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JOINING METHOD FOR MASS PRODUCTION OF BAMBOO BICYCLE FRAMES

A Major Qualifying Project Report

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Abstract

Bamboo bicycles are currently in production for sale in both domestic and foreign markets. In third world countries such as Ghana and Ecuador bamboo bicycles are targeted to be an inexpensive and sustainable method of transportation. Prior technology uses a time and labor-intensive composite layup to join frame tubes. This project set out to improve the production method for these bicycles by developing a more efficient method to create the joints. The result was a thermoformed plastic shell bonded to the bamboo using short fiber reinforced epoxy. To facilitate production of the bicycle, fixturing and manufacturing procedures were also developed.

Acknowledgements

We would like Christopher Brown for his guidance throughout the project process, also for providing us with the bamboo to assemble our prototype bicycle. Thanks to Marty Odlin and the Bamboo Bike Studio for donating resources and vital information to our project. We would also like to thank Bryce Lambert from Bamboo Fencer for providing us with bamboo. Thank you James Loiselle for working with us in the machine shop, Erica Stults for aiding us with our rapid prototype parts, and Adriana Hera for teaching us to use ANSYS. Finally we would like to thank Axiomatic Design Solutions for allowing us to use their Acclaro decomposition software.

Table of Contents

List of figures

List of Tables

1. Introduction

1.1 Objective

The objective of this project is to design and prototype a bamboo bicycle frame that is less expensive and easier to manufacture than current bamboo bicycle designs.

1.2 Rationale

Transportation is directly related to development (Simon, 1996). Walking is the primary method of transportation in underdeveloped countries, such as Ghana (Riverson & Carapetis, 1991). Columbia University conducted a study on the most affordable means of transportation, other than walking, available to residents living in Ghana. The top three transportation methods are scooter, bus and bicycle. Of these three, bicycles are the most efficient (Millennium Cities Initiative, 2008). Manufacturing bamboo bicycles in high volume with low cost provides an IMT, intermediate means of transport (Riverson & Carpetis, 1991). IMT's decrease travel time and effort (Riverson & Carpetis, 1991), allowing people to travel more efficiently. Along with increasing mobility, manufacturing the bicycles in third world countries adds to the local economy and reduces shipping and distribution costs (Bamboo Bike Project Blog, 2011).

The new design will streamline the manufacturing process while enhancing the overall appeal of the bamboo bicycle to customers and potential factory owners. Its implementation would enable current bamboo bicycle manufacturers to further influence the economy and development of their region.

Recently the Bamboo Bike Project opened factories in Ghana and Ecuador (Odlin, 2012). The current mass-produced bamboo bicycle costs approximately 55 USD (Millennium

Cities Initiative, 2008) and each employee can craft about two bicycles per day (2008). Simplifying the design and manufacturing process will reduce costs, time and worker training.

1.3 State of the Art

The current bamboo bicycle design requires each joint to be wrapped by hand with a fiberglass tape and epoxy composite. First the bamboo and metal bicycle components are fixed in the jig. Currently two types of jigs are used during bamboo bicycle production. The tabletop jig fixes the head tube, bottom bracket support tube, and dropouts in place. The foam or balsa wood lugs and bamboo tubes are temporarily epoxied prior to the wrapping process. The stand-up jigs are more conducive to factory production (Odlin, 2012). They also fix the metal parts in place. Lugs, plastic for mass production, and bamboo are temporarily fixed in the same way. The stand-up jigs are advantageous for mass production because it is easier and faster to wrap the joints when the bicycle is vertical. See figure below.

Figure 1: Standup jig in Kimusu (Millennium Cities Initiative, 2009)

After the bicycle is temporarily assembled in the jig, fiberglass strips soaked in epoxy are wrapped around the joints along the "high load paths," (Odlin, 2012). A vinyl tape compression wrap is applied to each joint approximately fifteen minutes after the fiberglass to prevent air bubbles during curing. The vinyl tape is removed and the joints are sanded to remove any sharp edges. Carbon fiber is used to wrap the dropouts instead of fiberglass. This method is time consuming and includes a lot of small, similar parts, making the joining process complicated.

Descriptions of traditional bamboo joining methods, such as the Induo method, lashing (Laroque, 2007), and PVC socket connectors (Albermani, Goh, Chan, 2011) can be found in Appendix 1.

Other research included trade studies of materials such as thermoset and thermoforming plastics. For further information see Appendix 2.

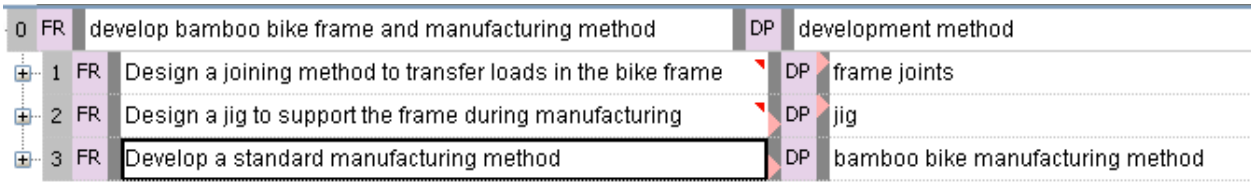
1.4 Approach

This design diverges from traditional bamboo fastening methods and applies current technology to simplify the bicycle joining system. Customer needs and the functional requirements of a bamboo bicycle joining method were listed using axiomatic design (Suh, 2001). The design parameters derived from these functional requirements led to the selection of the new joining and bicycle manufacturing methods.

Two manufacturing methods considered for producing the shells were single-point incremental forming and vacuum forming. Single-point incremental forming (SPIF) is a manufacturing method used to prototype sheet metal or thermoplastic parts. A sheet metal blank is clamped into place and a rounded forming tool is attached to a multi-axis CNC milling machine (Hamilton, 2010). As the tool spins and applies pressure, the sheet metal heats up and stretches into the desired shape (Padrao, 2009). This method of forming cannot make parts that include undercuts (Ham, 2011). Also, multiple passes must be run to create 90 degree angles. Vacuum forming is a plastic forming process. Molds are placed onto a vacuum forming machine. The most basic vacuum forming machine includes a flat perforated plate for the molds to sit on. The plate is the top surface of a sealed chamber. The sealed chamber is connected to a vacuum. A sheet of plastic is heated to its softening point. It is then pushed over a mold. The air underneath the plastic sheet is sucked out using a vacuum, pulling the plastic over the mold. This forming method requires the parts to be trimmed from the excess plastic and cannot create undercuts.

2. Design Decomposition

The original decomposition included the frame design, the tooling design, and the assembly process design. See figure below.



0	FR	develop bamboo bike frame and manufacturing method	DP	development method
1	FR	Design a joining method to transfer loads in the bike frame	DP	frame joints
2	FR	Design a jig to support the frame during manufacturing	DP	jig
3	FR	Develop a standard manufacturing method	DP	bamboo bike manufacturing method

Figure 2: Top level decomposition

Although all three ideas are separate, ease of mass production was an important aspect of the joint design. Incorporating all three branches of the project into one decomposition ensured that tooling and assembly process design were considered when designing the final joining method. The complete decomposition is listed in Appendix 3.

2.1 FR1 Transfer loads

The top level functional requirement of the frame design was to transfer the loads. The frame was analyzed at each tube connection. See Appendix 4 for specific images. The next level of functional requirements ensured that each connection transfers loads and moments in the x, y, and z directions. See Appendix 5 for the coordinate systems at each connection. The loads were analyzed around each tube in the connection and between the tubes. Loads were analyzed in the positive and negative directions. See Appendix 10 for labeled frame elements.

2.2 FR2 Design a jig

The second FR was "Design a jig to support the frame during manufacturing." The jig must position the standard bicycle parts and the bamboo on the x, y and z axes. Each standard bicycle part was analyzed separately to determine the best way to fix their position on the jig. To position the bamboo in the y and z axes, self-centering clamps were developed. The clamps fix the centerline of each tube in the same position regardless of tube diameter. The standard bicycle parts fixed the bamboo tubes along the x-axis.

2.3 FR3 Develop manufacturing method

The third FR was "Develop a standard manufacturing method" so that this assembly method could be implemented in factories. The first step was to prepare the tubes, namely cutting them to length, roughening the ends for bonding, filling the ends of the tubes and checking to make sure the process was completed correctly. Next the bicycle must be assembled in the jig for molding. First, the standard bicycle parts are fixed. Second, the shells are added. Third, the bamboo tubes are centered and the assembly is checked. The space between the plastic shells and the bamboo are sealed. Next, the fiberglass is mixed into the epoxy resin and hardener is added. The epoxy fiberglass composite is then injected into the joints until they are completely filled. Each joint is then checked for fullness and air bubbles.

3. Physical integration

The top level functional requirement, transfer loads, along with the mass production and limited resource constraints, were used to develop the preliminary joint design, a cast molded epoxy joint. After producing the first test joint, it was determined that it would be best to transfer loads through an external shell and use the epoxy primarily for bonding the bamboo to the shell. The functional requirements and design parameters that analyzed each tube connection were used to design the shape of each joint. See the full decomposition and physical integration diagram in Appendices 4 and 6. The second design was composed of sheet metal shells; however, resources for single-point incremental forming were not readily available. It was determined that the most feasible way to prototype the new joining method was vacuum forming. PETG was selected as the material for the shells because it is the easily thermoformed (Midland Plastics, 2012), and has similar properties to polycarbonate. See Appendix 2 for physical and mechanical properties of PETG. The prototype joints proved that an epoxy filled shell could adequately join the bamboo into the correct geometry, however they did not exhibit strong enough properties to transfer the bicycle loads.

3.1 Head tube joint

The top tube and down tube connect to the head tube at the head tube joint. This joint corresponds to FR's 1.1, 1.9, and their respective children. The plastic shell covers the length of the head tube and has two cylindrical protrusions that are connected by a flange, which corresponds to FR's 1.1.5.3, 1.1.6.3, 1.9.5.3, and 1.9.6.3. The inner diameter for the top tube and down tube cylinders are 1.7 and 1.94 inches respectively. These cylinders accommodate bamboo tubes with the largest currently accepted tolerance. They also leave a 0.075 inch buffer for epoxy to bond the culms to the plastic. The design includes 0.2 inch fillets at all corners to reduce stress concentrations. This was addressed in FR 1.10. See solid model below.

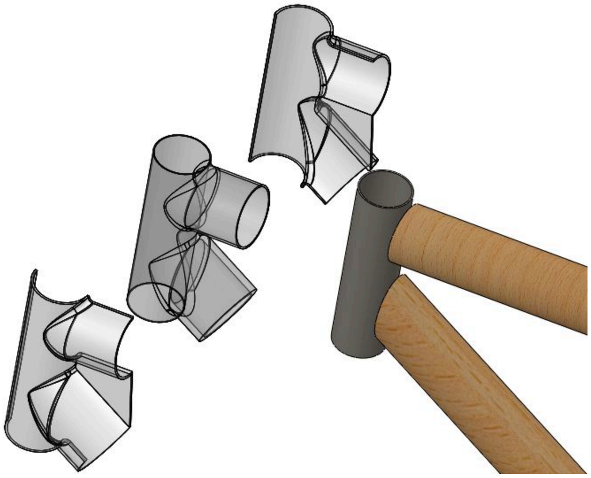


Figure 3: Exploded view of the head tube joint

3.2 Seat post joint

The seat post joint connects the top tube and the seat stays to the seat post. It has a main cylinder for the seat post with a nearly perpendicular cylinder for the top tube. Two small cylinders attach to the sides of the seat post at an angle of 50.79 degrees. The outer shape of the stay holders was altered from a perfect cylinder to accommodate for the limitations of vacuum forming and to reduce stress concentrations in the joint design. FR's 1.5, 1.8 and their corresponding children relate to the seat post joint. The seat post cylinder inner diameter is 1.55 inches and the stay cylinders inner diameters are 1 inch to accommodate the largest currently used bamboo and a 0.075 inch epoxy bonding space. See solid model below.

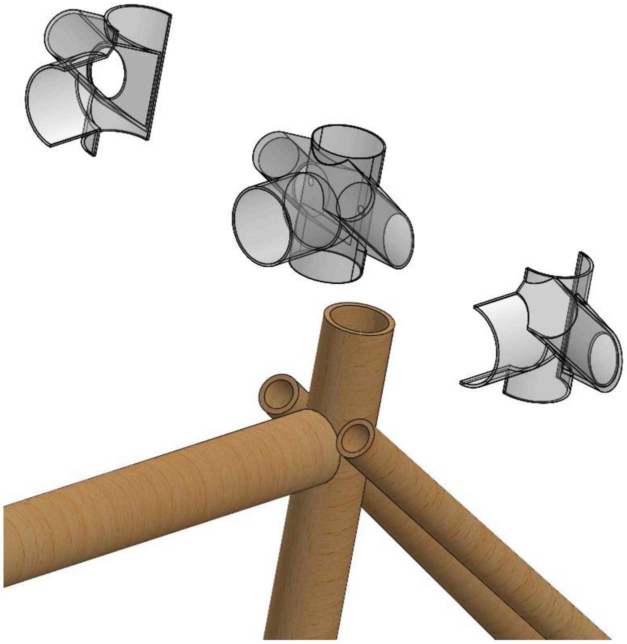


Figure 4: Exploded view of the seat post joint

3.3 Bottom bracket joint

The bottom bracket joint houses the bottom bracket support tube, the seat post, the down tube and the chain stays. See alignment in the solid model below.

