did not test as well as the un-cracked bamboo, but the team concluded that the un-cracked bamboo had close enough results to steel and could still be used to create a usable and safe bicycle frame.

Bamboo rods with 1 inch diameters were used to create the rear dropouts on the bicycle frame. Both cracked and non-cracked bamboo were tested, although the un-cracked bamboo far out preformed the cracked. The Tonkin 1 inch bamboo was selected for use because it tested extremely well. The un-cracked sample was able to sustain 324lbf load, a stress over double the tensile strength per unit length than the cracked bamboo. The Carbonized 1 inch bamboo tested relatively similarly to the cracked Tonkin bamboo, with a tensile strength around 150lbf. The Carbonized bamboo only withstood compressive forces between 3000lbf and 4000lbf, while both 1 inch and 2 inch Tonkin bamboo withstood compressive forces upwards of 7000lbf. Since the Tonkin Bamboo tested, on average, about twice as well as the carbonized bamboo, the Tonkin 1 inch was the clear choice for the rear dropouts.

Carbonized 1 inch and Tonkin 2 inch bamboo were tested for the main bicycle frame. The Carbonized 2 inch saw very similar results to the Carbonized 1 inch, again resulting in a tensile strength around 150lbf. The Tonkin 2 inch bamboo resulted in a tensile strength upwards of 518lbf which we believe would be sufficient in meeting the ASTM standards for a bicycle frame as outlined in section 6. Since the test results of the Carbonized and Tonkin bamboo were vastly different, the team decided to use Tonkin bamboo throughout the bicycle frame.

8. Discussion

This section summarizes the accomplishments of each design team, and offers commentary on constraints, the design process, and possibilities for further work. Because the teams worked together to design the bicycle, some commentary addresses interactions between the groups.

8.1 Joints Discussion

The initial objectives set out for this project were to:

- Minimize assembly time
- Minimize cost
- Maximize strength in order to comply with ASTM testing standards for condition II bicycles.

To achieve these objectives, the designed joints consist of 1/8 inch laser-cut steel gussets attached to the bamboo rods with SynthoGlass pre-impregnated wrap. This design combines the strength of the steel joints used in the 2014 project with the ease of manufacture and weight advantages of the PETG joints used in the 2012 project. The joint design also made the frame quick to manufacture, though not as quickly as the 2014 project. The full bicycle frame was constructed in two hours, which is a marked improvement from the 40 hours needed when producing a commercial bamboo bicycle (Calfee Design 2015).

The joint design changed throughout the design and manufacturing processes. The initial designs did not consider manufacturability of the individual parts, something that was later remedied. When manufacturing, the team learned that it was far more difficult than anticipated to hold the joints in place, especially the seat tube joint, in order to wrap them. When modeling the parts, the team did not consider how the wrap would be applied. When the team attempted to wrap the bicycle, the small triangular piece from the seat tube joint was too small to wrap effectively and was omitted. This is shown in figure 71.

While the cost of the bicycle needs to be brought down (mass-producing can help reduce this), the team succeeded in creating a prototype bamboo bicycle. The bicycle was lightweight and able to be assembled quickly by unskilled workers, fulfilling the core objectives.

Figure 71.

Most of the constraints of the joints team were either met or there was insufficient data to confirm. When creating the joints, he flat plate parts were laser cut out of the house by New England Wire Products in Fitchburg, Massachusetts, which complies with the constraint to be manufacturable at or near WPI's facilities. The bicycle frame was made out of bamboo, easily assembled, and modular. The frame was assembled in two hours, but with further experience, it is feasible that assembly could be completed in one hour. The use of steel joints, rather than aluminum, added an estimated five pounds to the bicycle frame, but the bicycle was still lighter than past frames. In theory, the bicycle could support an adult, but due to the lack of full frame testing, the ability of the frame to support the weight of a 300 lb person is unknown.

From a design perspective, the project lacked Finite Element Analysis and extensive research about torsional loads in a bicycle frame. This lead to torsional weakness in the front joint of the bicycle. While it is speculated that the frame can support the downward force of a rider sitting on the seat, any movement causes the frame to fluctuate. This lack of rigidity would make the bicycle difficult or dangerous to ride. Additionally, the joint design eliminated saddles that lay flat against the bamboo rod in order to simplify the joint and reduce its weight. This caused stress concentrations where the edge of the laser cut plate metal rested perpendicular to the bamboo. Reintroducing saddles into the joint design to support frame and reduce stress would help fix this.

When analyzing the project in regard to process and management, the project suffered from lack of organization. There were simply too many team members that weren't being properly overseen, and communication between groups was minimal. Manufacturing, as a result, began too late in the project, eliminating the possibility of testing the completed frame to comply with ASTM standards.

For future projects, the team recommends further researching the material selection to lower the cost of the joints. The saddles on the joints should be reassessed. Completing Finite Element Analysis of the bicycle frame would contribute greatly to the assessment of the current joint system, as well as a joint system including saddles. ASTM testing needs to be conducted on the completed bicycle frame so that a full dynamic analysis of the frame can be completed.

8.2 Jig Discussion

8.2.1 Accomplishments

The jig designed is highly adjustable and able to accommodate variations in the size and shape of bamboo components during bicycle frame assembly. The setup is simple enough that an operator with little instruction could interpret the functions of each fixture based on its components. Critical joints of the frame are restrained in less adjustable fixtures to reduce alignment time, while the bamboo fixtures are adjustable with a single fastener for each degree of rotation. The initial configuration of the fixtures for the chosen bicycle frame geometry took approximately 15 minutes, and additional bicycles produced with the same geometry could be prepared for manufacturing in approximately 10 minutes. A picture of the final jig frame prototype with the bicycle frame held in place is shown below in figure 72.

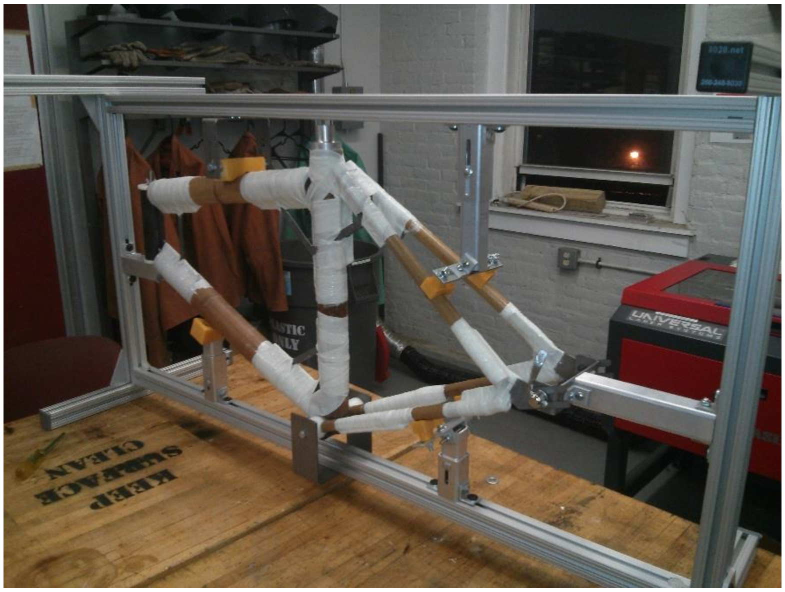


Figure 72.

Axiomatic design was instrumental to the success of the jig by providing clear and focused functions and a framework for evaluating competing designs to create a final product. It allowed the team to minimize iteration since designs that did not correspond to design parameters were easily identified and discarded. Creating an axiomatic design decomposition did take up a considerable amount of time, but it did eliminate blindly designing and potentially not meeting the requirements and constraints needed. However, the team's use of this design process did not completely account for manufacturability. Ease of manufacturability was an initial constraint, but it was not appropriately used because the team focused more on making designs that would meet the functional requirements, but were not necessarily easy to make. For a number of parts, changes to the design were needed in order to make them more manufacturable. This would be something to take into account for future projects.

The final design met nearly all of the original constraints. The adjustability of the fixtures were able to account for variance in the straightness and geometry of the bamboo. The fixtures did not interfere with the workspace of the joints during manufacturing. Securing the bicycle frame components was a simple process using the jig fixtures designed. Once the bicycle frame was manufactured, it was removable with minor adjustment of the fixtures. There were a few constraints not met satisfactorily. The top tube was not well secured by the jig, though this was overcome with temporary tape and cable ties around the joints. Similarly, the v-block fixtures for the bamboo joints had no provision for clamping and also required a combination of tap and cable ties to maintain alignment during bicycle frame assembly.

Though a powerful tool, axiomatic design was a challenge as none of the Jig Team had much experience working with it. This meant that at the beginning of the project there was a period during which the majority of the team’s effort was used to create and revise decompositions. This delayed the iteration of concepts and models for the frame itself compared to previously encountered coursework and projects at WPI.

With such a large team of engineers, the division into subgroups was necessary from an organizational perspective, but created challenges in communication. The Joint Design Team and Jig Design Team attempted to designate workspace and requirements at the start of the project, but as designs were iterated there were cases of overlap that were not communicated effectively. As the joint designs had priority in the overall project, this meant that any time overlap in workspace occurred the jig design had to be iterated, delaying manufacturing.

As noted in the critical analysis section, there are two fixture related concerns with the current design. First, the seat tube had to be secured using cable ties and tape during manufacturing. Second, the v-block system for the bamboo did not have a means of clamping, and also used cable ties and tape to maintain alignment. Future work could be done to address these issues and reduce assembly time by implementing a self-centering clamp system such as the ones designed but not implemented due to time and manufacturing constraints.

While the jig prototype functioned satisfactorily, material choices and geometries were primarily based on personal experience. Further work could be done to analyze the forces in the jig via finite element analysis and evaluate whether stress concentrations could be mitigated through the use of alternate materials or design changes.

The current prototype is limited in the bicycle frame geometries it can be used for primarily due to the height of the jig. The vertical portions of the exo-frame are standard 15 series 8020 extrusion, and could be easily replaced with longer sections to allow for taller frames to be assembled.

8.3 Safety and Testing Discussion

The objectives of Safety and Testing team were to test the bamboo and the bicycle frame to comply with ASTM standards. The Tonkin and Carbonized bamboo stock was tested to determine the best type of bamboo for use in the frame. The team tested the bamboo to meet ASTM standards by performing a 3-point bend test, 4-point bend test, and a compression test on each type of bamboo. Each test was conducted twice, once for bamboo in good condition and once for cracked bamboo. Cracked bamboo was tested in order to determine if it was suitable for use in the bicycle frame. The data obtained from the cracked bamboo testing could also be applied to bicycle frames that have cracked due to weathering. The data proves the structural integrity of bamboo bicycle frames throughout their lifetime. After completing the tests, the data was compiled into tables that can be seen in section 7. These tables were used to generate graphs that compare the strengths of the different bamboo rods. The team selected Tonkin as the bamboo most suited for the bicycle frame.

Due to time constraints, the team was unable to test the full bicycle frame. Problems occurred during the shipping of the bamboo that lead to a long delay in its delivery. Additionally, the gusset donation from New England Wire was delivered later than expected. Because of the late bicycle frame construction, the team did not have time to perform full frame tests. Additionally, WPI lacks the proper equipment to complete the ASTM bicycle frame tests. In order to complete the vertical and horizontal loading tests, a fixture would need to be designed and constructed to secure the frame in the Civil Engineering lab's static load compression machine. The impact test could not be completed on campus due to the specialized machinery needed to perform it. The team was unable to find bicycle testing facilities located near campus to test the frame. In the future, a fixture should be designed and constructed to perform the vertical and horizontal loading tests on campus. Additional research should be conducted in order to locate a facility with impact testing equipment.

There are several improvements that could have been made to increase the quality of the safety and testing. As discussed earlier, much of the bamboo had arrived in poor conditions, with cracks and imperfections. Only a small amount of the bamboo was in usable shape. Due to this, we were unable to perform multiple trials of each test on each bamboo to further validate our results. We also were not able to construct a jig for the frame test that could be used for future years. This was mostly due to time constraints. However, our group did outsource to local bicycle companies to try utilize their testing equipment. None of the companies in the area possessed the equipment necessary. Because of these two issues our team moved to a full FEA test on the frame. This was unsuccessful due to compliance issues within SolidWorks. There was not enough time to work out the issue within SolidWorks.

8.4 Impact of Engineering Solutions

Bamboo is readily available in multiple countries, making it an easy material to harvest and utilize. Due to the ease of production, bamboo is an inexpensive material that can be used as a replacement for wood. The bamboo bicycle project provides an alternative method to personal transportation in developing nations. For citizens living below the poverty line in these countries, bicycles are excellent transportation solutions. The use of bicycles increases the distance an individual can travel to find work, sell goods, and obtain resources. This project provides these people with a low cost and quickly assembled bicycle to use. Even for those without advanced educations, the process to build the bicycle is simple. One cause for concern would be the ability to test the bicycles in undeveloped nations due to a lack of proper machinery. If the Columbia University model is followed and bicycle manufacturing facilities are set up, testing machinery can be acquired (Columbia University 2011).

8.5 Deficiency in Prior Designs

The bamboo bicycle project began in 2010 with the MQP entitled "Hole Boring Device for the Manufacture of a Bamboo Bicycle Frame". The device was designed to remove a node in the seat tube, allowing the insertion of the seat post. The device can also be utilized to drill holes in the nodes to allow for more even drying of the bamboo. The current MQP team ultimately did not need to bore into the bamboo.