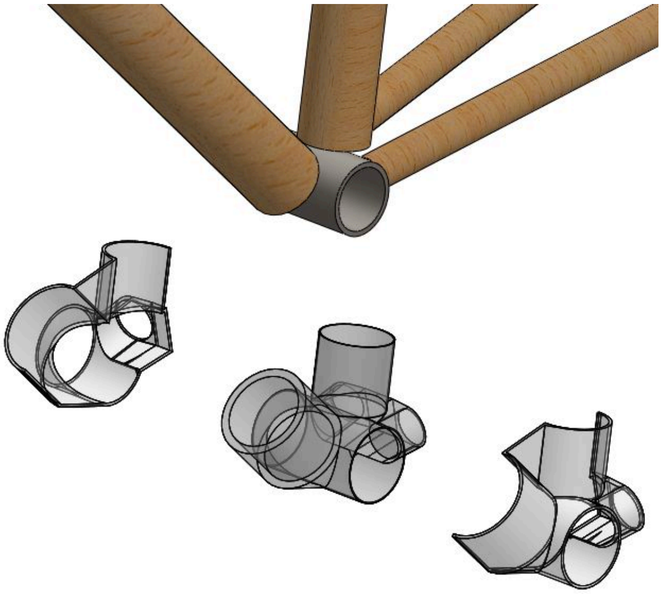


Figure 5: Exploded view of the bottom bracket joint

The diameters of the seat post and down tube do not allow them to sit on the bottom bracket support tube so their center axes align with the center axis of the bottom bracket support tube. Based on the loading analyzed in FR's 1.3, 1.4 and their respective children the best arrangement for load transfer was selected. The chain stay connections to the bottom bracket support tube also posed a challenge because vacuum forming does not allow undercuts, making individual casings for the stays impossible. An elliptical protrusion encases both stays and drafts outward, reducing stress concentrations as listed in FR 1.10. See figure below.

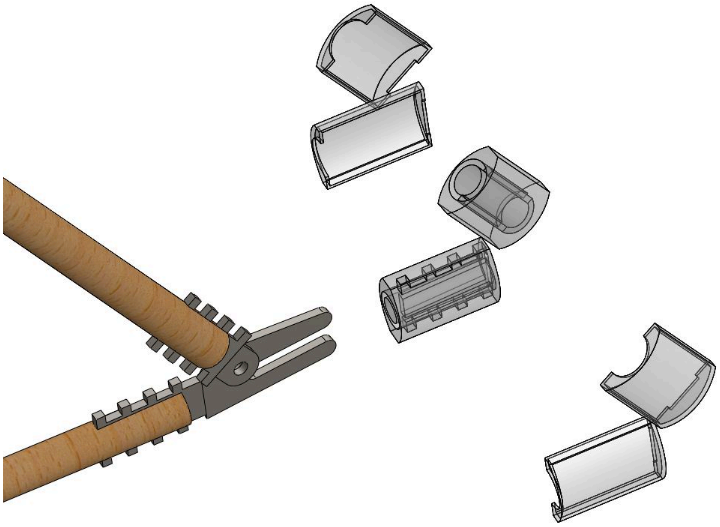


Figure 6: Exploded view of the dropout joints

3.4 Dropout joints

The dropout joints are composed of two pieces, a plastic shell that holds the seat stay to the metal dropout and a separate plastic shell that holds the chain stay to the dropout. The two shells were not connected because there was no common plane to divide both bodies, preventing prototyping by vacuum forming. It was determined that the dropouts did not need the added support of a rib between the two stays because the metal is transferring most of the load. The shell is mainly used to contain the epoxy during injection. Functional requirements 1.6, 1.7 and their children relate to the dropout joints.

4. Finite Element Analysis

Finite element analysis was conducted on a bamboo test joint and the final frame design. Both bamboo and bicycles present difficult challenges in producing accurate results from finite element analysis. Bamboo is a natural orthotropic material that varies in strength and flexibility as you diverge radially outward from the center of the tube. Bicycle loading during riding varies significantly per person and the combination of torsional and impact loads cause the frame to behave unpredictably. See Appendices 7 and 8 for research on bicycle loading and bamboo material properties respectively.

4.1 Test joint

The test joint held two bamboo tubes perpendicular to each other using the plastic shell and epoxy joining method. See figure below.

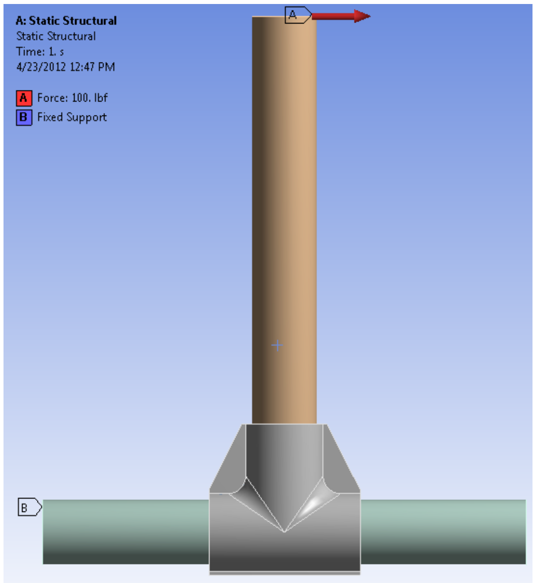


Figure 7: Labeled test joint diagram

Bamboo tube B had fixed supports at both ends. A 100 lb. load was applied to tube A in the x direction. Solutions were found for total deformation and total Von Mises stresses using both longitudinal and transverse bamboo properties. See figures below.

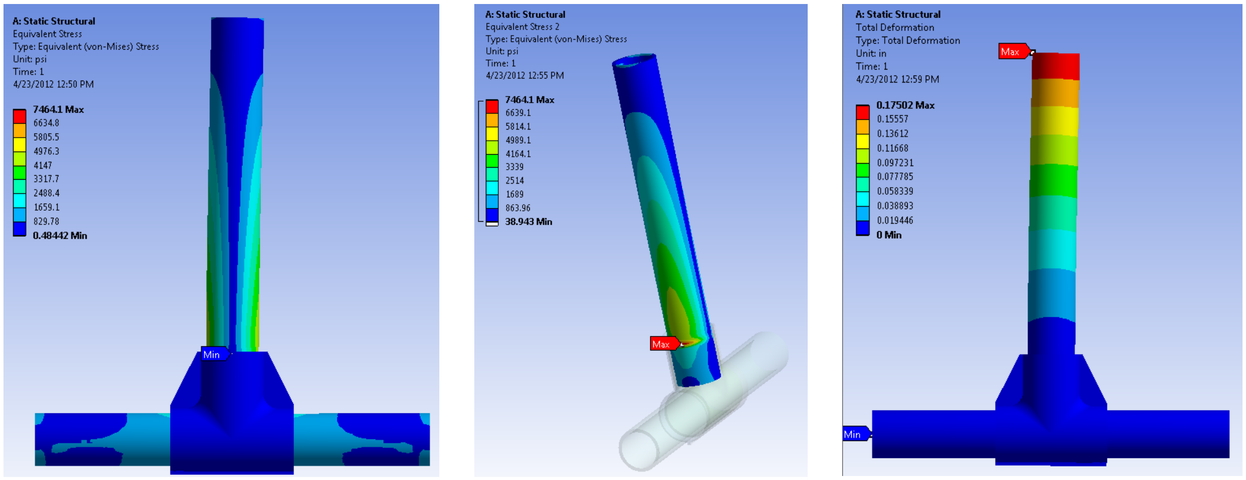


Figure 8: From left to right: Minimum stress, maximum stress, minimum and maximum deformation

See data tables below for the locations of the maximum Von Mises stresses, the maximum and minimum Von Mises stresses, and the maximum and minimum deformations.

Table 1: Longitudinal bamboo properties test joint FEA

Loading	Maximum stress location	Maximum Von Mises (psi)	Minimum Von Mises (psi)	Maximum Deformation (in)	Minimum Deformation (in)
Tube A	Tube A	7464.1	0.48442	0.17502	0.0

Table 2: Transverse bamboo properties test joint FEA

Loading	Maximum stress location	Maximum Von Mises (psi)	Minimum Von Mises (psi)	Maximum Deformation (in)	Minimum Deformation (in)
Epoxy	Tube A	15402	3.3922	1.4518	0.0

4.2 Bicycle Frame

The bicycle frame was fixed at the dropouts and the bottom of the head tube to mimic the supports from the wheels on the ground. Loads of 300lbs each were applied vertically downward at the seat post, the top of the head tube and the inside of the bottom bracket tube. These scenarios would be consistent with someone sitting with all of their weight on the seat, handle bars, and pedals respectively. Total deformation and Von Mises stresses were calculated for each load separately and for all three loads applied at once. See the solutions for all three loads in the tables below.

Table 3: Longitudinal bamboo properties bicycle FEA

Loading	**Maximum stress location**	**Maximum Von Mises (psi)**	**Minimum Von Mises (psi)**	**Maximum Deformation (in)**	**Minimum Deformation (in)**
Head tube	Head tube	6818.4	0.0158891	0.0017030	0.0
Seat post	Head tube	3469.5	0.0669410	0.0104000	0.0
Bottom bracket support tube	Head tube	4599.2	0.0378900	0.0075945	0.0
All three loads	Head tube	12897.0	0.1533200	0.0154580	0.0

Table 4: Transverse bamboo properties bicycle FEA

Loading	**Maximum stress location**	**Maximum Von Mises (psi)**	**Minimum Von Mises (psi)**	**Maximum Deformation (in)**	**Minimum Deformation (in)**
Head tube	Head tube	6818.4	0.0158910	0.0017026	0.0
Seat post	Head tube	4622.0	0.0757730	0.0019954	0.0

Bottom bracket support tube	Head tube	6515.9	0.0667710	0.0015779	0.0
All three loads	Head tube	14237.0	0.1834100	0.0030226	0.0

The actual stresses in the bicycle frame did not match those recorded in the finite element analysis. When the top of the seat post was impacted, the bottom bracket joint gave way. As a result, the seat post joint also failed.

5. Prototype Production

5.1 Computer Aided Design

A CAD model was used to design joints that matched the frame geometry. A top down assembly was used so that joint models would be updated when changes to the tubes or the frame geometry were made. Since the focus of the project was on the joints, two assumptions were made that simplified the modeling process. The first was that current popular bicycle frame geometry is the best geometry to replicate for our purposes. The second was that bamboo can be directly substituted for other bicycle frame materials. Both of these statements can be proven true by the success of the Bamboo Bike Studio as well as other manufactures of bamboo bicycles.

With the previous stated assumptions in mind, the geometry of the frame was modeled after a Trek 3700 mountain bicycle. The exact tube dimensions were not much of a concern since the bamboo tubes have much more variability than the metal tubes they would be replacing, however the locations of the parts that would not be replaced by bamboo are all critical. These parts interface with other components of the bicycle; the dropouts with the rear wheel, the bottom bracket shell with the cranks, and the head tube with the fork. In order to make a CAD model for the bamboo bicycle, first the critical parts listed above were placed. Next, the bamboo tubes could be added to connect these components. Learning from the experience of the Bamboo Bike Studio, it is unnecessary and cost prohibitive to miter the ends of the bamboo tubes, therefore tubes were modeled with straight cut ends (Odlin, 2012). First the tubes connecting the previously placed components were sketched as lines. Later, these lines were used as paths to extrude tubes representing a piece of bamboo. Since the focus of this project is the joint design the diameter for each frame member was taken from data developed by the Bamboo Bike Studio. For each member a nominal size was used although there are tolerances associated with these dimensions. These sizes and tolerances can be found in Appendix 9.

Once all the frame members and stock parts were placed the joints could be developed. Although the joint system was to place shells and then fill them with epoxy they were modeled by doing just the opposite. First, the desired epoxy shape was created. This was done by extruding material around each part, using the tolerances in Appendix 9. The joint was sized by adding 0.075 inches of extra epoxy around the largest tube diameter. This ensured that even the largest diameter tube for a given member would still have enough space between the shell and tube for epoxy to be injected and to create a bond. For the stock parts, tighter tolerances could be used because there is virtually no variability in part size. Just before creating shells, additional features were added such as fillets to reduce stress concentrations and excess material to avoid having undercuts during the vacuum forming process.

With the epoxy shape created the plastic shell could then be modeled. To do this, a block was placed over the joint, and then the SolidWorks cavity tool was used to remove any material overlapping with the previously modeled joint components. Next the shell tool was used to leave a thin plastic layer surrounding the epoxy. Finally the edges of the remaining shell were trimmed. Where appropriate, a rib was left to help transfer loads between adjacent tubes.

5.2 Prototype Manufacturing

In order to build a prototype, correctly sized bamboo was ordered through the Bamboo Bike Studio's website. A kit was purchased that included a top tube, a bored seat tube, a down tube, chain stays and seat stays.

A homemade vacuum forming machine with a forming area of 10 inches by 12 inches was constructed. To make the shells, molds were placed on the top of the vacuum forming machine. A household kitchen oven was used to heat PETG plastic to 325˚F. The plastic sheets were attached to a metal frame for support during heating. When the sheet of PETG plastic sagged to approximately three inches, it was removed from the oven and pushed over the molds and vacuum forming machine while the vacuum pump was turned on, removing air from underneath the sheet to form plastic around the mold.

The basic shapes of the molds were developed from the epoxy layer in the CAD model. First the original epoxy joint was split in half. The mold component that corresponds to the overlapping section of the plastic shell halves was added by extruding the base 0.375 inches midplane. Another 0.375 inches was extruded downward to create the base of the mold. This extrusion was necessary to eliminate the radius created between the bottom of the mold and the forming surface. The base and overlapping section of one mold from each pair was increased by 0.0625 inches to accommodate for the overlapping of the plastic. The molds were made of ABS plastic, using a rapid prototype machine.

The vacuum formed sheets were then cut on the bandsaw, then the ends were cut so that the bamboo could be inserted into the shell. The plastic shell halves were deburred and bonded using Weld-on along the overlapping section. The diameters of each bamboo tube were measured and the plastic tapers were cut to the corresponding diameter. Once the shells were assembled, they were fixed to the jig. The jig included fixtures to hold the dropouts, the bottom bracket support tube, and the head tube in place based on the bicycle geometry. Ten self-centering clamps held the bamboo in place. The clamps were designed to hold the centerline of any tube between 0.7 inches and 2.0 inches in diameter at a fixed distance from the jig. This is accomplished by changing the shape of the 'v-block' contact from a standard straight V to a V with specially designed curved sides. The curves compensates for any change in position of the center of the object that would occur as a function of diameter. The clamping mechanism uses a geared five bar linkage. See figure below.

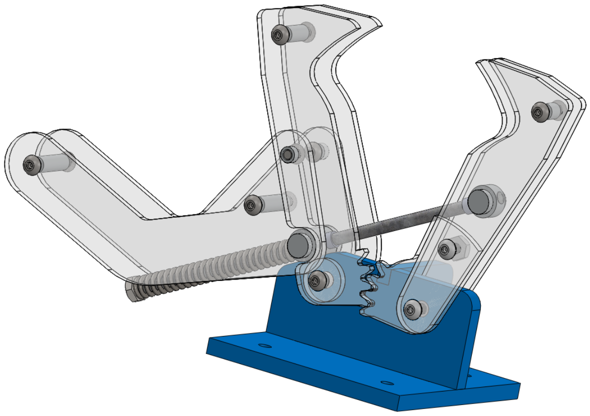


Figure 9: Self-centering clamp

Self-centering clamps were designed in SolidWorks and then cut from acrylic sheet using a laser cutter. Once the clamps were assembled, they were positioned on the jig to hold the bamboo during assembly of the bicycle. The top tube, the down tube and the seat post were each held by two clamps. The stays were each held by one clamp because the interface between the stays and the dropout located the other end of the stay. The clamps were fixed to the jig based on the bicycle geometry. See picture of the jig below.

Figure 10: Bamboo fixed in place on the jig using self-centering clamps

Bamboo was marked and cut to the desired length. Mitering was generally deemed unnecessary based on input by Marty Odlin from the Bamboo Bike Studio (2012). The down tube was the only piece cut at angle. This was done to reduce the amount of epoxy needed to fill the joint. The ends of the bamboo tubes were roughened for better bonding with the epoxy.

The first step in attaching all of the bicycle components to the jig was fixing the metal pieces, head tube, bottom bracket support tube, and dropouts, into their allotted fixturing. The head tube, along with plastic shell, was bolted into place on the head tube stand. The bottom bracket support tube was then screwed into place, elevated in the jig with metal spacers. The dropout fixturing was composed of two metal blocks with through holes for 0.375 inch threaded rod.   The left dropout was placed between the two metal blocks and the right dropout sat on top of the outer metal block. The threaded rods were inserted into the holes in the blocks and the slots on the dropouts. The entire assembly was then bolted down. The bamboo tubes were placed into the clamps, positioning the tubes in the correct geometry. The plastic shells, minus the head tube shell, were then placed in the jig by sliding the bamboo tubes into the plastic shells. Electrical tape was applied at the ends of the plastic shells to prevent epoxy from leaking out during application.

Holes were drilled out in the plastic shells in order to inject the epoxy and to allow air to escape during filling. The position of these holes was determined after consulting with Marty Odlin (2012) who recommended several low stress regions. This information was cross referenced with the most strategic locations based on their height. West Systems resin was mixed with short fiberglass strands. The resin was heated to remove air bubbles. The hardener was then added to the resin. Syringes were used to inject the epoxy into the joints. After the joints were filled, the frame sat in the jig for about 4 hours to allow the epoxy to cure. Once the epoxy cured, the other bicycle components were added to the frame.

6. Testing and Analysis

Marty Odlin, engineering design guru at the Bamboo Bike Studio (2012), stated that every new bicycle design is tested by bicycle couriers in New York City. Each bicycle is ridden for approximately 3,000 miles to test the structural integrity and life of the bicycle. The bicycles are then visually inspected for cracks.

The American Society of Testing and Materials (ASTM) have published standards regarding bicycle frame testing methods. These include tests on frame fatigue with horizontal and vertical loading and frame impact strength (American Society of Testing and Materials, 2012).

Physical testing was not conducted on the prototype. However repetitive impact loading was applied during assembly, fracturing the frame. The loads applied did not exceed those expected during normal cycling. The fractured surfaces were preserved for further analysis.

7. Discussion

As described in the state of the art, the current joining method is time consuming and requires approximately eight hours of training per individual (Yang, Sandgren, Dragsbaek, 2011). The placement of the fiberglass strips is very important to transferring the loads (Odlin, 2012), so a basic understanding of the bicycle design is required for proper assembly. The plastic shell joining method reduces the technical aspect of building the bicycles, which decreases the amount of time and number of steps required to build each bicycle. The permanent shell manufacturing method includes only five steps. The steps are listed below with an approximation of the amount of time necessary to complete each step.

1. Cut the tapered ends of each shell to the correct inner diameter (ten minutes)
2. Roughen the edges of the bamboo (twenty minutes)
3. Slip all of the bicycle components into the jig (five minutes)
4. Seal the interface between the bamboo and the plastic shells (ten minutes)
5. Fill the shells with epoxy (fifteen minutes)

According to the approximate times listed above, each bicycle can be manufactured in sixty minutes. Currently an experienced worker can complete one joint in forty minutes (This statement does not include wrapping of the dropouts, which can be completed in two minutes each by a skilled worker (Odlin, 2012)) (Yang, Sandgren, Dragsbaek, 2011). This is a significant decrease in the amount of time per bicycle. Also, simplifying the manufacturing process would allow bamboo bicycle factories to hire a wider range of employees, helping to fulfill the Bamboo Bike Studio's goal of stimulating local economies.

The new design relies on the permanent shell to transfer most of the load and requires the epoxy simply for bonding. Another similar joining method could use the shells with a thicker layer of epoxy and use both the outer shell and the epoxy to transfer the bicycle loads. The first method requires stronger shells. This could be achieved by changing the material from plastic to sheet metal. However, tooling for manufacturing these shells would result in higher startup costs for the company, but would decrease the cost per bicycle if mass produced. The second method would increase the weight of the bicycle and the cost per bicycle by using more epoxy. However, the original manufacturing costs of the shells would be significantly less.

As stated in the Finite Element Analysis section, bicycles are very difficult to model. A better understanding of the loads each shell must handle is necessary to select a shell material for implementing this joining method on a mass production scale.

8. Conclusions

- There are two options for increasing the joint strength using permanent shells:
  - Use only the shell to transfer loads and select a material that can withstand higher loading than PETG.
  - Use both the shell and the shell bonding material, preferably a reinforced epoxy, to transfer loads. This would increase the weight of the bicycle as more of the composite is added to the joints, however curing time for each joint would decrease, shortening the manufacturing time.
- A better understanding of the loading on a bicycle during normal riding is important for selecting the correct shell material.

Work on this project produced two potentially patentable inventions. Provisional patents have been filed for both the bamboo joining method and the self-centering clamp.

7. Recommendations

A prototype of the bamboo bicycle frame was successfully constructed. However, the joining method did not fulfill all of the “transfer loads” functional requirements. The functional requirements that were not met should be reviewed and improvements should be made to the design parameters.

The bicycle frame prototype proved that a pre-fabricated shell could replace the current bamboo bicycle joining method. Joint strength could be improved by selecting an alternative material for the shells and shell bonding material. Further research should be conducted before the shells are put into production. The joints were made of PETG plastic because vacuum forming was a practical prototyping method. The mass produced shells could be stamped from sheet metal or made from a more resilient material than PETG. Another possibility would be creating the shells from a fiberglass layup. This could be achieved in a similar fashion to vacuum forming, draping fiberglass cloth on the molds to create each shell half. Improvements could also be made by using the epoxy to transfer loads rather than solely for bonding the shell to the bamboo. The epoxy layer thickness should be optimized and further research should be conducted on filler materials.

The process of filling the shells should be refined for mass production due to extensive epoxy leakage during prototype production. A better material should be selected for sealing the joints during epoxy injection. Some suggestions include permanently applying epoxy putty to the plastic-bamboo interface or using shrink-wrapped plastic that could be removed after the epoxy cured.

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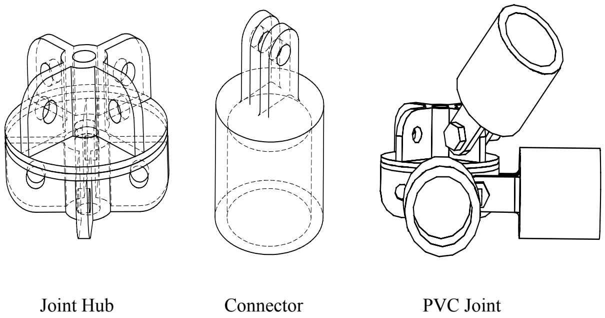
Appendix 1: Bamboo Joining Methods

1.1 PVC joint:

Albermani, Goh and Chan designed a joint that uses metal and PVC to fasten bamboo culms together. Their design consists of two parts, the joint hub and the cylindrical connectors. Up to eight cylindrical connectors can be fastened with a 20 mm bolt. The culms can then slide into the cylindrical (PVC) connectors where they are held in with megapoxy grouting material (Albermani, Goh, Chan, 2011). See figure below


Joint Hub Connector PVC Joint

1.

Figure 11: PVC joint components

1.2 Lashing:

This is the most traditional bamboo fastening method. Soaked friction tight rope is used to bind the culms into position. Once the rope dries it shrinks, securing the bamboo (Laroque, 2007). Bolts can be used to enforce the lashings but according to Albermani, Goh and Chan, drilling increases the likelihood of failure (Albermani, Goh, & Chan, 2011)

1.3 Induo system:

This system screws a sphere onto the end of the bamboo culm and transfers, “the maximum rated load of large bamboo diameters,” (Laroque, 2007).

1.4 Drilling:

Drilling into bamboo is a difficult task. “Drilling through the culm for sake of fastening reduce[s] the bamboo’s [sic] carrying capacity through cleavage failure,” (Albermani, Goh & Chan, 2011).

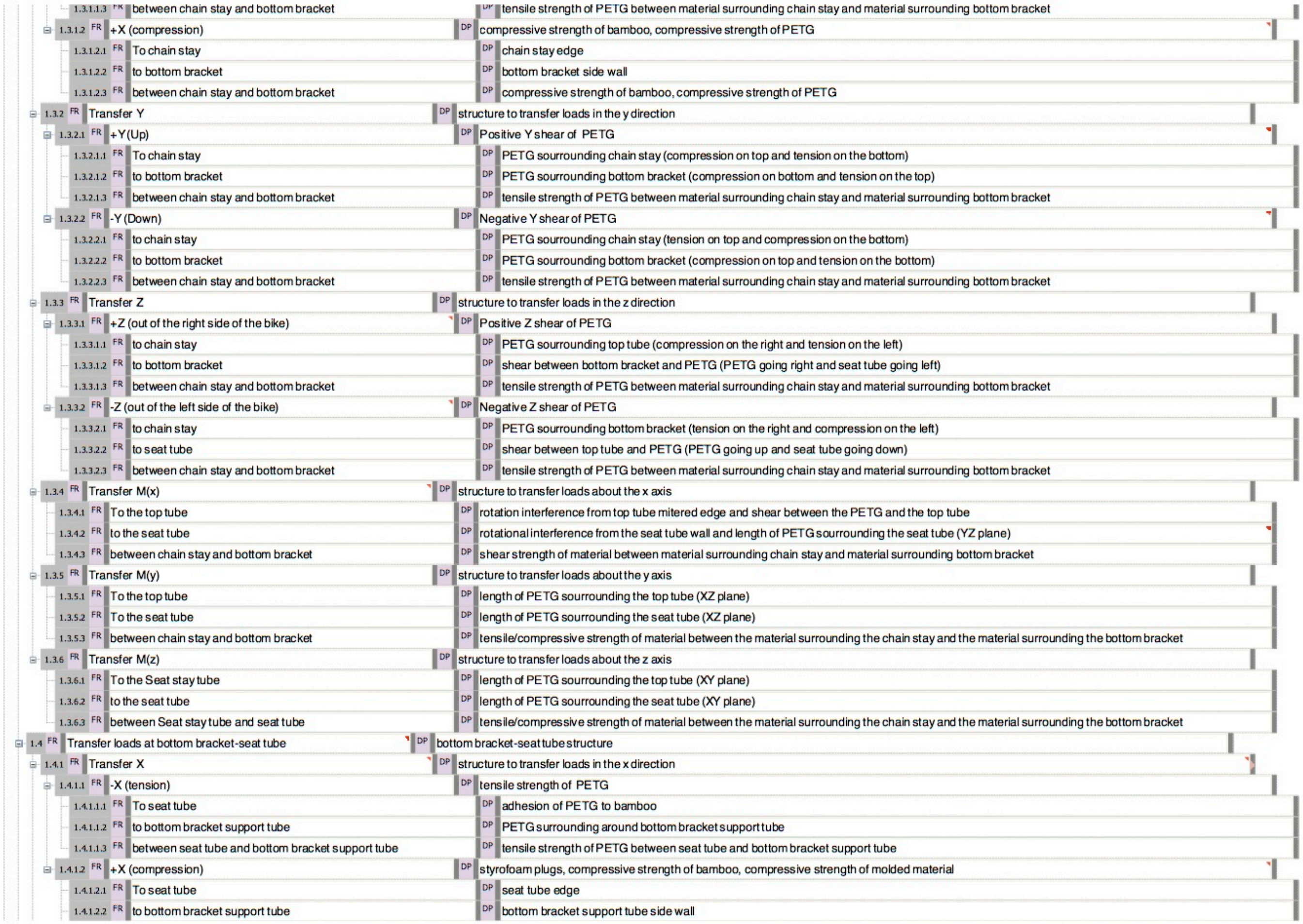
Appendix 2: Trade studies of shell materials

	solvent bond	toughness (ksi*in^5)	tensile	compressive (ksi)	Young's M (psi)	Poisson R	cost ($/lb)	color
Polystyrene (high impact)	Weld-on	.91-2.69	2.9-6.19 psi	3.31-7.21	.168-.37e06	.397-.418	.948-1.04	opaque white
PETG	Weld-on	1.92-2.31	8.7-9.57 ksi	8.34-9.21	.292-.305e06	.395-.411	1.14-1.25	transparent
ABS	Weld-on	1.08-3.24	4.39-6.29 ksi	4.5-8.01	.16-.35e06	.399-.419	1.1-1.55	black or white w/ texture
Kydex	special solvent	3.22-3.52	6.67-8.41	7.25-9.72	.316-.495	.35-.38	1.19-1.31	many colors
Acrylic	Weld-on	.637-1.46	7.01-10.5	10.5-18	.325-.47	.387-.403	1.25-1.37	variety
Polyethylene	welds to itself?	1.38-1.66	3.21-4.5	2.7-3.6	.155-.158	.41-.427	.78-.858	milky
recommended w/ reservations								