During the 2011 bamboo bicycle project, entitled "Production System for Bamboo Bicycles", the team designed a system of joint shells. Bamboo rods were inserted into the shells and wrapped in epoxy and carbon fiber. According to the team's notes, the shell design was tedious and labor intensive, though webs between joint elements were proficient for transferring loads through the joint. The shell design added structural integrity and simplified the assembly process, but was expensive and added steps in manufacturing. As mentioned in section 4, the shells design, used as temporary molds for the carbon fiber was considered. The design, however, is not modular or easily to assemble.

The 2012 MQP, entitled "Joining Method for Mass Production of Bamboo Bicycle Frames", used a clamshell method of joints held together by resin. During the process, workers would shrink wrap plastic around a mold to create the plastic shell, before placing it around the bamboo rods and injecting it with epoxy. The plastic shell joining method reduced technical building the bicycle in order to decrease time and number of steps in the process. The resin and plastics used in this design were not strong enough and were too brittle to sustain the loads. A better understanding of the loading at each joint was needed to create joints that would not fail during testing.

The 2013 MQP, entitled "Manufacturing Bamboo Bicycle Frames with Molded Composite Joints", was an improvement on the 2012 system. The new system used molds to form the plastics onto the bamboo rods. The system worked well and could withstand static loads of at least 300 pounds without failure. Prototype production was quick and easy for an unskilled worker to complete. The main concern of this system lies in the material required and the weight. The molds were made of aluminum, which was a lot of weight for the jig to hold. One design flaw was the process of filling the joints with epoxy. The epoxy could leak out of the molds, weakening joints significantly and leading inconsistent bicycle frames. Additionally, the molds incurred damage before they could be fully removed. A mold release agent was not used, and cured epoxy expanded into the molds preventing ease of release.

The 2014 MQP, entitled "Design for Bamboo Bicycle Frame", attempted to avoid the problems of the past MQPs by creating an entirely new system in which they used metal joints, gussets, and hose clamps to hold the frame together. The project featured the easiest assembly process for unskilled workers created thus far, and allowed for adjustability in the joint assembly. The entire frame could be assembled in 31 minutes. The steel joints and gussets provided strength and rigidity to the frame, but the hose clams used to attach them failed under applied loads during testing. The bicycle also ended up becoming extremely heavy, meaning that it would be more difficult for a variety of people to assemble and use.

Our 2015 MQP was built off of the work done by those before us. It resembles the 2014 MQP most in assembly, and is one of the most lightweight creations thus far. Future MQPs would benefit from adding a saddle to the joints we have created, but a good foundation has been laid down for later projects.

8.6 Potential Commercial Use

The Four P's of marketing consist of product, price, place, and promotion; these parameters are controllable and subject to constraints. The key objective to create perceived value and generate positive reception by revolving the four parameters around the customers in the chosen target market.

The first term, product, is a reference to the tangible (goods) or intangible (services) being offered to customers. The actual product itself, the bamboo bicycle, consists of three levels. The first level, the core product, is the benefits that the product offers. The second level is the actual product, which is the physical product itself and the final level is the augmented product, or the added value. The core product of the bamboo bicycle includes transportation, exercise, and any other benefits. Finally, the augmented product of the bicycle includes the saving of gas money instead of driving a vehicle and time saved compared to walking. In a developing nation, the augmented product also includes the opportunity to seek employment, sell goods, and obtain resources from a broader area. The classifications of the bamboo bicycle as a specialty good that is durable for multiple uses helps in determining how to brand the product.

The second term, pricing, includes the many decisions regarding prices. The first step in price planning is to set the pricing objectives. Many key objectives that should be determined include maximization of profit, revenue, and profit margin, as well as customer satisfaction, image management, and company survival. Next the estimated demand should be performed, accounting for the change in unit sale that will result from a price percentage change. After demands are estimated, costs should be determined taking into account fixed and variable costs and the pricing environment. The pricing environment is the trends of the economy and consumers, as well as the competition pricing.

The third term, placement, is all about getting the product to the customer. Objectives that need to be met include, but are not limited to: distribution channels, market coverage, inventory management, warehousing, distribution, order processing, transportation, and reverse logistics. The desired structure of distribution would go from the manufacturer to the retailer to the customer. Since this company is part of the project, we would manufacture and distribute the products at WPI. Since this is where our target market is, it makes the most sense for us to manufacture our bicycles closest to the customer to cut down on distribution costs. However, if we end up with an inventory so large that we can no longer fit on campus, we would then need to look into other storage facilities and factor in that new cost into the cost of the bicycle. If we decided to move our production and storage off campus, new costs would include, inventory costs, processing costs, and shipping and handling costs. As we are not currently using a space off campus, we do not yet have a projected expense.

If the business were strong enough that the bicycles could be sold in retail stores, the stores would most likely be specialty stores. A bamboo bicycle is a unique product and would attract very specific customers.

The fourth and final ‘P’ of marketing is promotion. Promotion represents anything related to communicating information about the product to the customers. The goal of this is to generate a positive customer response. We would need to utilize as many marketing methods as possible and appropriate to have the most successful business.

Our first tactic would be to use direct marketing. These advertising techniques involve communicating directly with the customer. This can include things such as TV or radio commercials, newspaper or magazine advertisements, fliers, and catalog distribution. Along with this type of advertising, we would have to keep a database of all of the people we distribute our catalogs to. In this database we might include name, contact information, order history, demographic information. All of these will help us improve our marketing techniques and make sure we are meeting customer demands.

We would also use the push and pull strategy of sales promotion. The push strategy would mean making sure the customer knows about our product and selling the brand. This involves creating unique and appropriate packaging, sale displays, and working with retailers to make sure they are stocking our product. The pull strategy involves getting the customer to come to us. This would mean advertising everywhere possible, generating good customer/management relationships so that they tell their friends about our product, and offering sales and discounts. Utilizing both the push and pull strategies together is important because you can’t really have a successful business with only one or the other.

9. Conclusions

9.1 Joints Group

9.1.1 Accomplishments

- Designed joints that combine the strength of the steel joints (2014 project) with the ease of manufacture/attachment of the 2012 project
- Joints make the frame quick to manufacture
- Manufactured and assembled prototype bamboo bicycle frame

9.1.2 Criticism

- Project suffered from a lack of organization
- Manufacturing should have started earlier
- Joints were manufactured out of steel instead of aluminum due to a communication error with New England Wire
- Design did not take torsional loads into account

9.1.3 Recommendations

- Future projects could focus on optimizing the joint design in this project
- Applying FEA, investigating alternate materials
- Find minimum acceptable dimensions of joint geometry
- Work on bringing down costs of joints

9.2 Jig Group

9.2.1 Accomplishments

- Designed jig that is adjustable to be able to accommodate varying sizes and shapes of frames and bamboo
- Jig makes the frame quick to manufacture with minimal training
- Jig aligns bamboo pieces with joints to maintain proper frame geometry during assembly
- Manufactured and assembled prototype jig frame

9.2.2 Criticism

- Project suffered from a lack of organization
- Manufacturing should have started earlier
- Were not able to manufacture self-centering bamboo clamps
- Could be somewhat more adjustable

9.2.3 Recommendations

- Future projects could focus on optimizing the bamboo clamp design in this project

- Applying FEA, investigating alternate materials, etc
- Find range of potential positions so that any range of positions can be met by the fixtures
- Work on coordination with other groups and efficiency of work

9.3 Safety and Testing Group

9.3.1 Accomplishments

- Determined the best bamboo to build the bicycle with
- Tested both cracked and normal bamboo to see changes in performance

9.3.2 Criticism

- Bamboo should be ordered earlier.
- Make sure we are getting high quality bamboo with no cracks.
- Better inter subgroup communication to produce better results.
- Struggled to have a successful FEA due to Solidworks complications.

9.3.3 Recommendations

- Order all parts and bamboo by end of A-term.
- Submit report section by section to Prof. Brown immediately after drat is complete.
- Full frame testing in compliance with ASTM standards
    - Find a company to outsource to if possible.
    - Develop testing jig if only testing in house is possible.
        - Wouldn't be the best for results, but is a solid back-up plan.

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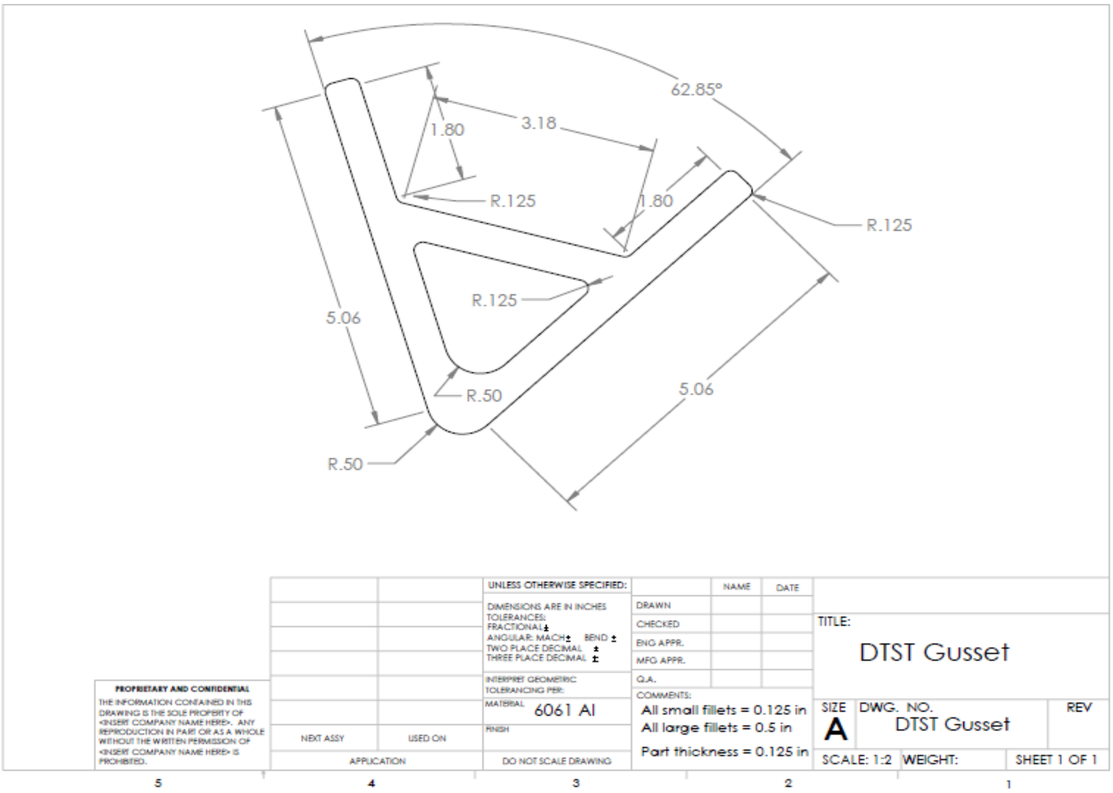
Appendices

Appendix A: SolidWorks Models of Joints

Down Tube Seat Tube Gusset



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NEXT ASSY
USED ON
APPLICATION

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL 6061 Al
FINISH
DO NOT SCALE DRAWING

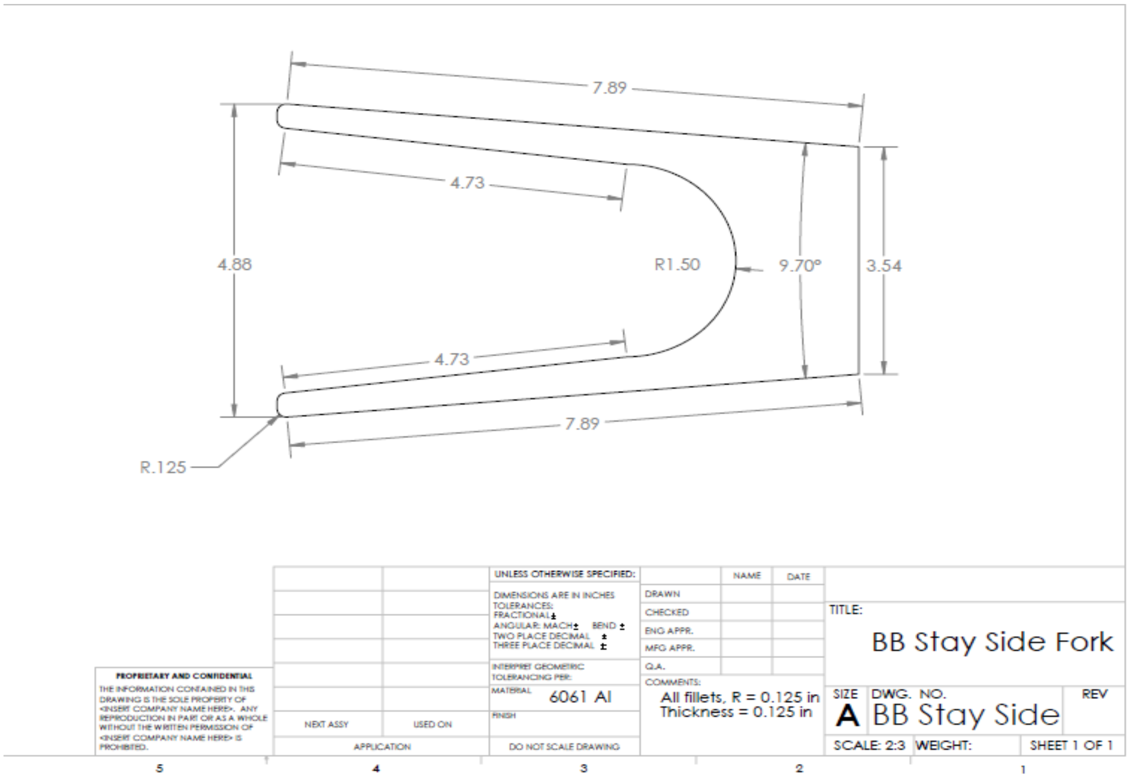
	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:
All small fillets = 0.125 in
All large fillets = 0.5 in
Part thickness = 0.125 in