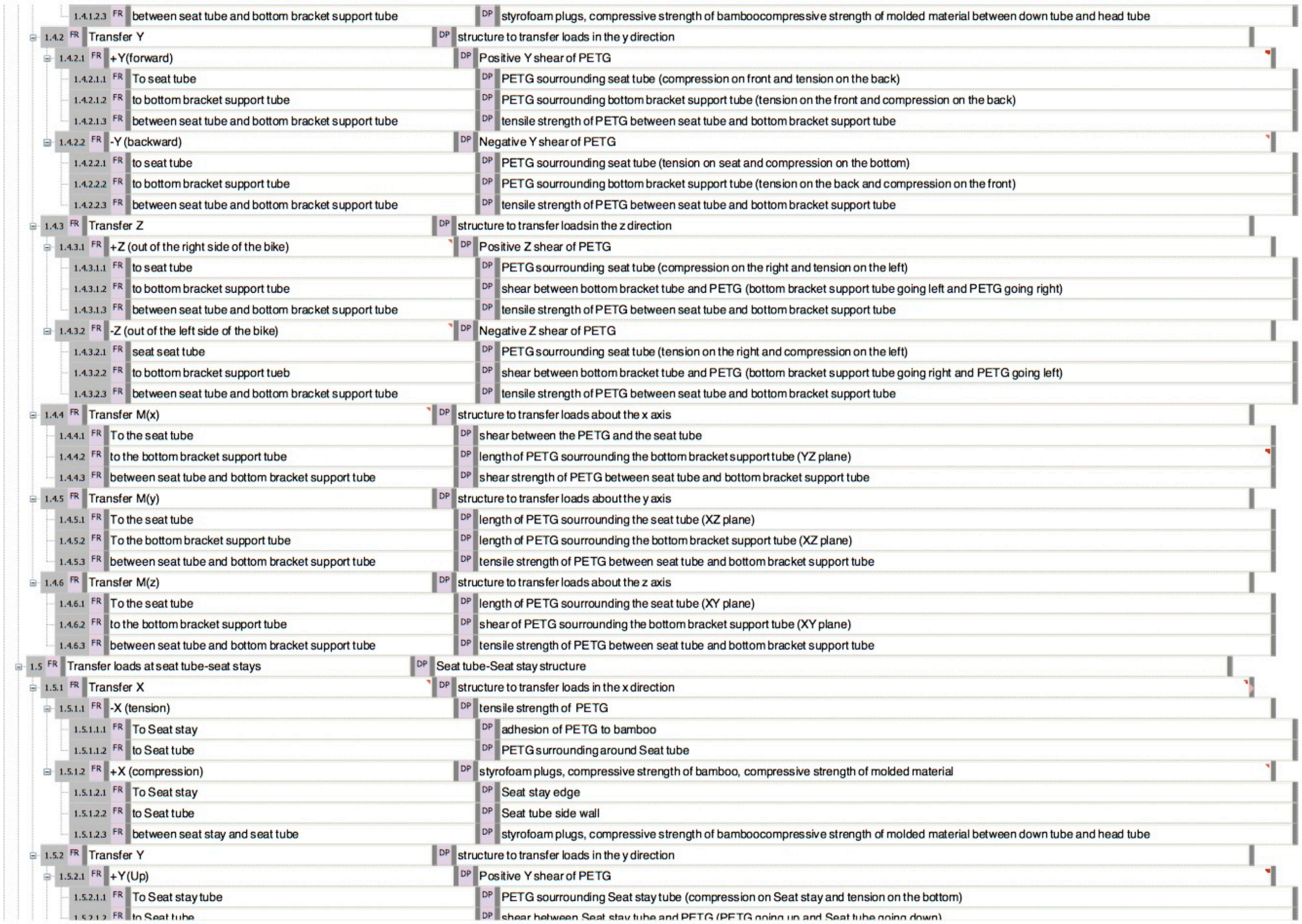
Appendix 3: Decomposition and design matrix

	FR	DP
0	develop bamboo bike frame and manufacturing method	development method
1	Design a joining method to transfer loads in the bike frame	frame joints
1.1	Transfer loads at down tube-head tube	down tube-head tube load structure
1.1.1	Transfer X (along down tube)	structure to transfer loads in the x direction at down tube-head tube connection
1.1.1.1	-X (tension)	tensile strength of epoxy and PETG part
1.1.1.1.1	transfer to the down tube	adhesion of epoxy to bamboo
1.1.1.1.2	transfer to the head tube	PETG part surrounding tube
1.1.1.1.3	transfer between the head tube and down tube	tensile strength of PETG between head tube and down tube
1.1.1.2	+X (compression)	compressive strength of bamboo, compressive strength of PETG
1.1.1.2.1	transfer to the down tube	down tube edge
1.1.1.2.2	transfer to the head tube	head tube side wall
1.1.1.2.3	transfer between the head tube and down tube	compressive strength of bamboo, compressive strength of epoxy and PETG between down tube and head tube
1.1.2	Transfer Y (perpendicular to down tube, towards top tube)	structure to transfer loads in the y direction at down tube-head tube connection
1.1.2.1	+Y (Up)	Positive Y shear of PETG part at down tube-head tube connection
1.1.2.1.1	to down tube	PETG surrounding down tube (compression on top)
1.1.2.1.2	to head tube	shear between head tube and PETG (PETG going up and head tube going down)
1.1.2.1.3	between down tube and head tube	tensile strength of PETG between material surrounding down tube and material surrounding head tube
1.1.2.2	-Y (Down)	Negative Y shear of PETG part at down tube-head tube connection
1.1.2.2.1	to down tube	PETG surrounding down tube (compression on bottom)
1.1.2.2.2	to head tube	shear between down tube and PETG (PETG going down and head tube going up)
1.1.2.2.3	between down tube and head tube	tensile strength of PETG between material surrounding down tube and material surrounding head tube
1.1.3	Transfer Z (perpendicular to down tube, pointing out side of bike)	structure to transfer loads in the z direction at down tube-head tube connection
1.1.3.1	+Z (out of the right side of the bike)	Positive Z shear of PETG part at down tube-head tube connection
1.1.3.1.1	to down tube	PETG surrounding down tube (compression on top)
1.1.3.1.2	to head tube	shear between head tube and PETG (PETG going up and head tube going down)
1.1.3.1.3	between down tube and head tube	tensile strength of PETG between material surrounding down tube and material surrounding head tube
1.1.3.2	-Z (out of the left side of the bike)	Negative Z shear of PETG part at down tube-head tube connection
1.1.3.2.1	to down tube	PETG surrounding down tube (compression on bottom)
1.1.3.2.2	to head tube	PETG sourrounding head tube (compression on the right and tension on the left)
1.1.3.2.3	between down tube and head tube	tensile strength of PETG between down tube and head tube (joining material surrounding down tube with material surrounding head tube)
1.1.4	Transfer M(x)	structure to transfer loads about the x axis at down tube-head tube connection
1.1.4.1	To the down tube	shear between PETG and the down tube
1.1.4.2	to the head tube	length of PETG sourrounding the head tube (YZ plane)
1.1.4.3	between down tube and head tube	shear of PETG joining down tube to head tube (connecting material surrounding down tube to material surrounding head tube)
1.1.5	Transfer M(y)	structure to transfer loads about the y axis at down tube-head tube connection
1.1.5.1	To the down tube	length of PETG surrounding down tube (XZ plane)
1.1.5.2	to the head tube	length of PETG surrounding head tube (XZ plane)
1.1.5.3	between down tube and head tube	PETG web between top tube and down tube (in tension when rotating counterclockwise, in compression when rotating clockwise)
1.1.6	Transfer M(z)	structure to transfer loads about the z axis at down tube-head tube connection
1.1.6.1	To the down tube	length of PETG surrounding down tube (XY plane)
1.1.6.2	to the head tube	length of PETG surrounding head tube (XY plane)
1.1.6.3	between down tube and head tube	shear of PETG web between top tube and down tube
1.2	Transfer loads at down tube-bottom bracket	down tube-bottom bracket structure
1.2.1	Transfer X (along down tube)	structure to transfer loads in the x direction at down tube-bottom bracket connection

1.2.1.1	FR	X- tension	DP	tensile strength of PETG
1.2.1.1.1	FR	transfer to down tube	DP	adhesion of epoxy to bamboo
1.2.1.1.2	FR	transfer to bottom bracket	DP	compressive strength of PETG on back of bottom bracket (facing rear wheel) tensile strength of PETG surrounding the rest of bottom bracket
1.2.1.1.3	FR	transfer between down tube and bottom bracket	DP	tensile strength of PETG between down tube and bottom bracket (material that connects material surrounding down tube and surrounding bottom bracket)
1.2.1.2	FR	X+ compression	DP	compressive strength of bamboo, compressive strength of PETG
1.2.1.2.1	FR	transfer to down tube	DP	down tube edge
1.2.1.2.2	FR	transfer to bottom bracket	DP	bottom bracket side wall
1.2.1.2.3	FR	transfer between down tube and bottom bracket	DP	compressive strength of bamboo, compressive strength of PETG between down tube and head tube
1.2.2	FR	Transfer Y (perpendicular to down tube, towards top tube)	DP	structure to transfer loads in the y direction at down tube-bottom bracket connection
1.2.2.1	FR	Y+(up)	DP	Positive Y shear of PETG at down tube-bottom bracket connection
1.2.2.1.1	FR	to down tube	DP	PETG surrounding down tube (compression on top)
1.2.2.1.2	FR	to bottom bracket	DP	shear between PETG and bottom bracket (PETG going up bracket going down)
1.2.2.1.3	FR	between down tube and bottom bracket	DP	tensile strength of PETG between material surrounding down tube and material surrounding bottom bracket
1.2.2.2	FR	Y-(down)	DP	Negative Y shear of PETG at down tube-bottom bracket connection
1.2.2.2.1	FR	to down tube	DP	PETG surrounding down tube (compression on bottom)
1.2.2.2.2	FR	to bottom bracket	DP	shear between PETG and bottom bracket (PETG going down bracket going up)
1.2.2.2.3	FR	between down tube and bottom bracket	DP	tensile strength of PETG between material surrounding down tube and material surrounding bottom bracket
1.2.3	FR	Transfer Z (perpendicular to down tube, pointing out side of bike)	DP	structure to transfer loads in the z direction at down tube-bottom bracket connection
1.2.3.1	FR	+Z (out right side of bike)	DP	Positive Z shear of PETG at down tube-bottom bracket connection
1.2.3.1.1	FR	to down tube	DP	PETG sourrounding down tube (compression on the right and tension on the left)
1.2.3.1.2	FR	to bottom bracket	DP	PETG sourrounding bottom bracket (compression on the right and tension on the left)
1.2.3.1.3	FR	between down tube adn bottom bracket	DP	tensile strength of PETG between material surrounding down tube and material surrounding bottom bracket
1.2.3.2	FR	-Z (out left side of bike)	DP	Negative Z shear of PETG at down tube-bottom bracket connection
1.2.3.2.1	FR	to down tube	DP	PETG sourrounding down tube (compression on the left and tension on the right)
1.2.3.2.2	FR	to bottom bracket	DP	PETG sourrounding bottom bracket (compression on the left and tension on the right)
1.2.3.2.3	FR	between down tube adn bottom bracket	DP	tensile strength of PETG between material surrounding down tube and material surrounding bottom bracket
1.2.4	FR	Transfer M(x)	DP	load transfering about the x axis at down tube-bottom bracket connection
1.2.4.1	FR	To the down tube	DP	shear between PETG and the down tube
1.2.4.2	FR	to the bottom bracket	DP	length of PETG sourrounding the bottom bracket (YZ plane)
1.2.4.3	FR	between down tube and bottom bracket	DP	shear of PETG joining down tube to bottom bracket (connecting material surrounding down tube to material surrounding bottom bracket)
1.2.5	FR	Transfer M(y)	DP	structure to transfer loads about the y axis at down tube-bottom bracket connection
1.2.5.1	FR	To the down tube	DP	length of PETG sourrounding the bottom bracket (XZ plane)
1.2.5.2	FR	to the bottom bracket	DP	length of PETG sourrounding the bottom bracket (XZ plane)
1.2.5.3	FR	between down tube and bottom bracket	DP	PETG web between down tube and seat tube (in tension when rotating clockwise, in compression when rotating counterclockwise)
1.2.6	FR	Transfer M(z)	DP	structure to transfer loads about the z axis at down tube-bottom bracket connection
1.2.6.1	FR	To the down tube	DP	length of PETG sourrounding the bottom bracket (XY plane)
1.2.6.2	FR	to the bottom bracket	DP	length of PETG sourrounding the bottom bracket (XY plane)
1.2.6.3	FR	between down tube and bottom bracket	DP	shear of PETG web between down tube and seat tube
1.3	FR	Transfer loads at bottom bracket-chain stays	DP	bottom bracket-chain stays structure
1.3.1	FR	Transfer X	DP	structure to transfer loads in x direction at bottom bracket-chain stays
1.3.1.1	FR	-X (tension)	DP	tensile strength of PETG
1.3.1.1.1	FR	To chain stay	DP	adhesion of epoxy to bamboo
1.3.1.1.2	FR	to bottom bracket	DP	PETG sourrounding bottom bracket



	FR	DP
1.3.1.1.3	between chain stay and bottom bracket	tensile strength of PETG between material surrounding chain stay and material surrounding bottom bracket
1.3.1.2	+X (compression)	compressive strength of bamboo, compressive strength of PETG
1.3.1.2.1	To chain stay	chain stay edge
1.3.1.2.2	to bottom bracket	bottom bracket side wall
1.3.1.2.3	between chain stay and bottom bracket	compressive strength of bamboo, compressive strength of PETG
1.3.2	Transfer Y	structure to transfer loads in the y direction
1.3.2.1	+Y (Up)	Positive Y shear of PETG
1.3.2.1.1	To chain stay	PETG sourrounding chain stay (compression on top and tension on the bottom)
1.3.2.1.2	to bottom bracket	PETG sourrounding bottom bracket (compression on bottom and tension on the top)
1.3.2.1.3	between chain stay and bottom bracket	tensile strength of PETG between material surrounding chain stay and material surrounding bottom bracket
1.3.2.2	-Y (Down)	Negative Y shear of PETG
1.3.2.2.1	to chain stay	PETG sourrounding chain stay (tension on top and compression on the bottom)
1.3.2.2.2	to bottom bracket	PETG sourrounding bottom bracket (compression on top and tension on the bottom)
1.3.2.2.3	between chain stay and bottom bracket	tensile strength of PETG between material surrounding chain stay and material surrounding bottom bracket
1.3.3	Transfer Z	structure to transfer loads in the z direction
1.3.3.1	+Z (out of the right side of the bike)	Positive Z shear of PETG
1.3.3.1.1	to chain stay	PETG sourrounding top tube (compression on the right and tension on the left)
1.3.3.1.2	to bottom bracket	shear between bottom bracket and PETG (PETG going right and seat tube going left)
1.3.3.1.3	between chain stay and bottom bracket	tensile strength of PETG between material surrounding chain stay and material surrounding bottom bracket
1.3.3.2	-Z (out of the left side of the bike)	Negative Z shear of PETG
1.3.3.2.1	to chain stay	PETG sourrounding bottom bracket (tension on the right and compression on the left)
1.3.3.2.2	to seat tube	shear between top tube and PETG (PETG going up and seat tube going down)
1.3.3.2.3	between chain stay and bottom bracket	tensile strength of PETG between material surrounding chain stay and material surrounding bottom bracket
1.3.4	Transfer M(x)	structure to transfer loads about the x axis
1.3.4.1	To the top tube	rotation interference from top tube mitered edge and shear between the PETG and the top tube
1.3.4.2	to the seat tube	rotational interference from the seat tube wall and length of PETG sourrounding the seat tube (YZ plane)
1.3.4.3	between chain stay and bottom bracket	shear strength of material between material surrounding chain stay and material surrounding bottom bracket
1.3.5	Transfer M(y)	structure to transfer loads about the y axis
1.3.5.1	To the top tube	length of PETG sourrounding the top tube (XZ plane)
1.3.5.2	To the seat tube	length of PETG sourrounding the seat tube (XZ plane)
1.3.5.3	between chain stay and bottom bracket	tensile/compressive strength of material between the material surrounding the chain stay and the material surrounding the bottom bracket
1.3.6	Transfer M(z)	structure to transfer loads about the z axis
1.3.6.1	To the Seat stay tube	length of PETG sourrounding the top tube (XY plane)
1.3.6.2	to the seat tube	length of PETG sourrounding the seat tube (XY plane)
1.3.6.3	between Seat stay tube and seat tube	tensile/compressive strength of material between the material surrounding the chain stay and the material surrounding the bottom bracket
1.4	Transfer loads at bottom bracket-seat tube	bottom bracket-seat tube structure
1.4.1	Transfer X	structure to transfer loads in the x direction
1.4.1.1	-X (tension)	tensile strength of PETG
1.4.1.1.1	To seat tube	adhesion of PETG to bamboo
1.4.1.1.2	to bottom bracket support tube	PETG surrounding around bottom bracket support tube
1.4.1.1.3	between seat tube and bottom bracket support tube	tensile strength of PETG between seat tube and bottom bracket support tube
1.4.1.2	+X (compression)	styrofoam plugs, compressive strength of bamboo, compressive strength of molded material
1.4.1.2.1	To seat tube	seat tube edge
1.4.1.2.2	to bottom bracket support tube	bottom bracket support tube side wall

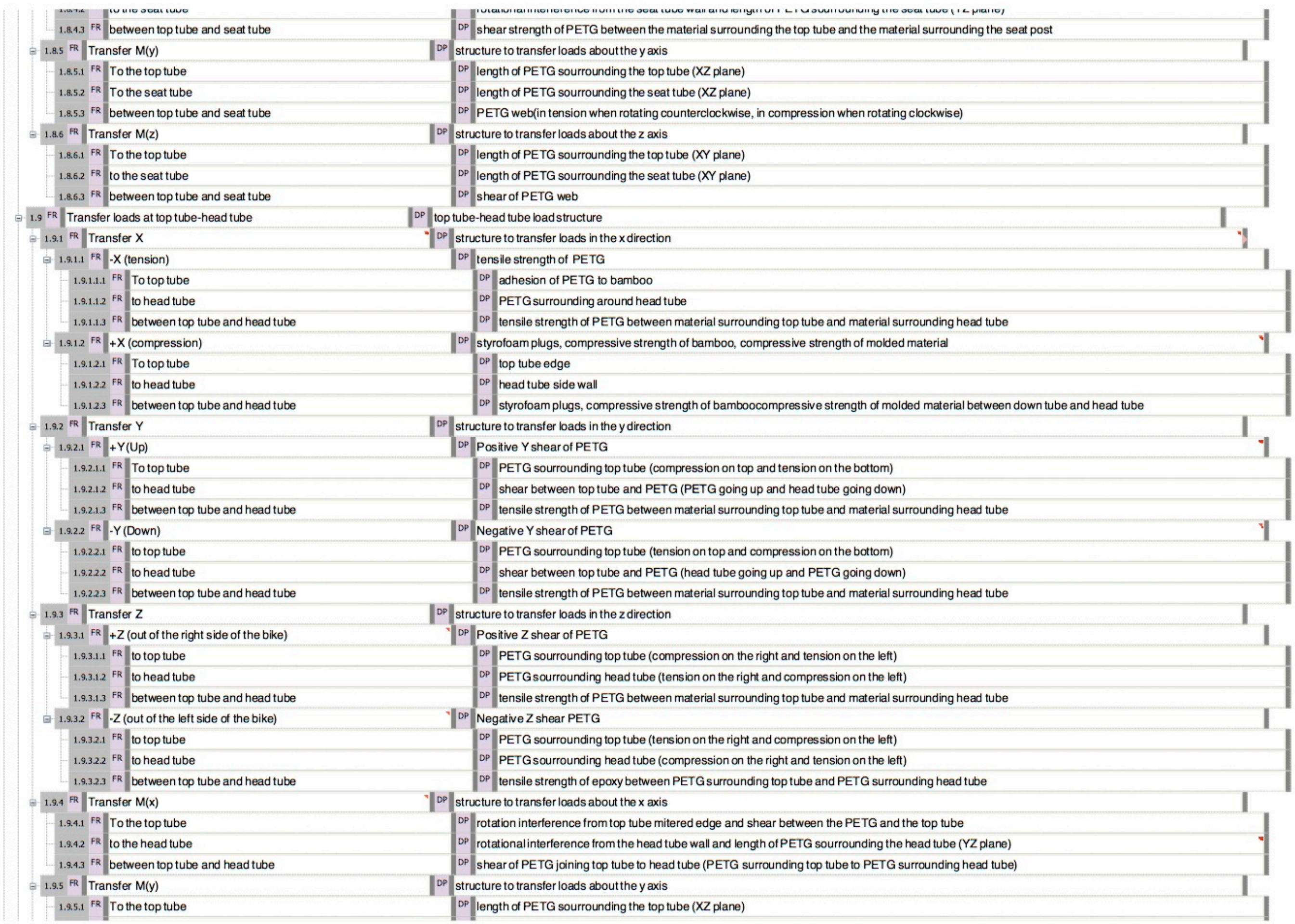


1.4.1.2.3	FR	between seat tube and bottom bracket support tube	DP	styrofoam plugs, compressive strength of bamboocompressive strength of molded material between down tube and head tube
1.4.2	FR	Transfer Y	DP	structure to transfer loads in the y direction
1.4.2.1	FR	+Y(forward)	DP	Positive Y shear of PETG
1.4.2.1.1	FR	To seat tube	DP	PETG sourrounding seat tube (compression on front and tension on the back)
1.4.2.1.2	FR	to bottom bracket support tube	DP	PETG sourrounding bottom bracket support tube (tension on the front and compression on the back)
1.4.2.1.3	FR	between seat tube and bottom bracket support tube	DP	tensile strength of PETG between seat tube and bottom bracket support tube
1.4.2.2	FR	-Y (backward)	DP	Negative Y shear of PETG
1.4.2.2.1	FR	to seat tube	DP	PETG sourrounding seat tube (tension on seat and compression on the bottom)
1.4.2.2.2	FR	to bottom bracket support tube	DP	PETG sourrounding bottom bracket support tube (tension on the back and compression on the front)
1.4.2.2.3	FR	between seat tube and bottom bracket support tube	DP	tensile strength of PETG between seat tube and bottom bracket support tube
1.4.3	FR	Transfer Z	DP	structure to transfer loadsin the z direction
1.4.3.1	FR	+Z (out of the right side of the bike)	DP	Positive Z shear of PETG
1.4.3.1.1	FR	to seat tube	DP	PETG sourrounding seat tube (compression on the right and tension on the left)
1.4.3.1.2	FR	to bottom bracket support tube	DP	shear between bottom bracket tube and PETG (bottom bracket support tube going left and PETG going right)
1.4.3.1.3	FR	between seat tube and bottom bracket support tube	DP	tensile strength of PETG between seat tube and bottom bracket support tube
1.4.3.2	FR	-Z (out of the left side of the bike)	DP	Negative Z shear of PETG
1.4.3.2.1	FR	seat seat tube	DP	PETG sourrounding seat tube (tension on the right and compression on the left)
1.4.3.2.2	FR	to bottom bracket support tueb	DP	shear between bottom bracket tube and PETG (bottom bracket support tube going right and PETG going left)
1.4.3.2.3	FR	between seat tube and bottom bracket support tube	DP	tensile strength of PETG between seat tube and bottom bracket support tube
1.4.4	FR	Transfer M(x)	DP	structure to transfer loads about the x axis
1.4.4.1	FR	To the seat tube	DP	shear between the PETG and the seat tube
1.4.4.2	FR	to the bottom bracket support tube	DP	length of PETG sourrounding the bottom bracket support tube (YZ plane)
1.4.4.3	FR	between seat tube and bottom bracket support tube	DP	shear strength of PETG between seat tube and bottom bracket support tube
1.4.5	FR	Transfer M(y)	DP	structure to transfer loads about the y axis
1.4.5.1	FR	To the seat tube	DP	length of PETG sourrounding the seat tube (XZ plane)
1.4.5.2	FR	To the bottom bracket support tube	DP	length of PETG sourrounding the bottom bracket support tube (XZ plane)
1.4.5.3	FR	between seat tube and bottom bracket support tube	DP	tensile strength of PETG between seat tube and bottom bracket support tube
1.4.6	FR	Transfer M(z)	DP	structure to transfer loads about the z axis
1.4.6.1	FR	To the seat tube	DP	length of PETG sourrounding the seat tube (XY plane)
1.4.6.2	FR	to the bottom bracket support tube	DP	shear of PETG sourrounding the bottom bracket support tube (XY plane)
1.4.6.3	FR	between seat tube and bottom bracket support tube	DP	tensile strength of PETG between seat tube and bottom bracket support tube
1.5	FR	Transfer loads at seat tube-seat stays	DP	Seat tube-Seat stay structure
1.5.1	FR	Transfer X	DP	structure to transfer loads in the x direction
1.5.1.1	FR	-X (tension)	DP	tensile strength of PETG
1.5.1.1.1	FR	To Seat stay	DP	adhesion of PETG to bamboo
1.5.1.1.2	FR	to Seat tube	DP	PETG surrounding around Seat tube
1.5.1.2	FR	+X (compression)	DP	styrofoam plugs, compressive strength of bamboo, compressive strength of molded material
1.5.1.2.1	FR	To Seat stay	DP	Seat stay edge
1.5.1.2.2	FR	to Seat tube	DP	Seat tube side wall
1.5.1.2.3	FR	between seat stay and seat tube	DP	styrofoam plugs, compressive strength of bamboocompressive strength of molded material between down tube and head tube
1.5.2	FR	Transfer Y	DP	structure to transfer loads in the y direction
1.5.2.1	FR	+Y(Up)	DP	Positive Y shear of PETG
1.5.2.1.1	FR	To Seat stay tube	DP	PETG sourrounding Seat stay tube (compression on Seat stay and tension on the bottom)
1.5.2.1.2	FR	to Seat tube	DP	shear between Seat stay tube and PETG (PETG going up and Seat tube going down)