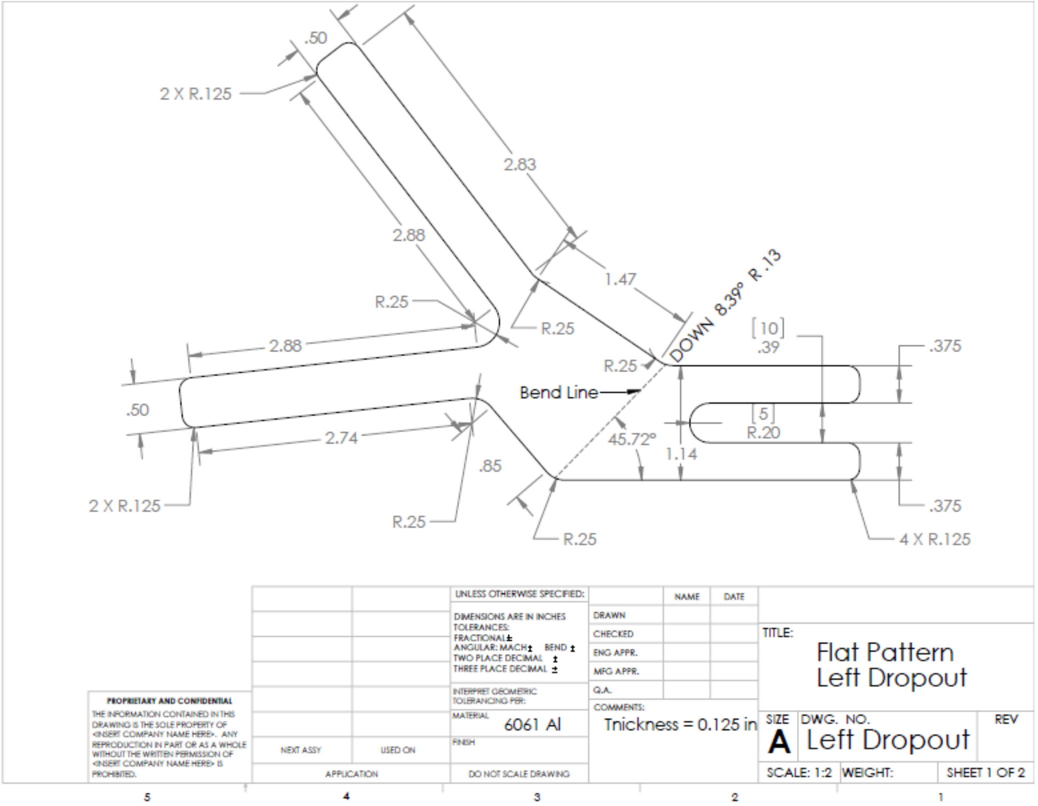
TITLE:
DTST Gusset

SIZE A
DWG. NO. DTST Gusset
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1

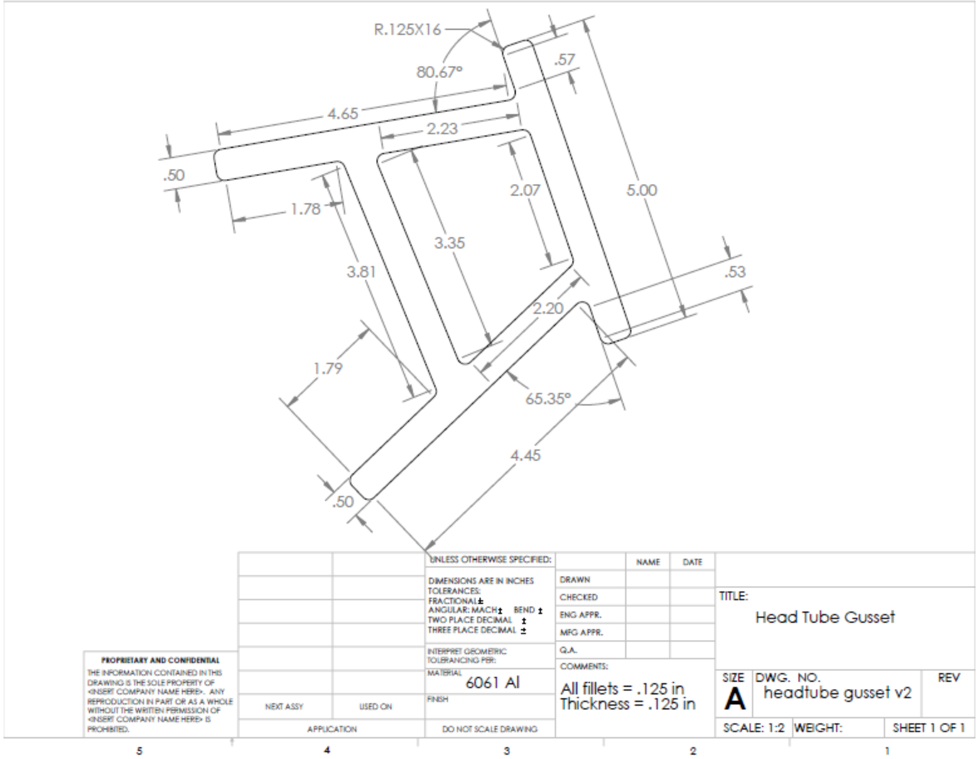
Bottom bracket stay side fork



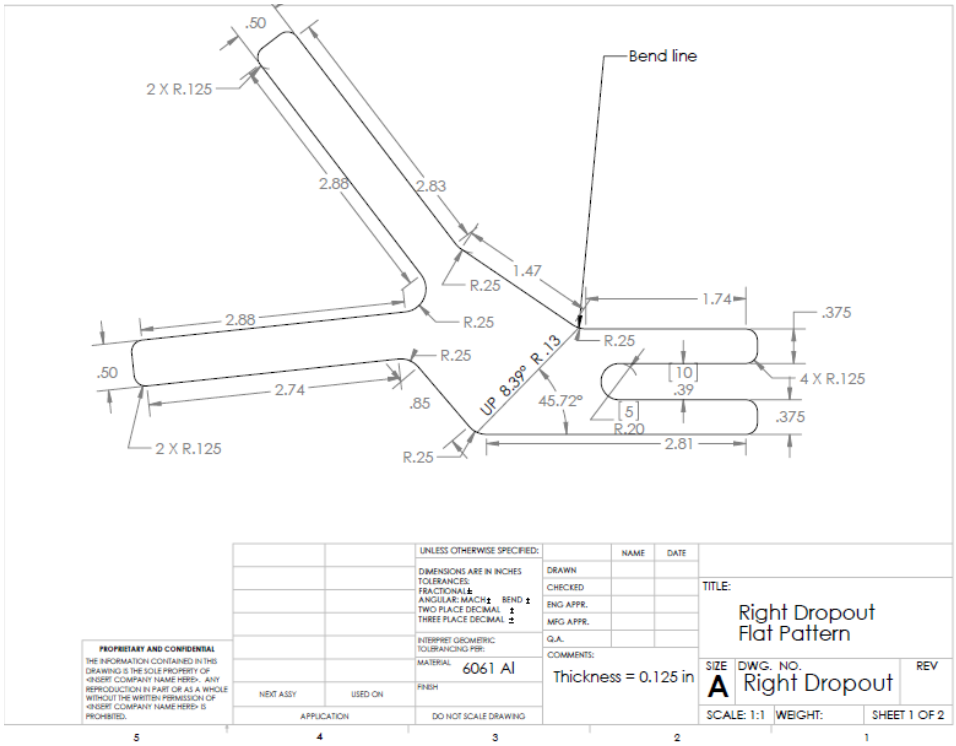
Bottom Bracket Down Tube Arm



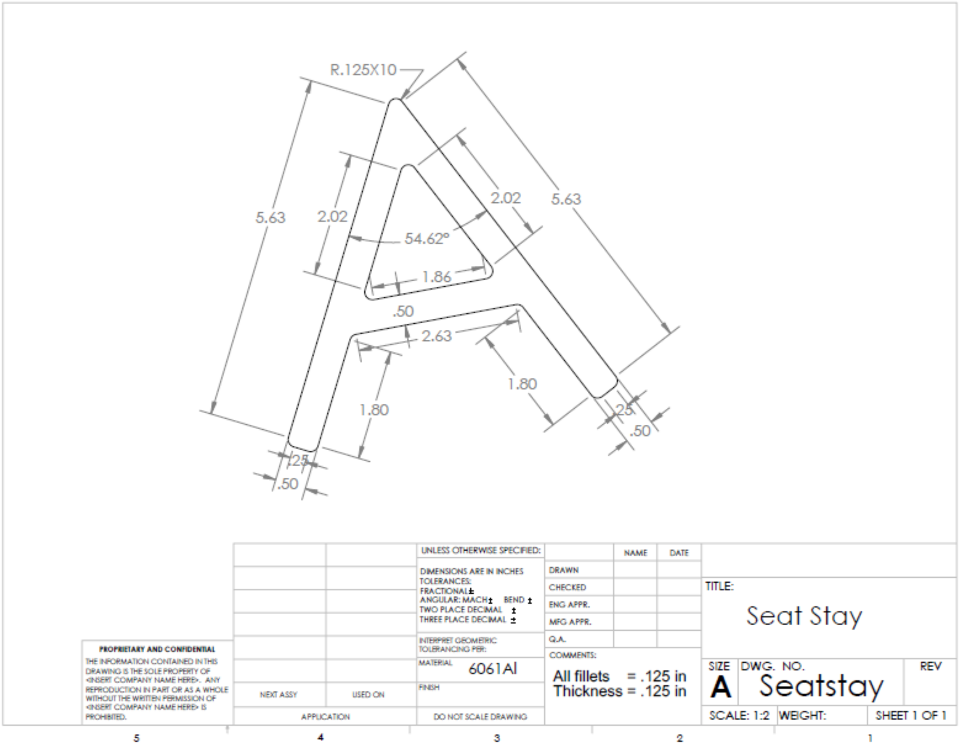
Head Tube Gusset



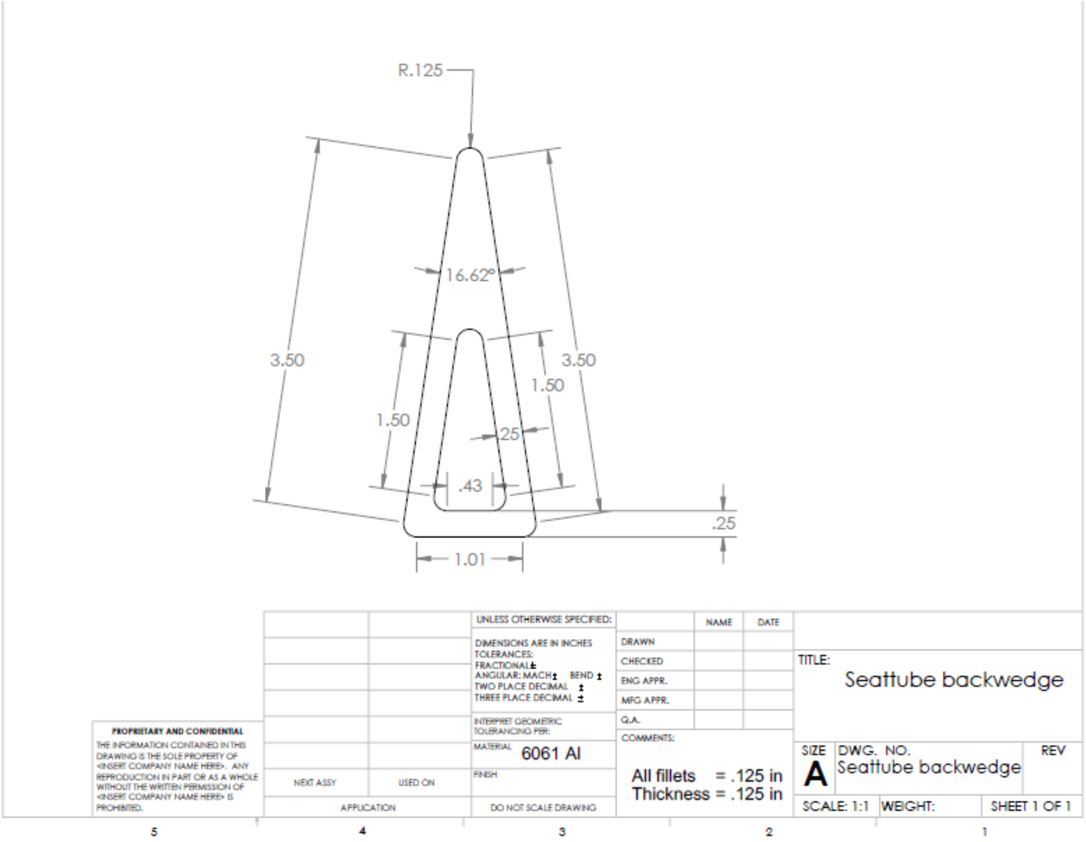
Right Dropout Flat gusset



Seat Stay Gusset



Seat tube back wedge gusset



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TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL 6061 Al
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:
All fillets = .125 in
Thickness = .125 in

TITLE: Seattube backwedge
SIZE A
DWG. NO. Seattube backwedge
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1

NEXT ASSY
USED ON
APPLICATION

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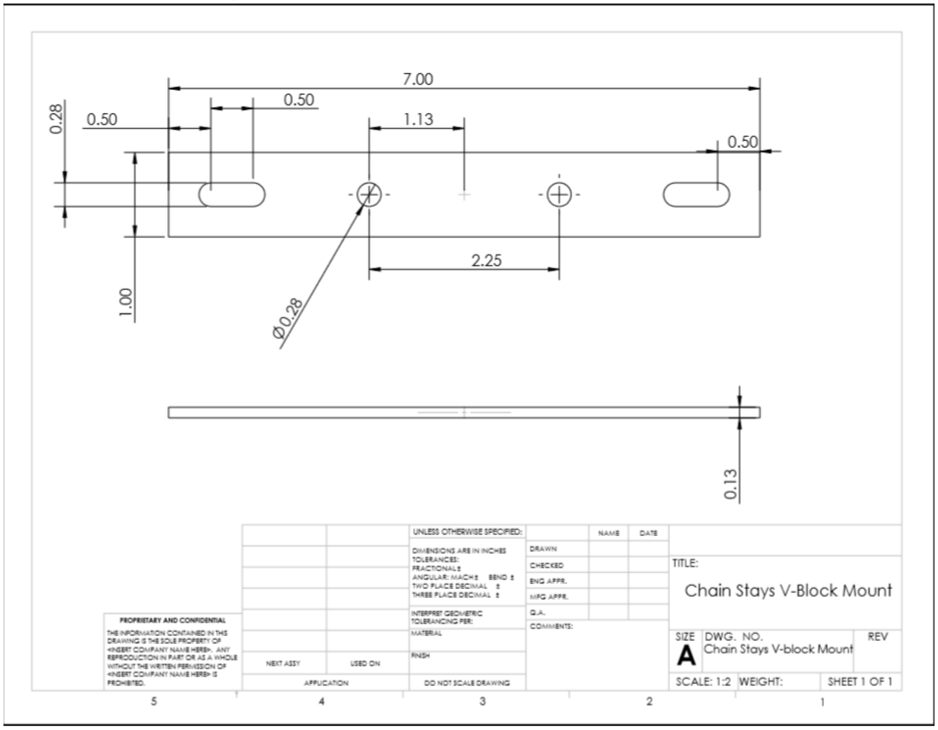
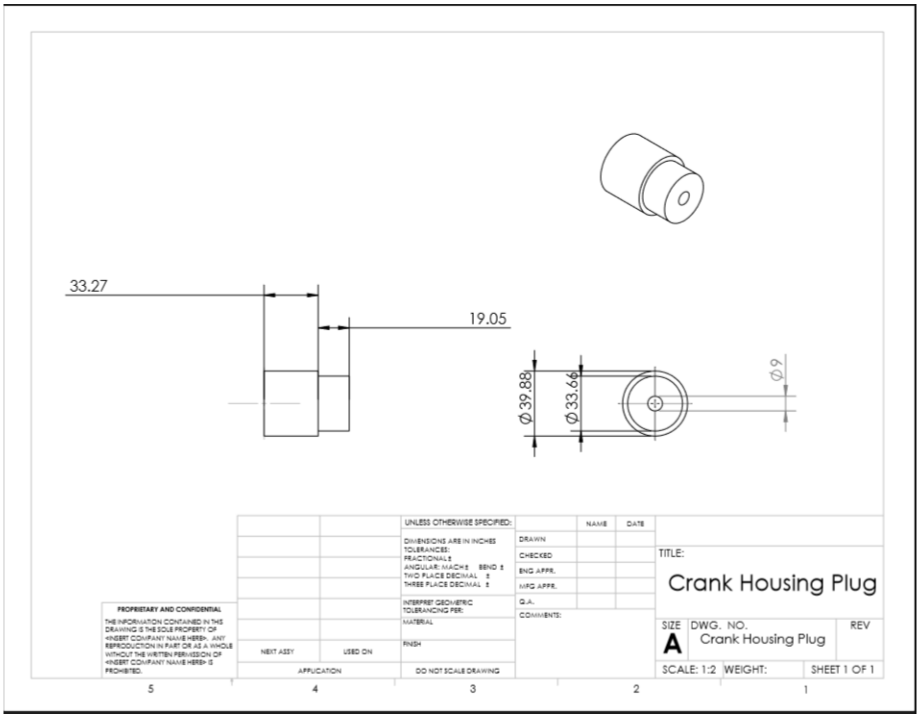
Top tube gusset

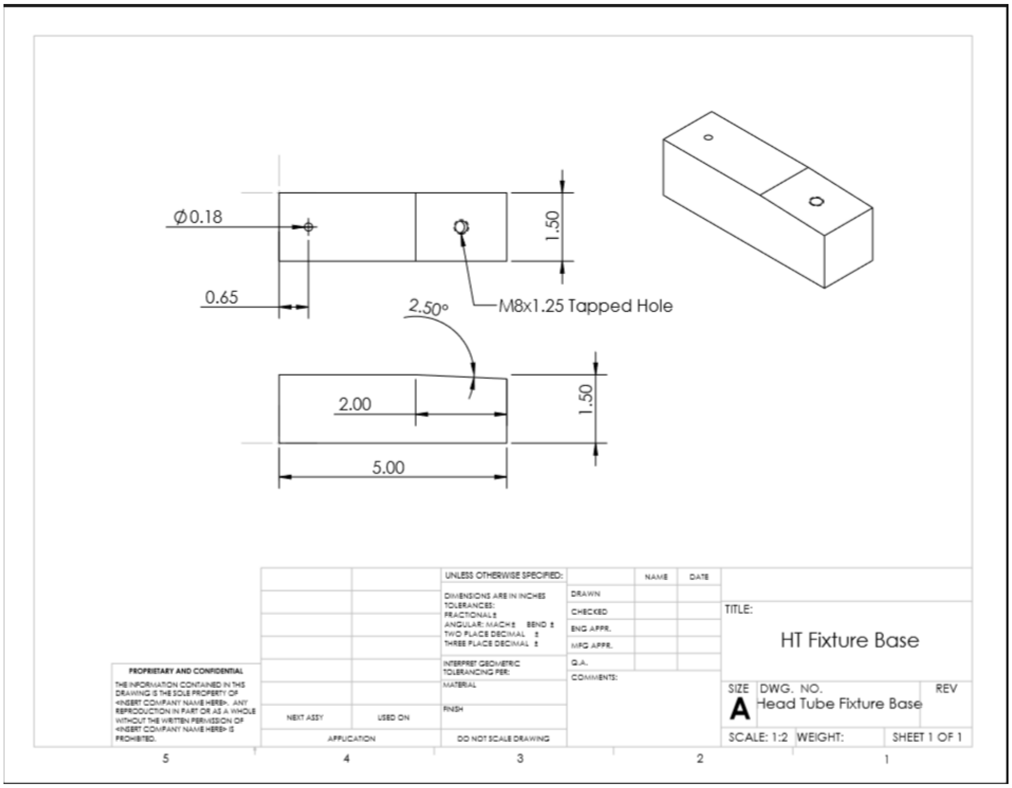
Appendix B: Jig Components SolidWorks Models