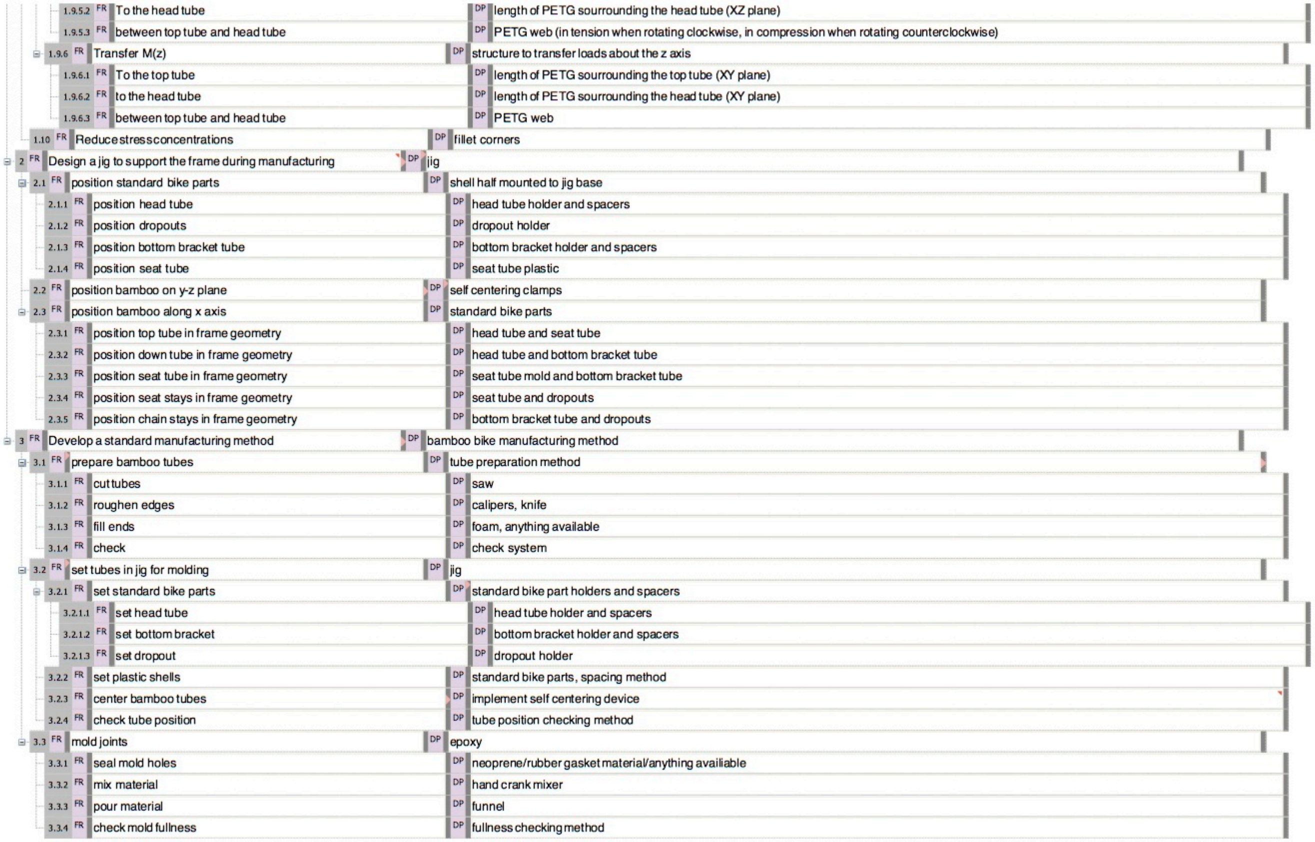
	FR	DP
1.5.2.2	-Y (Down)	Negative Y shear of PETG
1.5.2.2.1	to Seat stay	PETG sourrounding Seat stay tube (tension on top and compression on the bottom)
1.5.2.2.2	to Seat tube	shear between Seat tube and PETG (Seat tube going up and PETG going down)
1.5.3	Transfer Z	structure to transfer loads in the z direction
1.5.3.1	+Z (out of the right side of the bike)	Positive Z shear of PETG
1.5.3.1.1	to Seat stay	PETG sourrounding Seat stay (compression on the right and tension on the left)
1.5.3.1.2	to Seat tube	PETG sourrounding Seat tube (tension on the right and compression on the left)
1.5.3.2	-Z (out of the left side of the bike)	Negative Z shear of PETG
1.5.3.2.1	Seat stay tube	PETG sourrounding Seat stay (tension on the right and compression on the left)
1.5.3.2.2	to Seat tube	PETG sourrounding Seat tube (compression on the right and tension on the left)
1.5.4	Transfer M(x)	structure to transfer loads about the x axis
1.5.4.1	To the Seat stay	shear between the PETG and the Seat stay
1.5.4.2	to the Seat tube	length of PETG sourrounding the Seat tube (YZ plane)
1.5.5	Transfer M(y)	structure to transfer loads about the y axis
1.5.5.1	To the Seat stay	length of PETG sourrounding the Seat stay (XZ plane)
1.5.5.2	To the Seat tube	length of PETG sourrounding the Seat tube (XZ plane)
1.5.6	Transfer M(z)	structure to transfer loads about the z axis
1.5.6.1	To the Seat stay	length of PETG sourrounding the Seat stay (XY plane)
1.5.6.2	to the Seat tube	length of PETG sourrounding the Seat tube (XY plane)
1.5.6.3	between Seat stay and Seat tube	PETG web
1.6	Transfer loads at dropout-chain stays	drop out - chain stay load structure
1.6.1	Transfer X (along chain stays)	structure to transfer loads in the x direction at dropout-chain stays connection
1.6.1.1	-X (tension)	tensile strength of PETG at drop out-chain stays connection
1.6.1.1.1	Transfer to drop out	adhesion of PETG to bamboo
1.6.1.1.2	Transfer to chain stay	PETG surrounding chain stays
1.6.1.1.3	Transfer between drop out and chain stays	tensile strength of material between drop out and chain stays (material that connects material surrounding drop out and surrounding chain stays)
1.6.1.2	+X (compression)	styrofoam plugs, compressive strength of bamboo, compressive strength of molded material
1.6.1.2.1	Transfer to drop out	drop out edge
1.6.1.2.2	Transfer to chain stay	chain stay side wall
1.6.1.2.3	Transfer between drop out and chain stays	styrofoam plugs, compressive strength of bamboocompressive strength of molded material between down tube and head tube
1.6.2	Transfer Y (perpendicular to chain stays, towards top tube)	structure to transfer loads in the y direction at dropout-chain stays connection
1.6.2.1	+Y (Up)	Positive Y shear of PETG at drop out-chain stays connection
1.6.2.1.1	To drop out	PETG surrounding drop out (compression on top)
1.6.2.1.2	To chain stay	shear between PETG and chain stays (PETG going up chain stays going down)
1.6.2.1.3	Between drop out and chain stays	tensile strength of PETG between material surrounding drop out and material surrounding chain stays
1.6.2.2	-Y (Down)	Negative Y shear of PETG at drop out-chain stays connection
1.6.2.2.1	To drop out	PETG surrounding drop out (compression on bottom)
1.6.2.2.2	To chain stay	shear between PETG and chain stay (material going down chain stay going up)
1.6.2.2.3	Between drop out and chain stays	tensile strength of PETG between material surrounding drop out and material surrounding chain stays
1.6.3	Transfer Z (perpindicular to chain stays, pointing out side of bike)	structure to transfer loads in the z direction at dropout-chain stays connection
1.6.3.1	+Z (out of the right side of the bike)	Positive Z shear of PETG at dropout-chain stays connection
1.6.3.1.1	To drop out	PETG sourrounding drop out (compression on the right and tension on the left)
1.6.3.1.2	To chain stay	PETG sourrounding chain stay (compression on the right and tension on the left)

	FR	DP
1.6.3.1.3	Between the drop out and chain stays	tensile strength of material between material surrounding chain stays and material surrounding drop out
1.6.3.2	-Z (out of the left side of the bike)	Negative Z shear of PETG at dropout-chain stays connection
1.6.3.2.1	To drop out	PETG sourrounding drop out (compression on the left and tension on the right)
1.6.3.2.2	To chain stay	PETG sourrounding chain stays (compression on the left and tension on the right)
1.6.3.2.3	Between the drop out and chain stays	tensile strength of material between material surrounding chain stays and material surrounding drop out
1.6.4	Transfer M(x)	structure to transfer loads about the x axis at dropout-chain stays connection
1.6.4.1	To the drop out	shear between the PETG and the drop out
1.6.4.2	To the chain stay	length of PETG sourrounding the drop out (YZ plane)
1.6.4.3	Between drop out and chain stays	shear of PETG joining chain stays to drop out (connecting material surrounding chain stays to material surrounding drop out)
1.6.5	Transfer M(y)	structure to transfer loads about the y axis at dropout-chain stays connection
1.6.5.1	To the drop out	length of PETG surrounding the drop out (XZ plane)
1.6.5.2	The the chain stay	length of PETG surrounding the drop out (XZ plane)
1.6.5.3	Between the drop out and chain stays	PETG web (in tension when rotating clockwise, in compression when rotating counterclockwise)
1.6.6	Transfer M(z)	structure to transfer loads about the z axis at dropout-chain stays connection
1.6.6.1	To the drop out	length of PETG surrounding the drop out (XY plane)
1.6.6.2	To the chain stay	length of PETG surrounding the chain stay (XY plane)
1.6.6.3	Between drop out and chain stays	shear of PETG web
1.7	Transfer loads at dropout-seat stays	drop out - seat stay load structure
1.7.1	Transfer X (perpendicular to seat stays, toward down tube)	structure to transfer loads in the x direction at dropout-seat stays connection
1.7.1.1	-X (tension)	tensile strength of PETG at dropout-seat stays connection
1.7.1.1.1	To drop out	adhesion of PETG to bamboo
1.7.1.1.2	To seat stay	PETG surrounding seat stays
1.7.1.1.3	Between drop out and seat stays	tensile strength of material between drop out and seat stays (material that connects material surrounding drop out and surrounding seat stays)
1.7.1.2	+X (compression)	styrofoam plugs, compressive strength of bamboo, compressive strength of molded material
1.7.1.2.1	To drop out	drop out edge
1.7.1.2.2	To seat stay	seat stay side wall
1.7.1.2.3	Between drop out and seat stays	styrofoam plugs, compressive strength of bamboocompressive strength of molded material between down tube and head tube
1.7.2	Transfer Y (along seat stays)	structure to transfer loads in the y direction at dropout-seat stays connection
1.7.2.1	+Y(Up)	Positive Y shear of PETG at dropout-seat stays connection
1.7.2.1.1	To drop out	PETG surrounding drop out (compression on top)
1.7.2.1.2	To seat stay	shear between PETG and seat stays (material going up seat stays going down)
1.7.2.1.3	Between drop out and seat stays	tensile strength of PETG between material surrounding drop out and material surrounding seat stays
1.7.2.2	-Y (Down)	Negative Y shear of PETG at dropout-seat stays connection
1.7.2.2.1	To drop out	PETG surrounding drop out (compression on bottom)
1.7.2.2.2	To seat stay	shear between PETG and seat stay (material going down seat stay going up)
1.7.2.2.3	Between drop out and seat stays	tensile strength of PETG between material surrounding drop out and material surrounding seat stays
1.7.3	Transfer Z (perpendicular to seat stays, pointing out side of bike	structure to transfer loads in the z direction at dropout-seat stays connection
1.7.3.1	+Z (out of the right side of the bike)	Positive Z shear of PETG at dropout-seat stays connection
1.7.3.1.1	To drop out	PETG sourrounding drop out (compression on the right and tension on the left)
1.7.3.1.2	To seat stay	PETG sourrounding seat stay (compression on the right and tension on the left)
1.7.3.1.3	Between drop out and seat stays	tensile strength of PETG between material surrounding seat stays and material surrounding drop out
1.7.3.2	-Z (out of the left side of the bike)	Negative Z shear of PETG at dropout-seat stays connection
1.7.3.2.1	To drop out	PETG sourrounding drop out (compression on the left and tension on the right)
1.7.3.2.2	To seat stay	PETG sourrounding seat stays (compression on the left and tension on the right)