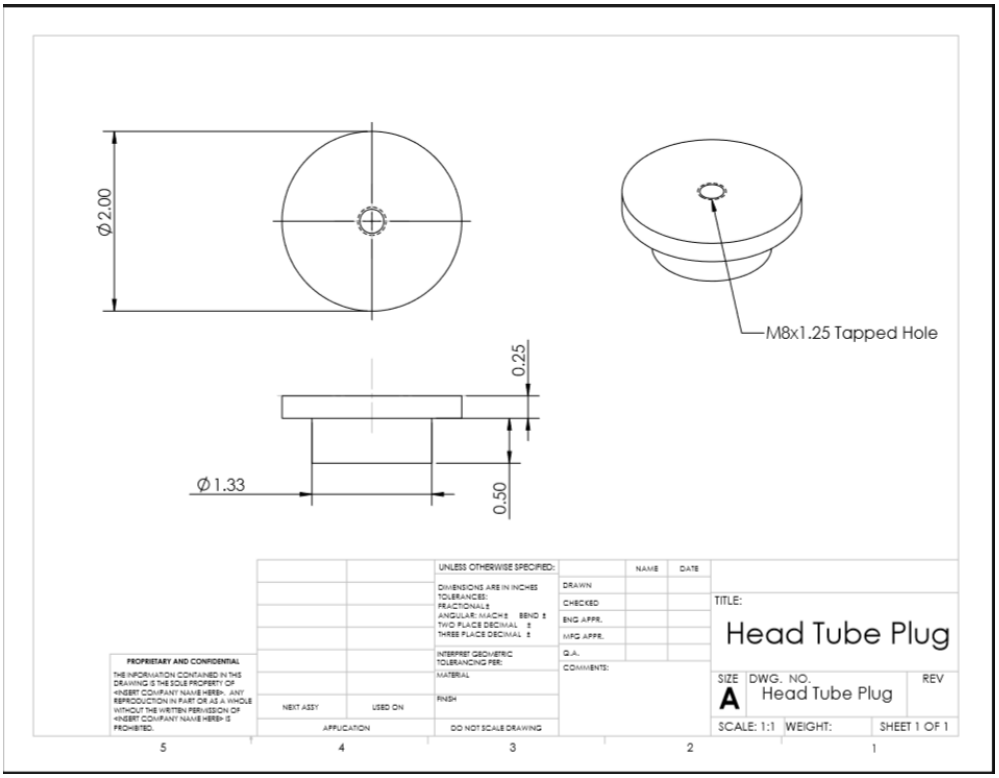
Chain Stays V-block Mount Drawing



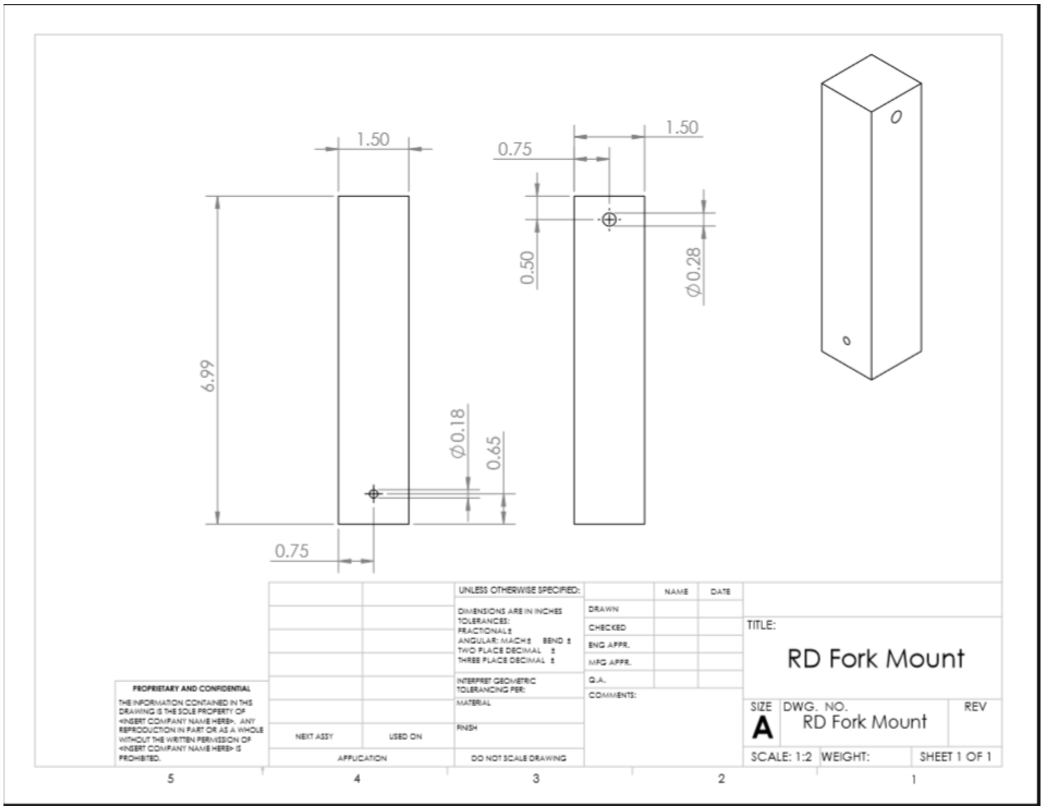
Crank Housing Plug



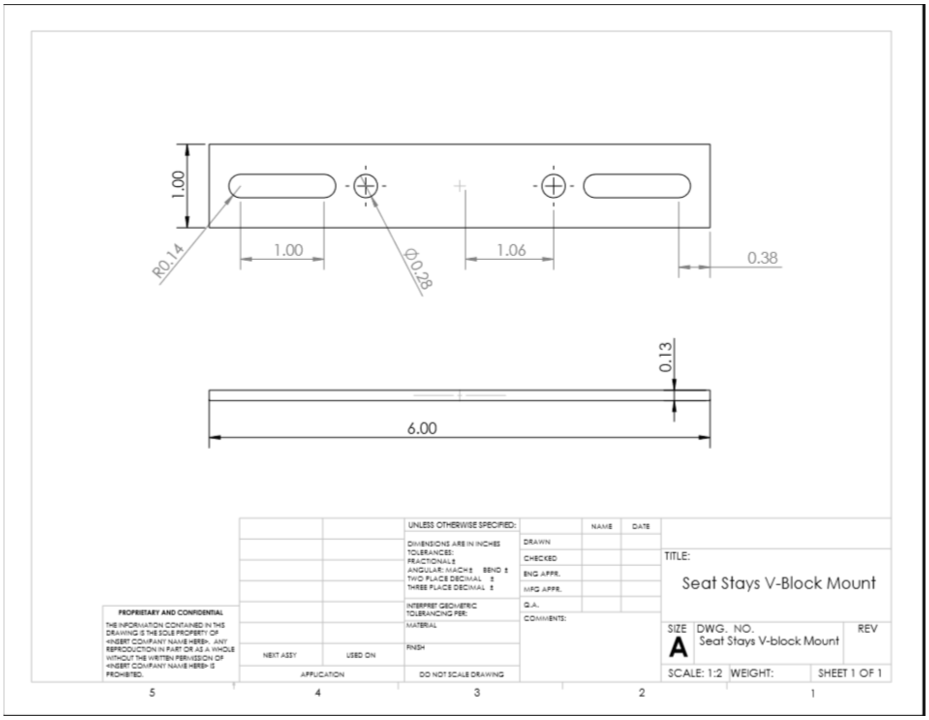
Head Tube Fixture Base



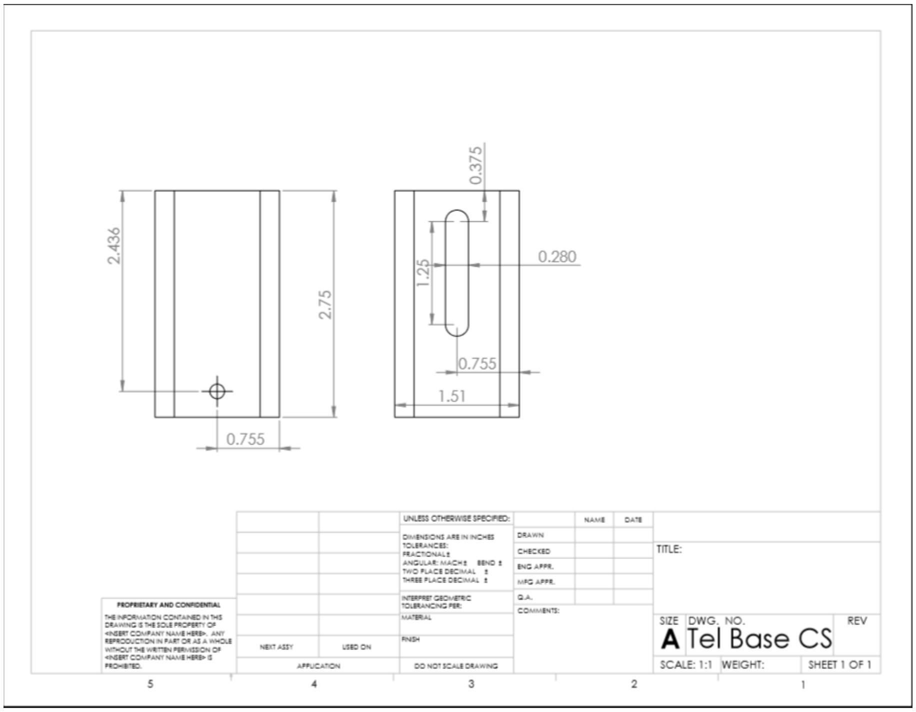
Head Tube Plug



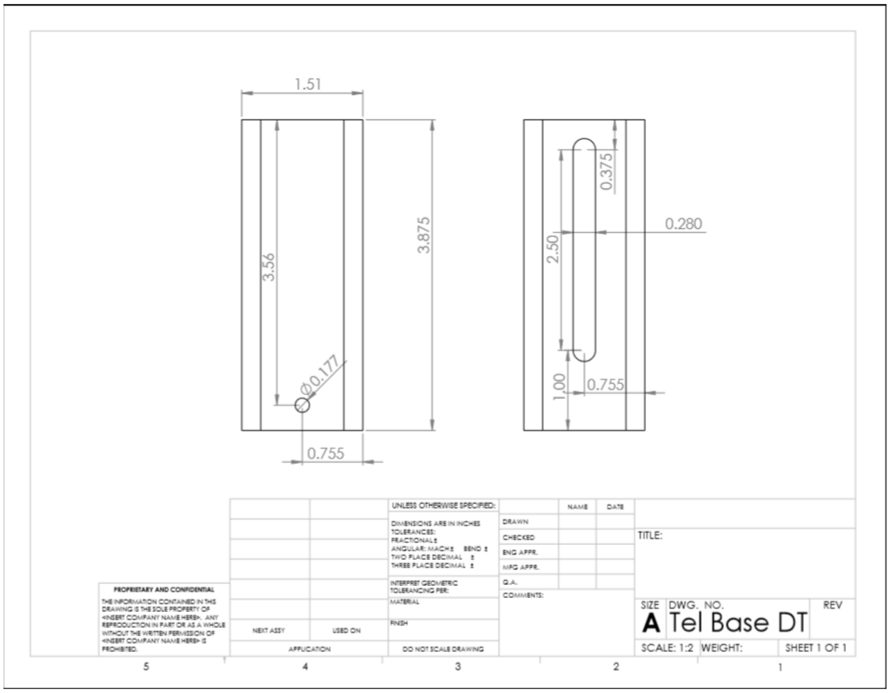
Rear Dropout Fork Mount



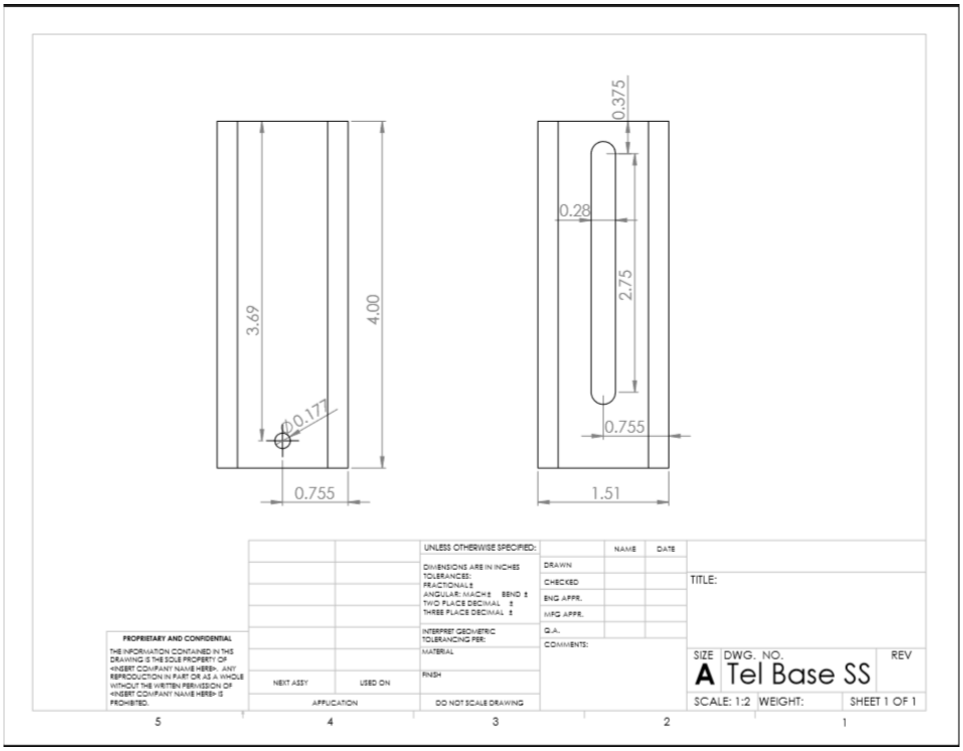
Seat Stays V-Block Mount



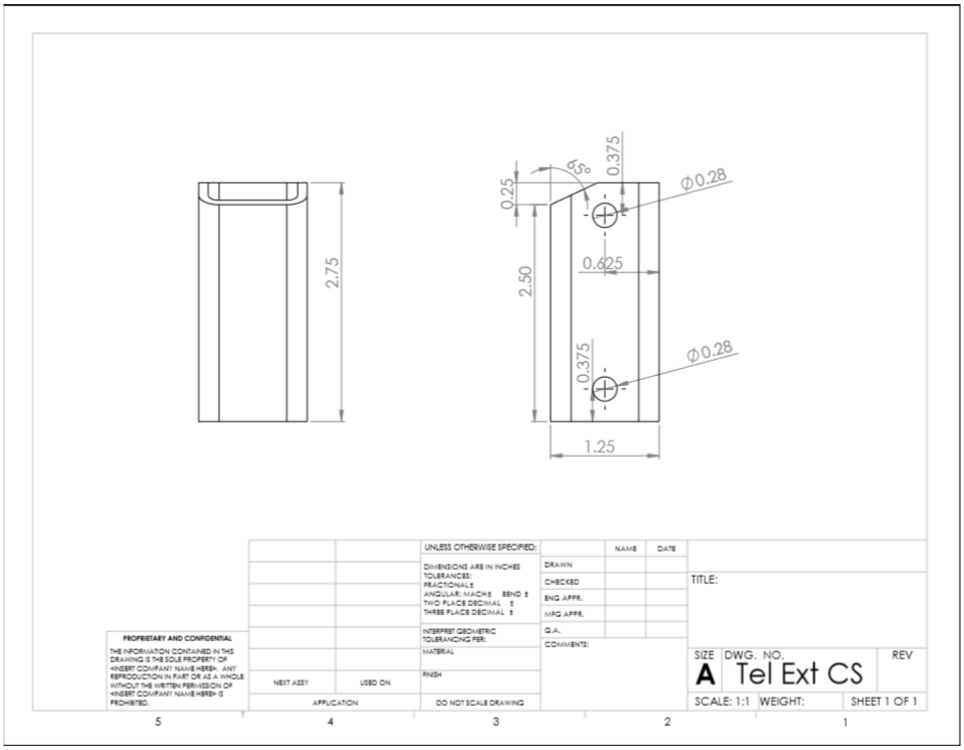
Telescoping Base Chain Stays



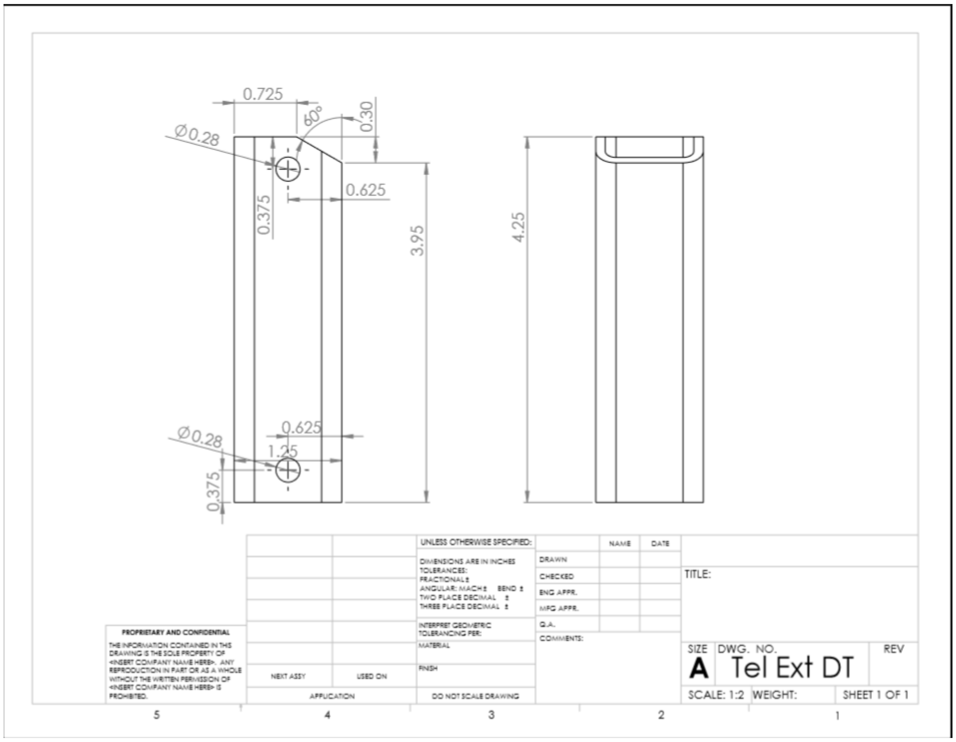
Telescoping Base Down Tube



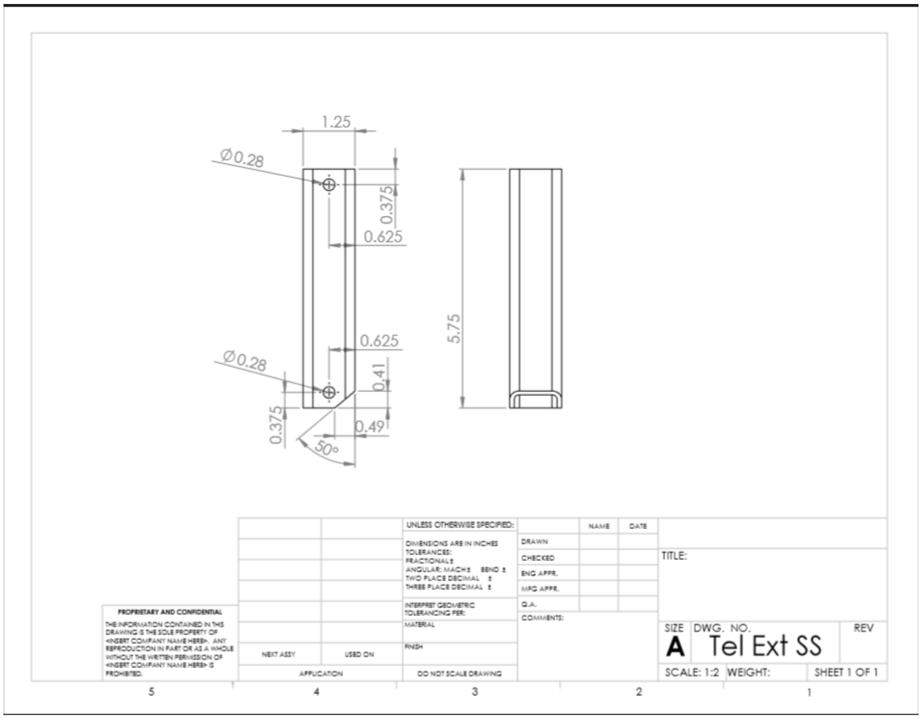
Telescoping Base Seat Stays



Telescoping Extension Chain Stays



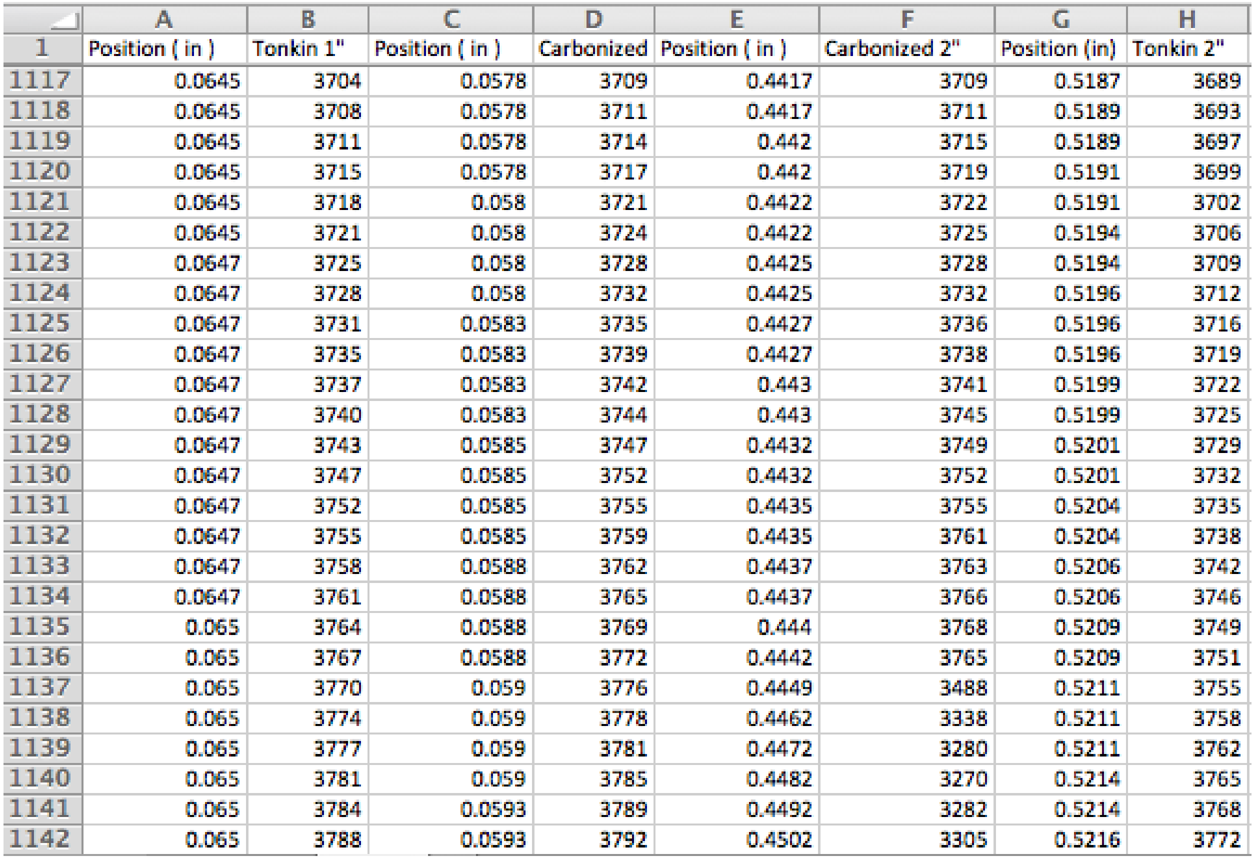
Telescoping Extension Down Tube



Telescoping Extension Seat Stays

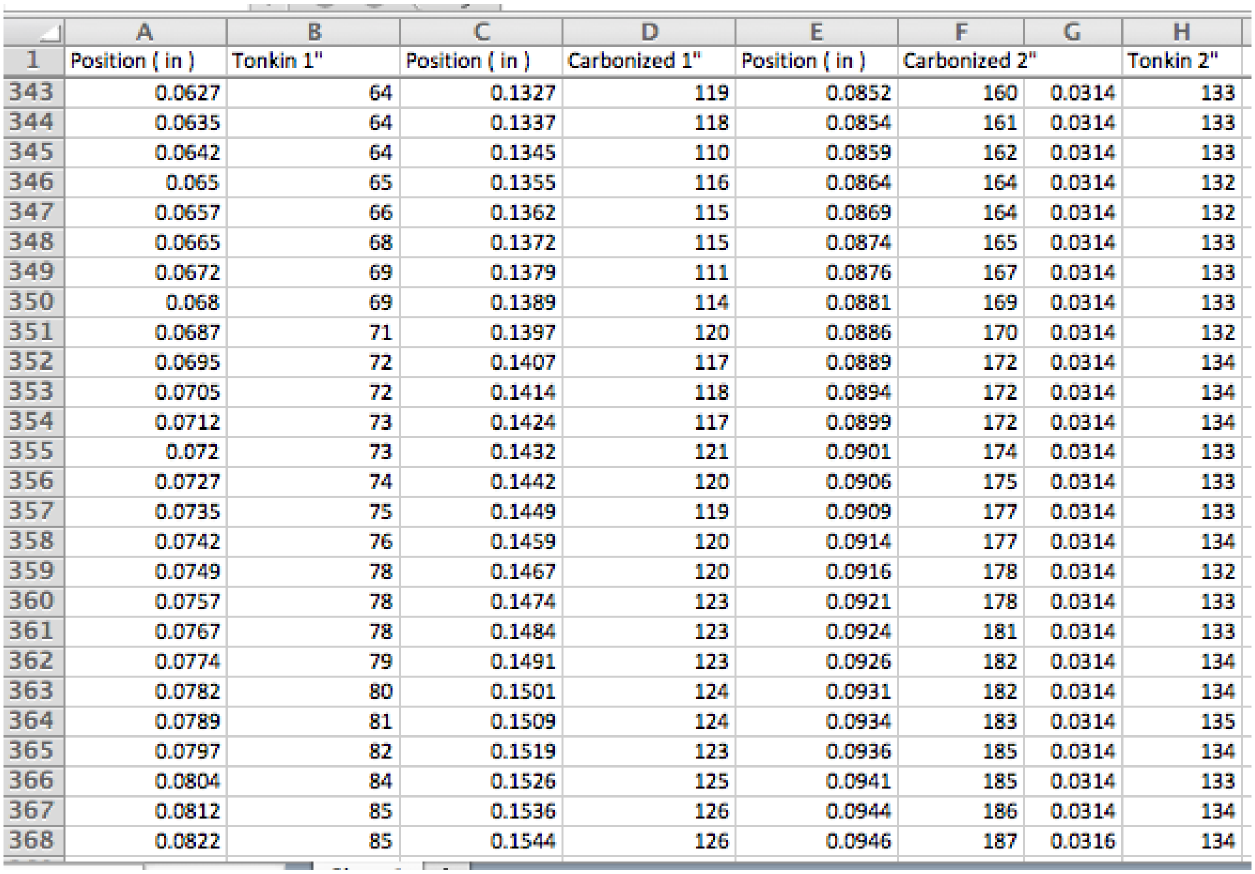
Appendix C: Safety and Testing Examples of Raw Data

Example of Raw Compression Test Results



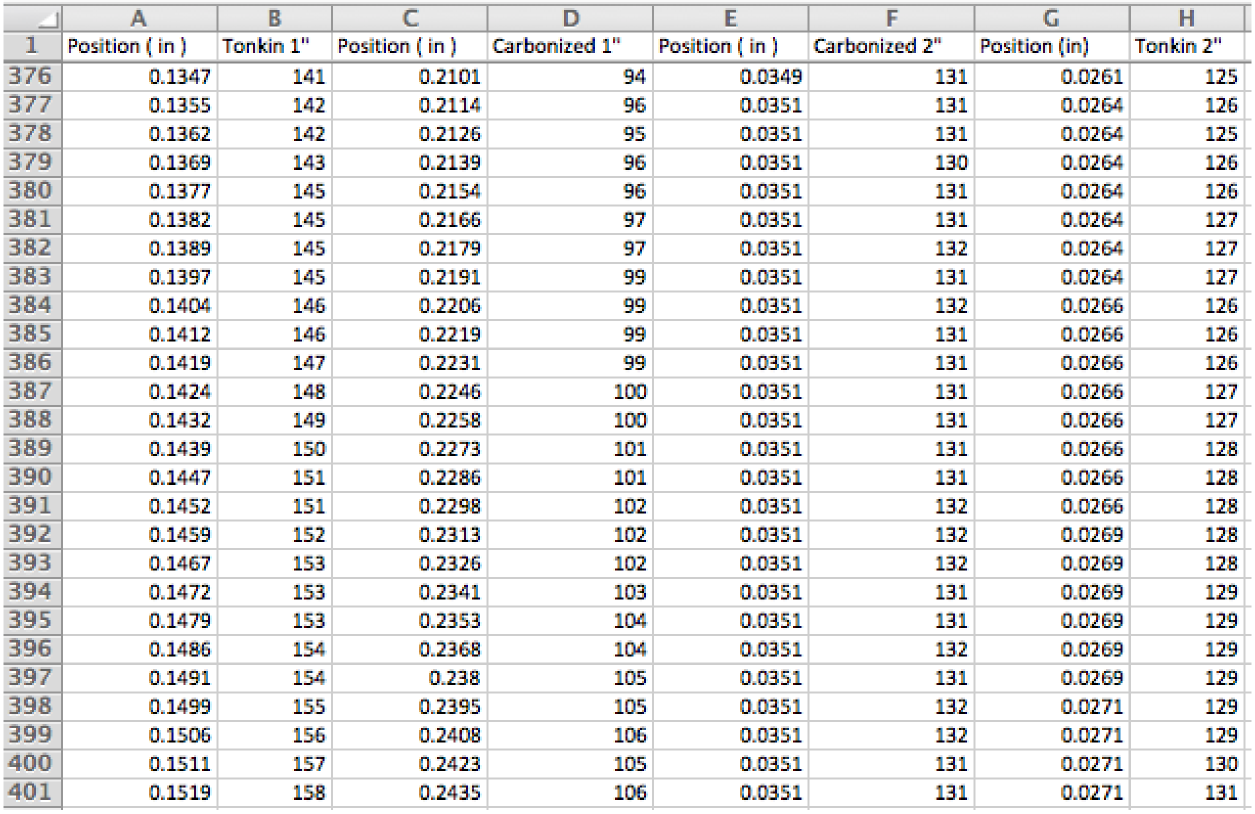
	A	B	C	D	E	F	G	H
1	Position (in)	Tonkin 1"	Position (in)	Carbonized	Position (in)	Carbonized 2"	Position (in)	Tonkin 2"
1117	0.0645	3704	0.0578	3709	0.4417	3709	0.5187	3689
1118	0.0645	3708	0.0578	3711	0.4417	3711	0.5189	3693
1119	0.0645	3711	0.0578	3714	0.442	3715	0.5189	3697
1120	0.0645	3715	0.0578	3717	0.442	3719	0.5191	3699
1121	0.0645	3718	0.058	3721	0.4422	3722	0.5191	3702
1122	0.0645	3721	0.058	3724	0.4422	3725	0.5194	3706
1123	0.0647	3725	0.058	3728	0.4425	3728	0.5194	3709
1124	0.0647	3728	0.058	3732	0.4425	3732	0.5196	3712
1125	0.0647	3731	0.0583	3735	0.4427	3736	0.5196	3716
1126	0.0647	3735	0.0583	3739	0.4427	3738	0.5196	3719
1127	0.0647	3737	0.0583	3742	0.443	3741	0.5199	3722
1128	0.0647	3740	0.0583	3744	0.443	3745	0.5199	3725
1129	0.0647	3743	0.0585	3747	0.4432	3749	0.5201	3729
1130	0.0647	3747	0.0585	3752	0.4432	3752	0.5201	3732
1131	0.0647	3752	0.0585	3755	0.4435	3755	0.5204	3735
1132	0.0647	3755	0.0585	3759	0.4435	3761	0.5204	3738
1133	0.0647	3758	0.0588	3762	0.4437	3763	0.5206	3742
1134	0.0647	3761	0.0588	3765	0.4437	3766	0.5206	3746
1135	0.065	3764	0.0588	3769	0.444	3768	0.5209	3749
1136	0.065	3767	0.0588	3772	0.4442	3765	0.5209	3751
1137	0.065	3770	0.059	3776	0.4449	3488	0.5211	3755
1138	0.065	3774	0.059	3778	0.4462	3338	0.5211	3758
1139	0.065	3777	0.059	3781	0.4472	3280	0.5211	3762
1140	0.065	3781	0.059	3785	0.4482	3270	0.5214	3765
1141	0.065	3784	0.0593	3789	0.4492	3282	0.5214	3768
1142	0.065	3788	0.0593	3792	0.4502	3305	0.5216	3772

Example of Raw 3-Point Bend Test Results



	A	B	C	D	E	F	G	H
1	Position (in)	Tonkin 1"	Position (in)	Carbonized 1"	Position (in)	Carbonized 2"		Tonkin 2"
343	0.0627	64	0.1327	119	0.0852	160	0.0314	133
344	0.0635	64	0.1337	118	0.0854	161	0.0314	133
345	0.0642	64	0.1345	110	0.0859	162	0.0314	133
346	0.065	65	0.1355	116	0.0864	164	0.0314	132
347	0.0657	66	0.1362	115	0.0869	164	0.0314	132
348	0.0665	68	0.1372	115	0.0874	165	0.0314	133
349	0.0672	69	0.1379	111	0.0876	167	0.0314	133
350	0.068	69	0.1389	114	0.0881	169	0.0314	133
351	0.0687	71	0.1397	120	0.0886	170	0.0314	132
352	0.0695	72	0.1407	117	0.0889	172	0.0314	134
353	0.0705	72	0.1414	118	0.0894	172	0.0314	134
354	0.0712	73	0.1424	117	0.0899	172	0.0314	134
355	0.072	73	0.1432	121	0.0901	174	0.0314	133
356	0.0727	74	0.1442	120	0.0906	175	0.0314	133
357	0.0735	75	0.1449	119	0.0909	177	0.0314	133
358	0.0742	76	0.1459	120	0.0914	177	0.0314	134
359	0.0749	78	0.1467	120	0.0916	178	0.0314	132
360	0.0757	78	0.1474	123	0.0921	178	0.0314	133
361	0.0767	78	0.1484	123	0.0924	181	0.0314	133
362	0.0774	79	0.1491	123	0.0926	182	0.0314	134
363	0.0782	80	0.1501	124	0.0931	182	0.0314	134
364	0.0789	81	0.1509	124	0.0934	183	0.0314	135
365	0.0797	82	0.1519	123	0.0936	185	0.0314	134
366	0.0804	84	0.1526	125	0.0941	185	0.0314	133
367	0.0812	85	0.1536	126	0.0944	186	0.0314	134
368	0.0822	85	0.1544	126	0.0946	187	0.0316	134

Example of Raw 4-Point Bend Test Results



	A	B	C	D	E	F	G	H
1	Position (in)	Tonkin 1"	Position (in)	Carbonized 1"	Position (in)	Carbonized 2"	Position (in)	Tonkin 2"
376	0.1347	141	0.2101	94	0.0349	131	0.0261	125
377	0.1355	142	0.2114	96	0.0351	131	0.0264	126
378	0.1362	142	0.2126	95	0.0351	131	0.0264	125
379	0.1369	143	0.2139	96	0.0351	130	0.0264	126
380	0.1377	145	0.2154	96	0.0351	131	0.0264	126
381	0.1382	145	0.2166	97	0.0351	131	0.0264	127
382	0.1389	145	0.2179	97	0.0351	132	0.0264	127
383	0.1397	145	0.2191	99	0.0351	131	0.0264	127
384	0.1404	146	0.2206	99	0.0351	132	0.0266	126
385	0.1412	146	0.2219	99	0.0351	131	0.0266	126
386	0.1419	147	0.2231	99	0.0351	131	0.0266	126
387	0.1424	148	0.2246	100	0.0351	131	0.0266	127
388	0.1432	149	0.2258	100	0.0351	131	0.0266	127
389	0.1439	150	0.2273	101	0.0351	131	0.0266	128
390	0.1447	151	0.2286	101	0.0351	131	0.0266	128
391	0.1452	151	0.2298	102	0.0351	132	0.0266	128
392	0.1459	152	0.2313	102	0.0351	132	0.0269	128
393	0.1467	153	0.2326	102	0.0351	132	0.0269	128
394	0.1472	153	0.2341	103	0.0351	131	0.0269	129
395	0.1479	153	0.2353	104	0.0351	131	0.0269	129
396	0.1486	154	0.2368	104	0.0351	132	0.0269	129
397	0.1491	154	0.238	105	0.0351	131	0.0269	129
398	0.1499	155	0.2395	105	0.0351	132	0.0271	129
399	0.1506	156	0.2408	106	0.0351	132	0.0271	129
400	0.1511	157	0.2423	105	0.0351	131	0.0271	130
401	0.1519	158	0.2435	106	0.0351	131	0.0271	131

Appendix D: Analysis of Bamboo Heat Transfer

Analysis of Bamboo Heat Transfer

Submitted to the Faculty of

WORCESTER POLYTECHNIC INSTITUTE

In partial fulfillment of the requirements for the

Degree of Bachelor of Science in Mechanical Engineering

By

Samuel Johnston

Dana Valentine

Introduction

The objective of this project is to analyze heat transfer in bamboo in the context of drying and curing bamboo culms at WPI.

Rationale

This year's bamboo bicycle MQP was significantly delayed while waiting on purchased bamboo culms. The distributor capable of supplying the chosen types of bamboo is located in California, and through a mistake with shipping the order was delayed months while the bamboo was in transit between California and WPI. A system to dry freshly harvested bamboo using WPI facilities will eliminate this delay from future bamboo projects on campus. Additionally, harvesting local bamboo will save shipping and retail costs, freeing up more project budget for other components. By analyzing the heat transfer that occurs during bamboo drying, this project brings WPI a step closer to producing its own bamboo.

State-Of-The-Art

There are many approaches to drying bamboo from around the world. The most common forms of drying are natural air drying and high temperature curing. One of the more interesting methods is that practiced by EcoBamboo in Colombia, where the nodes are bored out to circulate air for forced convection.

Natural Air Drying

Natural air drying is the simplest, as there are no energy requirements. The bamboo is harvested, then left to dry due to radiation from the sun and convection from the surrounding air. The bamboo can be oriented either in a vertical or horizontal position. Figure 1 shows bamboo curing outdoors.

Figure 73. Vertical Drying, from http://www.guaduabamboo.com/bamboo-poles/

While simple and effective, the process takes weeks (Minke 2012). Additionally, most bamboo curing using this method is done in tropical climates, where the process can be done year round. New England winters would prevent WPI project teams from curing during the winter, which is typically the middle of on-campus MQPs.

High Temperature Drying

Drying bamboo using high temperatures significantly reduces drying time, typically from weeks to a matter of hours or days (Minke 2012). The ovens used range from simple structures heated by wood fires, to more precise ovens for commercial applications. Figure 2 shows a simple bamboo curing oven using wood fire as a heat source.

Figure 74. Hight Temperature Drying with Wood Fire, from (Minke 2012)

Forced Convection

By far the most interesting method of drying bamboo is that used by EcoBamboo in Colombia. EcoBamboo's curing method involves boring out the bamboo so that hot air from a solar collector can be circulated via a fan to dry the bamboo from the inside out. Figure 3 shows bamboo being cured using this method. This method minimizes cracking due to the bamboo drying more evenly than an external heat or convection system.

Figure 75. Forced Convection Drying, from (Minke 2012)

State-of-the-art improvement

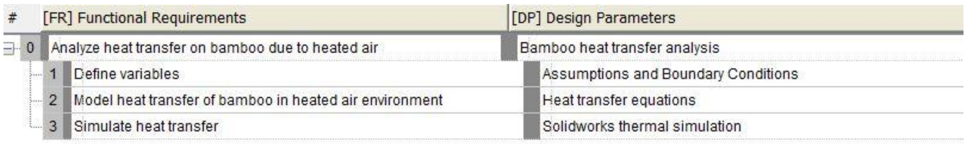
The bamboo drying method analyzed is tailored to fit WPI MQP projects. The heated drying system orients the bamboo vertically to minimize the impact of floor space, as there is limited space for storage of the oven. Drying time is significantly reduced compared to free air drying, and can be operated year round regardless of weather in Worcester, MA.

Approach

Axiomatic Design was used to decompose the problem of drying bamboo for WPI MQPs. Functional Requirements were defined, and corresponding DPs created to achieve a valid design. Once the method of drying bamboo was selected, the following steps were taken to analyze the heat transfer characteristics of bamboo oriented vertically in an oven.

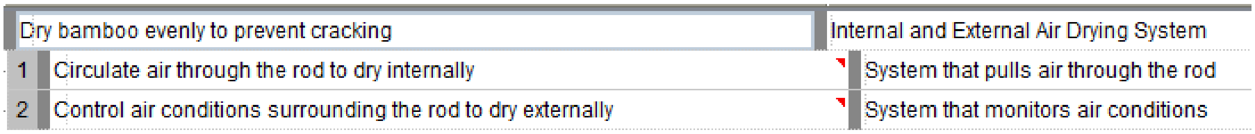
1. Derivation of formulas for convection
2. Setting assumptions and creating excel for convection calculations
3. Solidworks simulation to verify results

Design Decomposition



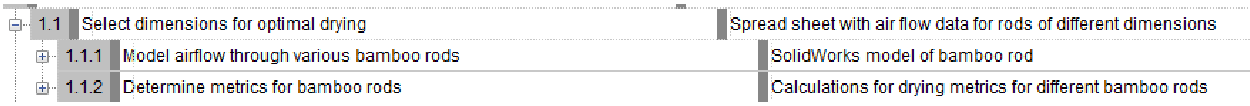
#	[FR] Functional Requirements	[DP] Design Parameters
0	Analyze heat transfer on bamboo due to heated air	Bamboo heat transfer analysis
1	Define variables	Assumptions and Boundary Conditions
2	Model heat transfer of bamboo in heated air environment	Heat transfer equations
3	Simulate heat transfer	Solidworks thermal simulation

The above decomposition shows the steps that were taken to model an oven drying system for WPI. The analysis was broken down into heat transfer calculations based on assumed boundary conditions, SolidWorks models of a bamboo rod and SolidWorks simulations of heating. These steps are shown in the following sections. In addition to the oven curing method, a forced convection, or air drying method was decomposed and analyzed. The decomposition is as follows.



	Dry bamboo evenly to prevent cracking	Internal and External Air Drying System
1	Circulate air through the rod to dry internally	System that pulls air through the rod
2	Control air conditions surrounding the rod to dry externally	System that monitors air conditions

The decomposition shown above breaks down the FR of drying bamboo evenly to prevent cracking into drying the bamboo rod internally and externally. Matching the rates of drying will lead to equal rates of contraction for the interior and the exterior the rod, preventing cracking. FRs 1 and 2 were further decomposed below.

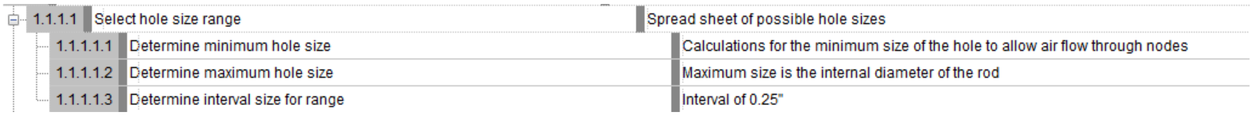


1.1	Select dimensions for optimal drying	Spread sheet with air flow data for rods of different dimensions
1.1.1	Model airflow through various bamboo rods	SolidWorks model of bamboo rod
1.1.2	Determine metrics for bamboo rods	Calculations for drying metrics for different bamboo rods

The problem was decomposed into modeling airflow through bamboo rods and determining metrics for those rods. Bamboo rods of varying dimensions would be modeled using computer simulations of air flow. The rates of heat and mass transfer (metrics) would be determined mathematically.

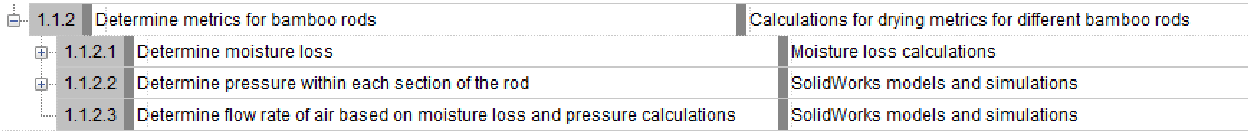
1.1.1	Model airflow through various bamboo rods	SolidWorks model of bamboo rod
1.1.1.1	Select hole size range	Spread sheet of possible hole sizes
1.1.1.2	Select rod length	Rods used in bicycle construction had approximately 3 internodes
1.1.1.3	Generate a model for each set of dimensions	SolidWorks model

To model the rods in SolidWorks, the length of the rod was determined based on the length of bamboo rods used to produce the bicycle. Additionally, the sizes of the holes drilled in the nodes to allow air flow through the rod were varied. This is decomposed below.



1.1.1.1	Select hole size range	Spread sheet of possible hole sizes
1.1.1.1.1	Determine minimum hole size	Calculations for the minimum size of the hole to allow air flow through nodes
1.1.1.1.2	Determine maximum hole size	Maximum size is the internal diameter of the rod
1.1.1.1.3	Determine interval size for range	Interval of 0.25"

Once the dimensions for each rod were determined, they could be modeled in SolidWorks and used in air flow simulations.



1.1.2	Determine metrics for bamboo rods	Calculations for drying metrics for different bamboo rods
1.1.2.1	Determine moisture loss	Moisture loss calculations
1.1.2.2	Determine pressure within each section of the rod	SolidWorks models and simulations
1.1.2.3	Determine flow rate of air based on moisture loss and pressure calculations	SolidWorks models and simulations

Using the dimensions determined above, metrics were determined using mathematical equations and SolidWorks Simulations. The metrics were moisture loss, pressure within each section of the rod, and the desired flow rate calculated based on moisture loss and pressure.

1.1.2.1	Determine moisture loss	Moisture loss calculations
1.1.2.1.1	Determine moisture loss due to air flow	Mass transfer calculations
1.1.2.1.2	Determine moisture loss due to temperature	Heat transfer calculations

The moisture loss is a function of both heat and mass transfer. Mass transfer equations would be used to determine the moisture loss due to air flow and heat transfer calculations could be used to determine moisture loss due to heat. The heat transfer calculations were further decomposed into conduction and convection, as seen in the decomposition below.

1.1.2.1.2	Determine moisture loss due to temperature	Heat transfer calculations
1.1.2.1.2.1	Determine moisture loss due to conduction	Conduction Equation
1.1.2.1.2.2	Determine moisture loss due to convection	Convection Equation

FR2 was to "control air conditions surrounding the rod externally." This was decomposed into controlling temperature and humidity. The simplest system would use ambient conditions. The fluctuation in heat and humidity, however, can provide an inconsistent drying rate. This makes it difficult to match the interior drying rate to the exterior rate. Because of this, the decomposition specifies that humidity and temperature should be kept constant using a thermostat and dehumidifier.

2	Control air conditions surrounding the rod to dry externally	System that monitors air conditions
2.1	Determine ideal air conditions for drying rate	Calculations to determine air conditions as a function of drying rate
2.2	Control humidity of air	Dehumidifier to keep humidity level constant
2.3	Control temperature of air	Thermostat to keep temperature constant

To determine the external drying rate for the rod, FR2.1 was further decomposed, as shown below.

2.1	Determine ideal air conditions for drying rate	Calculations to determine air conditions as a function of drying rate
2.1.1	Determine ideal temperature for drying rate	Calculations for temperature as a function of drying rate
2.1.2	Determine ideal humidity for drying rate	Calculations for humidity as a function of drying rate

"Determining the ideal temperature for drying" can be accomplished by calculating temperature as a function of drying rate, which was found when the internal drying rate was calculated for FR1.

2.1.1	Determine ideal temperature for drying rate	Calculations for temperature as a function of drying rate
2.1.1.1	Determine moisture loss from conduction	Conduction equation
2.1.1.2	Determine moisture loss from convection	Convection equation

The mathematical equations can be broken down, again, into moisture loss due to heat transfer from conduction and convection.

2.1.2	Determine ideal humidity for drying rate	Calculations for humidity as a function of drying rate
2.1.2.1	Determine effects of humidity on drying rate	Research on steam drying and smoking bamboo rods
2.1.2.2	Calculate humidity based on mass transfer	Mass transfer equation

The humidity needed for the drying rate can be found by determining the effect of humidity on drying rate. Several studies explore methods of drying from steaming, to water soaking, to smoking (Minke 2011). This suggests that the relationship between humidity and bamboo drying is complex. When the relationship is understood, mass transfer calculations can be used to mathematically model the effects of humidity on drying.

Calculations

In order to calculate the effect of oven temperature on time, several assumptions had to be made. They are listed in the following table.

Variable	Assumption

Diameter of bamboo rod	2” or 0.0508m, does not change during drying
Wall thickness	0.25” or 0.00635m
Length of bamboo rod	1m
Thermal conductivity	0.1125 W/mK
Density of bamboo	400 kg/m^3
Room temperature	296 K
Orientation of bamboo in oven	Vertical
β	Ideal gas, 1/T$_{\text{infinity}}$
H, latent heat of vaporization for water	2257 kJ/kg
dMc/dt	Rate does not change during the drying process

The following equations were used in the calculations (Bergman 2011):

(1) $$\overline{Nu_L} = \left\{ 0.825 + \frac{0.387 Ra_L^{\frac{1}{6}}}{\left[1+\left(\frac{0.492}{Pr}\right)^{\frac{9}{16}}\right]^{\frac{8}{27}}} \right\}^2$$

(2) $$Ra_L = Gr_L Pr = \frac{g\boldsymbol{\beta}(\boldsymbol{T_s}-\boldsymbol{T_{infinity}})\boldsymbol{L^3}}{\nu\alpha}$$

(3) $$h = \frac{\overline{Nu_L} K}{L}$$

(4) $$Q = h(\pi d L)(T_s - T_{infinity})$$

(5) $$Q = \rho(\pi r^2 l) H \frac{dMc}{dt}$$

The equations were entered into Microsoft Excel, along with the following table of values.

Oven Temperature (K)	v Value	Pr Value
300	15.89	0.707
350	20.92	0.7
400	26.41	0.69

Using oven temperature and tables detailing the thermophysical properties of air, the values of ν and Pr could be determined. The values were used in equation 2 to solve for Ra_L. The resulting value of Ra_L was used to find $\overline{Nu_L}$. This, in turn, was used to find h, using the assumed value of K for bamboo. K was estimated for bamboo using the average of the range of thermal conductivities for various woods. After h was found, it was used to find a value for Q, or heat transfer. Q was used to find the rate of moisture loss over time, or $\frac{dMc}{dt}$ (Wengert 2014). These calculations are summarized in the following table.

Oven Temperature (K)	v Value	Pr Value	RaL Value	NuL Value (Vertical Orientation)	h Value (Vertical Orientation)	Q value (Vertical Orientation)	Q Value (J/h)	dMc/dt (% moisture/h)
300	15.89	0.707	0.000518036	0.807652614	0.090860919	0.000172636	0.621488686	1.44927E-06
350	20.92	0.7	0.003458369	0.857392413	0.096628125	0.002478511	8.922641054	2.08069E-05
400	26.41	0.69	0.003656837	0.858680522	0.096773295	0.004780601	17.21016276	4.01328E-05

The calculations were conducted for three different temperatures: 27°C, slightly warmer than room temperature, 77 °C, the temperature of a warm oven, and 127°C, the temperature at which bamboo fibers begin to lose their strength (Ying et al. 2013). The results show that the rate of drying increases as oven temperature increases.

Air drying

While calculations were not actually completed for the air flow drying method due to their great complexity, the equations that could be used are listed below (Bergman 2011). Complexity was due to the presence of nodes in the bamboo, which is explained further in the discussion section.

(6) $$Re_D \equiv \frac{\rho \mu_m D}{\mu} = \frac{\mu_m D}{\nu}$$

The above equation models internal flow through a cylinder. μ_m is the mean fluid velocity over the tube cross section and D is the tube diameter.

(7) $$f = \frac{64}{Re_D}$$

In order to determine the pressure gradient throughout the rod, the friction factor shown above is used. This factor increases with the surface roughness inside the cylinder. Surface roughness is represented by e and is related to friction factor, f in the equation below.

(8) $$\frac{1}{\sqrt{f}} = -2.0\ log\left[\frac{e/D}{3.7} + \frac{2.51}{Re_D\sqrt{f}}\right]$$

(9) $$q_{cov} = \dot{m}c_p(T_{m,o} - T_{m,i})$$

Equation 9 shows the total heat transfer rate due to convection inside a rod. Equation 10 below shows the constant surface heat flux inside the rod.

(10) $$T_m(x) = T_{m,i} + \frac{q"P}{\dot{m}c_p}x$$

Where q” is a constant that comes from total heat transfer rate, q_{conv}.

SolidWorks Simulation

A SolidWorks simulation was run using the maximum temperature value of 400 K oven temperature to investigate the effect of the nodes on the convective heat transfer. The results of that simulation are shown below in figure 76. The nodes can be clearly seen on the figure as the low temperature areas, as they absorb thermal energy that would otherwise stay on the surface of the bamboo.

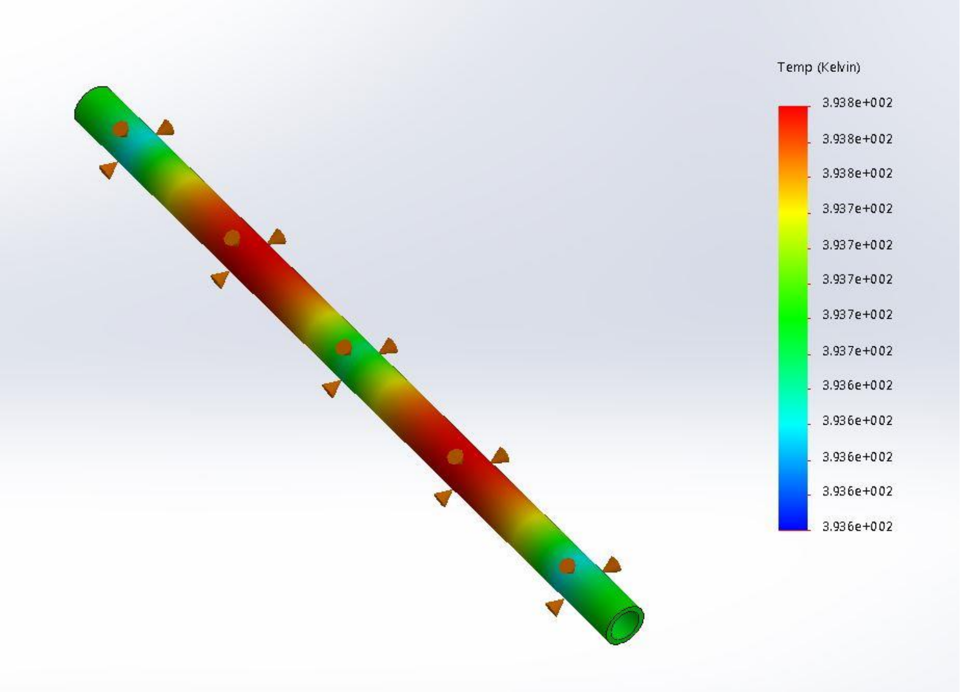


Figure 76.

Discussion

Oven drying is a common curing method for bamboo around the world. In addition to lowering the moisture content of the culm, it kills pathogens and insects that can cause the dried bamboo rods to deteriorate over time. The heat transfer analysis of this method shows that oven drying can significantly reduce the time needed to dry bamboo. The best temperature for drying bamboo would be 77 ^{o}C. This reduces drying time and does not compromise the strength of the bamboo fibers. A drawback of this method is the possibility of cracking the bamboo during the drying process. This occurs because the exterior of the rod dries faster than the interior. As shown in SolidWorks model above, heat concentrations are located between bamboo nodes. A way to combat cracking is to speed internal drying of the rods by allowing air flow between the nodes. This can be accomplished by boring holes in the nodes of the bamboo. This was explored in the air drying design shown in forced convection decomposition.

The design decomposition for air drying is much more complex than the decomposition for heat drying with an oven. This demonstrates the intricacy of the system, as well as the difficulty of implementation. The air drying system attempts to avoid the cracking of the bamboo rods by drying the interior and exterior of the rod at the same rate. To do this, holes are bored in the nodes of the bamboo rod and air is pulled through using a vacuum pump. The conditions surrounding the rod are held constant and, in theory, the interior and exterior of the bamboo contract at the same rate. The nodes present a large problem for this system. Because they form nearly 90^o angles with the interior wall of the rod, they block considerable air flow through the rod. The effect is a series of eddies. These are incredibly difficult to model mathematically and difficult to simulate using air flow software. The unknown effect of the eddies makes it difficult to predict the internal drying rate of the bamboo rod. This system also does not rid the bamboo of pathogens or insects because it operates at a significantly lower temperature. This can cause problems over the lifetime of the bamboo, as it can rot significantly (Minke 2011).

The main reason that supports the use of a simpler, oven curing method for curing bamboo at WPI is the effect of minor cracks on the strength of bamboo. As mentioned in section 6 of the report, the cracked bamboo tested in three and four point bending tests was still safe enough for use in bamboo bicycles. Because of this, there is no reason to opt for a more complex, expensive system to avoid cracking in the bamboo.