1.7.3.2.3	FR	Between drop out and seat stays	DP	tensile strength of PETG between material surrounding seat stays and material surrounding drop out
1.7.4	FR	Transfer M(x)	DP	structure to transfer loads about the x axis at dropout-seat stays connection
1.7.4.1	FR	To the drop out	DP	shear between the PETG and the drop out
1.7.4.2	FR	To the seat stay	DP	length of PETG sourrounding the drop out (YZ plane)
1.7.4.3	FR	Between drop out and seat stays	DP	shear of PETG joining seat stays to drop out (connecting material surrounding seat stays to material surrounding drop out)
1.7.5	FR	Transfer M(y)	DP	structure to transfer loads about the y axis at dropout-seat stays connection
1.7.5.1	FR	To the drop out	DP	length of PETG surrounding the drop out (XZ plane)
1.7.5.2	FR	The the seat stay	DP	length of PETG surrounding the drop out (XZ plane)
1.7.5.3	FR	Between drop out and seat stays	DP	PETG web (in tension when rotating clockwise, in compression when rotating counterclockwise)
1.7.6	FR	Transfer M(z)	DP	structure to transfer loads about the z axis at dropout-seat stays connection
1.7.6.1	FR	To the drop out	DP	length of PETG surrounding around the drop out (XY plane)
1.7.6.2	FR	To the seat stay	DP	length of PETG surrounding around the seat stay (XY plane)
1.7.6.3	FR	Between drop out and seat stays	DP	shear of PETG web
1.8	FR	Transfer loads at top tube-seat tube	DP	top tube-seat tube load structure
1.8.1	FR	Transfer X	DP	structure to transfer loads in the x direction
1.8.1.1	FR	-X (tension)	DP	tensile strength of PETG
1.8.1.1.1	FR	To top tube	DP	adhesion of PETG to bamboo
1.8.1.1.2	FR	to seat tube	DP	PETG sourrounding seat tube
1.8.1.1.3	FR	between top tube and seat tube	DP	tensile strength of PETG between the material surrounding the top tube and the material surrounding the seat post
1.8.1.2	FR	+X (compression)	DP	styrofoam plugs, compressive strength of bamboo, compressive strength of molded material
1.8.1.2.1	FR	To top tube	DP	top tube edge
1.8.1.2.2	FR	to seat tube	DP	seat tube side wall
1.8.1.2.3	FR	between top tube and seat tube	DP	styrofoam plugs, compressive strength of bamboocompressive strength of molded material between down tube and head tube
1.8.2	FR	Transfer Y	DP	structure to transfer loads in the y direction
1.8.2.1	FR	+Y (Up)	DP	Positive Y shear of PETG
1.8.2.1.1	FR	To top tube	DP	PETG sourrounding top tube (compression on top and tension on the bottom)
1.8.2.1.2	FR	to seat tube	DP	shear between top tube and PETG (PETG going up and seat tube going down)
1.8.2.1.3	FR	between top tube and seat tube	DP	tensile strength of PETG between the material surrounding the top tube and the material surrounding the seat post
1.8.2.2	FR	-Y (Down)	DP	Negative Y shear of PETG
1.8.2.2.1	FR	to top tube	DP	PETG sourrounding top tube (tension on top and compression on the bottom)
1.8.2.2.2	FR	to seat tube	DP	shear between top tube and PETG (seat tube going up and PETG going down)
1.8.2.2.3	FR	between top tube and seat tube	DP	tensile strength of PETG between the material surrounding the top tube and the material surrounding the seat post
1.8.3	FR	Transfer Z	DP	structure to transfer loads in the z direction
1.8.3.1	FR	+Z (out of the right side of the bike)	DP	Positive Z shear of PETG
1.8.3.1.1	FR	to top tube	DP	PETG sourrounding top tube (compression on the right and tension on the left)
1.8.3.1.2	FR	to seat tube	DP	PETG sourrounding seat tube (tension on the right and compression on the left)
1.8.3.1.3	FR	between top tube and seat tube	DP	tensile strength of PETG between the material surrounding the top tube and the material surrounding the seat post
1.8.3.2	FR	-Z (out of the left side of the bike)	DP	Negative Z shear of PETG
1.8.3.2.1	FR	to top tube	DP	PETG sourrounding top tube (tension on the right and compression on the left)
1.8.3.2.2	FR	to seat tube	DP	PETG sourrounding seat tube (compression on the right and tension on the left)
1.8.3.2.3	FR	between top tube and seat tube	DP	tensile strength of PETG between the material surrounding the top tube and the material surrounding the seat post
1.8.4	FR	Transfer M(x)	DP	structure to transfer loads about the x axis
1.8.4.1	FR	To the top tube	DP	rotation interference from top tube mitered edge and shear between the PETG and the top tube
1.8.4.2	FR	to the seat tube	DP	rotational interference from the seat tube wall and length of PETG sourrounding the seat tube (YZ plane)



1.8.4.2	FR	to the seat tube	DP	rotational interference from the seat tube wall and length of PETG sourrounding the seat tube (YZ plane)
1.8.4.3	FR	between top tube and seat tube	DP	shear strength of PETG between the material surrounding the top tube and the material surrounding the seat post
1.8.5	FR	Transfer M(y)	DP	structure to transfer loads about the y axis
1.8.5.1	FR	To the top tube	DP	length of PETG sourrounding the top tube (XZ plane)
1.8.5.2	FR	To the seat tube	DP	length of PETG sourrounding the seat tube (XZ plane)
1.8.5.3	FR	between top tube and seat tube	DP	PETG web(in tension when rotating counterclockwise, in compression when rotating clockwise)
1.8.6	FR	Transfer M(z)	DP	structure to transfer loads about the z axis
1.8.6.1	FR	To the top tube	DP	length of PETG sourrounding the top tube (XY plane)
1.8.6.2	FR	to the seat tube	DP	length of PETG sourrounding the seat tube (XY plane)
1.8.6.3	FR	between top tube and seat tube	DP	shear of PETG web
1.9	FR	Transfer loads at top tube-head tube	DP	top tube-head tube load structure
1.9.1	FR	Transfer X	DP	structure to transfer loads in the x direction
1.9.1.1	FR	-X (tension)	DP	tensile strength of PETG
1.9.1.1.1	FR	To top tube	DP	adhesion of PETG to bamboo
1.9.1.1.2	FR	to head tube	DP	PETG surrounding around head tube
1.9.1.1.3	FR	between top tube and head tube	DP	tensile strength of PETG between material surrounding top tube and material surrounding head tube
1.9.1.2	FR	+X (compression)	DP	styrofoam plugs, compressive strength of bamboo, compressive strength of molded material
1.9.1.2.1	FR	To top tube	DP	top tube edge
1.9.1.2.2	FR	to head tube	DP	head tube side wall
1.9.1.2.3	FR	between top tube and head tube	DP	styrofoam plugs, compressive strength of bamboocompressive strength of molded material between down tube and head tube
1.9.2	FR	Transfer Y	DP	structure to transfer loads in the y direction
1.9.2.1	FR	+Y(Up)	DP	Positive Y shear of PETG
1.9.2.1.1	FR	To top tube	DP	PETG sourrounding top tube (compression on top and tension on the bottom)
1.9.2.1.2	FR	to head tube	DP	shear between top tube and PETG (PETG going up and head tube going down)
1.9.2.1.3	FR	between top tube and head tube	DP	tensile strength of PETG between material surrounding top tube and material surrounding head tube
1.9.2.2	FR	-Y (Down)	DP	Negative Y shear of PETG
1.9.2.2.1	FR	to top tube	DP	PETG sourrounding top tube (tension on top and compression on the bottom)
1.9.2.2.2	FR	to head tube	DP	shear between top tube and PETG (head tube going up and PETG going down)
1.9.2.2.3	FR	between top tube and head tube	DP	tensile strength of PETG between material surrounding top tube and material surrounding head tube
1.9.3	FR	Transfer Z	DP	structure to transfer loads in the z direction
1.9.3.1	FR	+Z (out of the right side of the bike)	DP	Positive Z shear of PETG
1.9.3.1.1	FR	to top tube	DP	PETG sourrounding top tube (compression on the right and tension on the left)
1.9.3.1.2	FR	to head tube	DP	PETG sourrounding head tube (tension on the right and compression on the left)
1.9.3.1.3	FR	between top tube and head tube	DP	tensile strength of PETG between material surrounding top tube and material surrounding head tube
1.9.3.2	FR	-Z (out of the left side of the bike)	DP	Negative Z shear PETG
1.9.3.2.1	FR	to top tube	DP	PETG sourrounding top tube (tension on the right and compression on the left)
1.9.3.2.2	FR	to head tube	DP	PETG sourrounding head tube (compression on the right and tension on the left)
1.9.3.2.3	FR	between top tube and head tube	DP	tensile strength of epoxy between PETG surrounding top tube and PETG surrounding head tube
1.9.4	FR	Transfer M(x)	DP	structure to transfer loads about the x axis
1.9.4.1	FR	To the top tube	DP	rotation interference from top tube mitered edge and shear between the PETG and the top tube
1.9.4.2	FR	to the head tube	DP	rotational interference from the head tube wall and length of PETG sourrounding the head tube (YZ plane)
1.9.4.3	FR	between top tube and head tube	DP	shear of PETG joining top tube to head tube (PETG surrounding top tube to PETG surrounding head tube)
1.9.5	FR	Transfer M(y)	DP	structure to transfer loads about the y axis
1.9.5.1	FR	To the top tube	DP	length of PETG sourrounding the top tube (XZ plane)



1.9.5.2	FR	To the head tube	DP	length of PETG sourrounding the head tube (XZ plane)
1.9.5.3	FR	between top tube and head tube	DP	PETG web (in tension when rotating clockwise, in compression when rotating counterclockwise)
1.9.6	FR	Transfer M(z)	DP	structure to transfer loads about the z axis
1.9.6.1	FR	To the top tube	DP	length of PETG sourrounding the top tube (XY plane)
1.9.6.2	FR	to the head tube	DP	length of PETG sourrounding the head tube (XY plane)
1.9.6.3	FR	between top tube and head tube	DP	PETG web
1.10	FR	Reduce stress concentrations	DP	fillet corners
2	FR	Design a jig to support the frame during manufacturing	DP	jig
2.1	FR	position standard bike parts	DP	shell half mounted to jig base
2.1.1	FR	position head tube	DP	head tube holder and spacers
2.1.2	FR	position dropouts	DP	dropout holder
2.1.3	FR	position bottom bracket tube	DP	bottom bracket holder and spacers
2.1.4	FR	position seat tube	DP	seat tube plastic
2.2	FR	position bamboo on y-z plane	DP	self centering clamps
2.3	FR	position bamboo along x axis	DP	standard bike parts
2.3.1	FR	position top tube in frame geometry	DP	head tube and seat tube
2.3.2	FR	position down tube in frame geometry	DP	head tube and bottom bracket tube
2.3.3	FR	position seat tube in frame geometry	DP	seat tube mold and bottom bracket tube
2.3.4	FR	position seat stays in frame geometry	DP	seat tube and dropouts
2.3.5	FR	position chain stays in frame geometry	DP	bottom bracket tube and dropouts
3	FR	Develop a standard manufacturing method	DP	bamboo bike manufacturing method
3.1	FR	prepare bamboo tubes	DP	tube preparation method
3.1.1	FR	cut tubes	DP	saw
3.1.2	FR	roughen edges	DP	calipers, knife
3.1.3	FR	fill ends	DP	foam, anything available
3.1.4	FR	check	DP	check system
3.2	FR	set tubes in jig for molding	DP	jig
3.2.1	FR	set standard bike parts	DP	standard bike part holders and spacers
3.2.1.1	FR	set head tube	DP	head tube holder and spacers
3.2.1.2	FR	set bottom bracket	DP	bottom bracket holder and spacers
3.2.1.3	FR	set dropout	DP	dropout holder
3.2.2	FR	set plastic shells	DP	standard bike parts, spacing method
3.2.3	FR	center bamboo tubes	DP	implement self centering device
3.2.4	FR	check tube position	DP	tube position checking method
3.3	FR	mold joints	DP	epoxy
3.3.1	FR	seal mold holes	DP	neoprene/rubber gasket material/anything availiable
3.3.2	FR	mix material	DP	hand crank mixer
3.3.3	FR	pour material	DP	funnel
3.3.4	FR	check mold fullness	DP	fullness checking method

Figure 12: Full decomposition

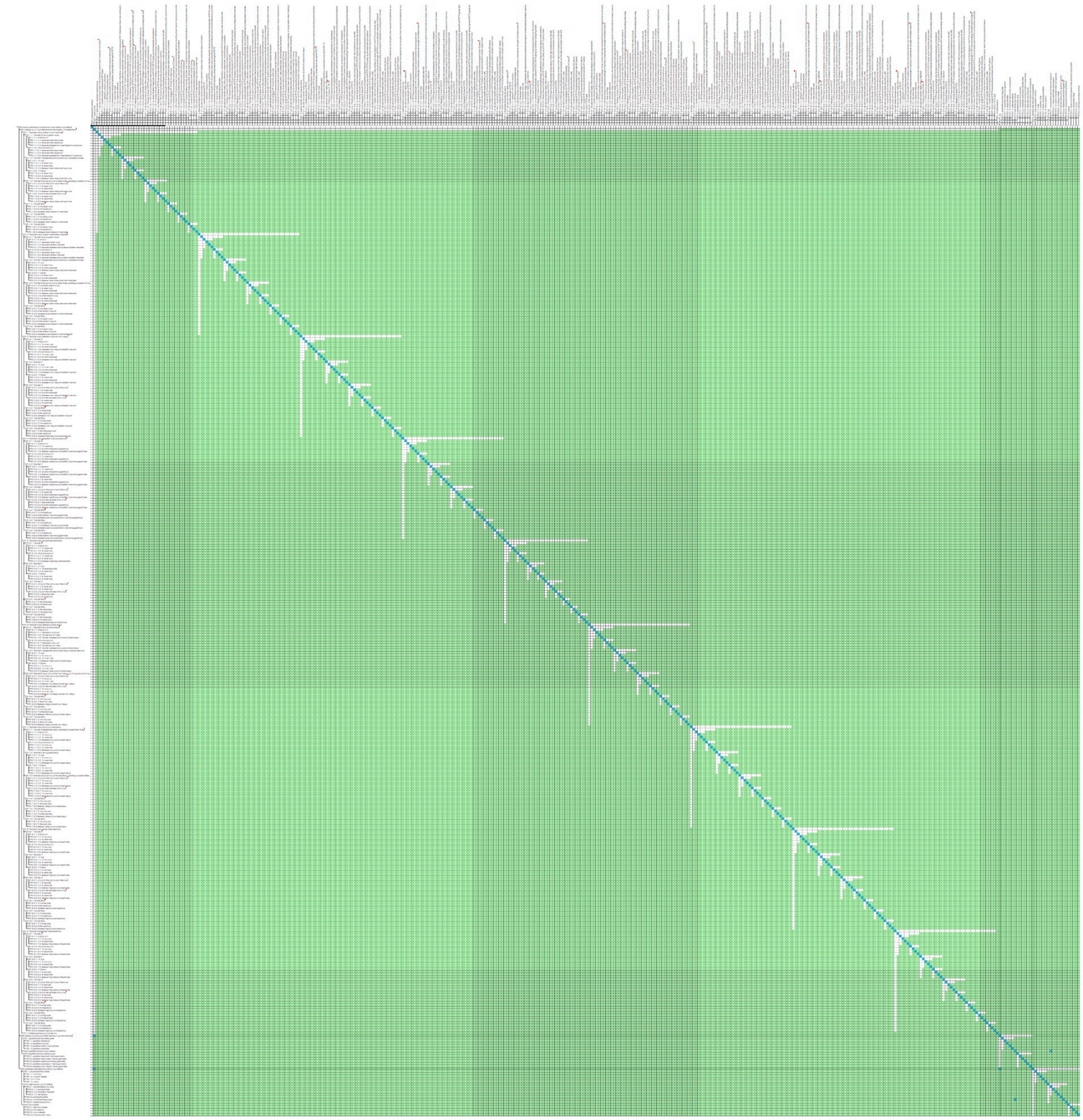


Figure 13: Full design matrix

Appendix 4: Joint images

Head tube joint:

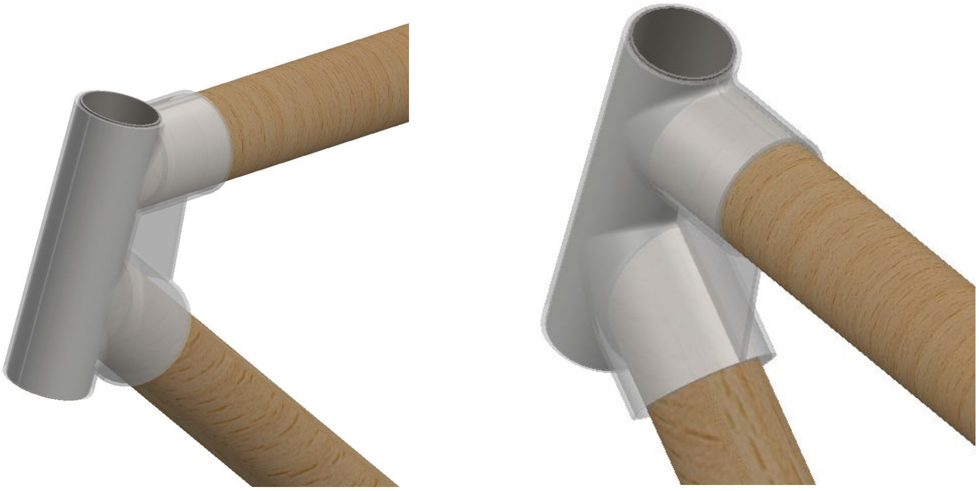


Figure 14: Head tube joint view 1(left) view 2(right)

Seat post joint:

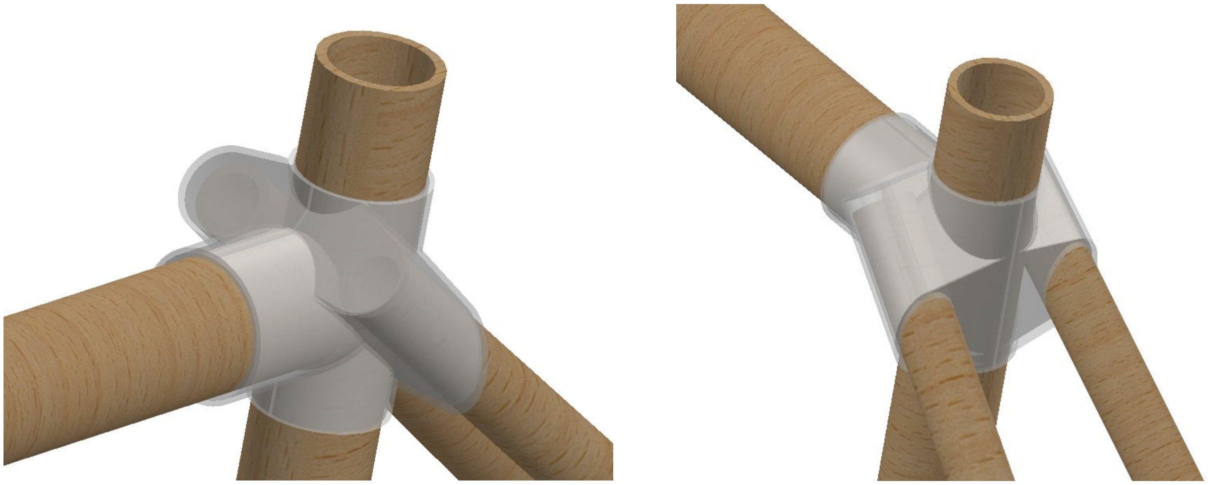


Figure 15: Seat post joint view 1(left) view 2(right)

Bottom bracket joint:

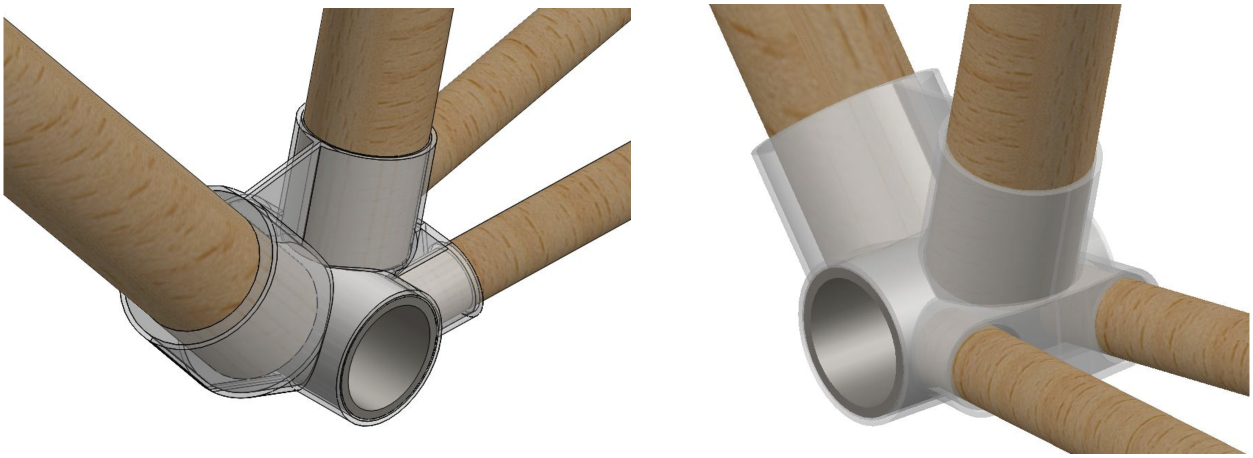


Figure 16: Bottom bracket joint view 1(left) view 2(right)

Dropout joint:

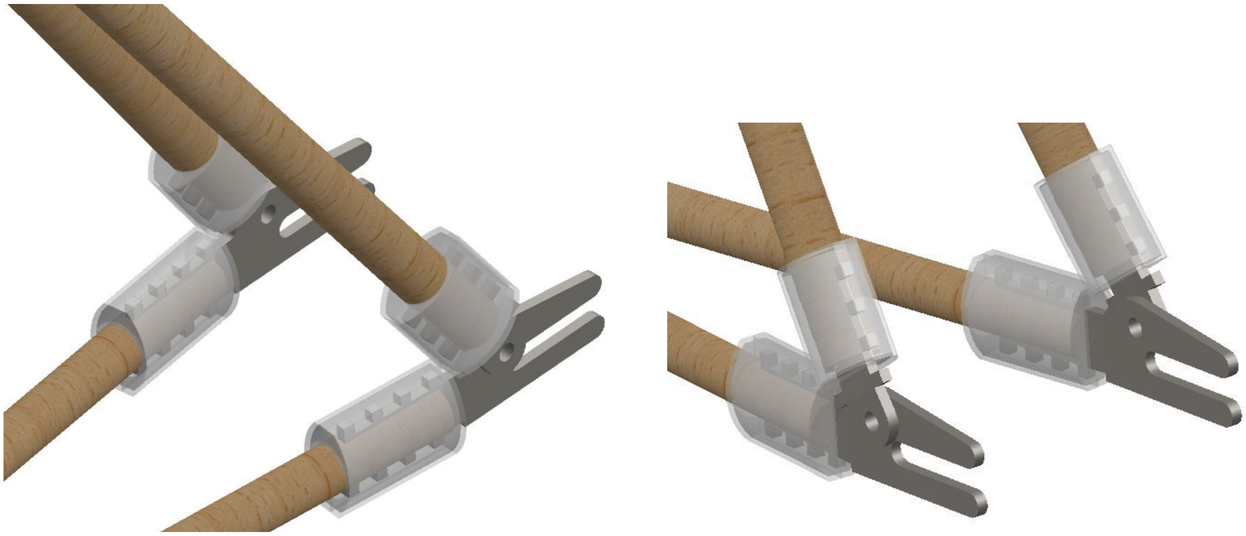


Figure 17: Dropout joint view 1(left) view 2(right)

Appendix 5: Coordinate systems at each tube connection

Top tube-head tube connection:

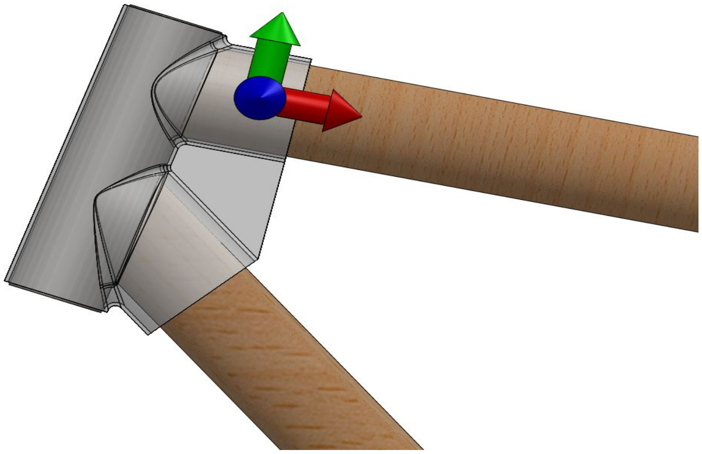


Figure 18: Top tube-head tube connection

Top tube-seat post connection:

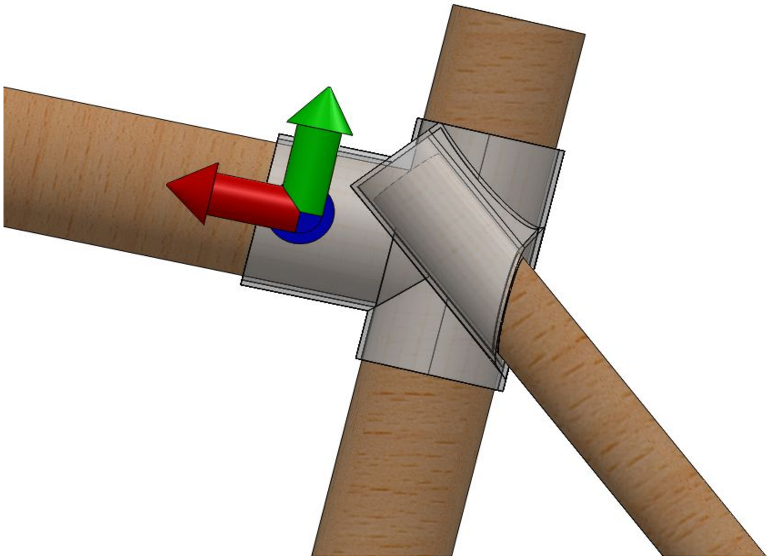


Figure 19: Top tube-seat post connection

Seat tube-bottom bracket connection:

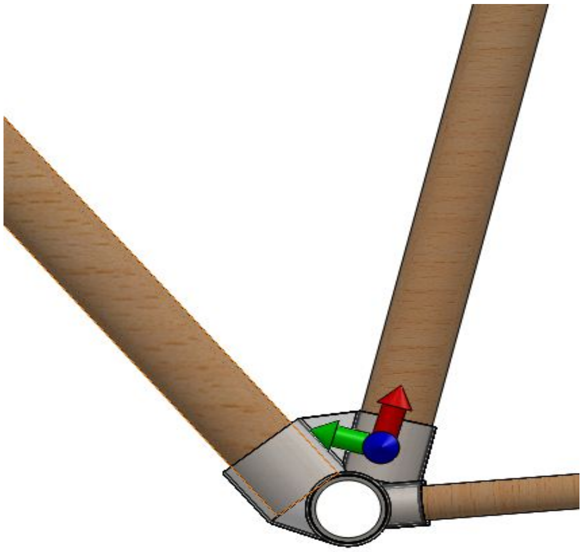


Figure 20: Seat tube-bottom bracket connection

Seat stay-dropout connection:

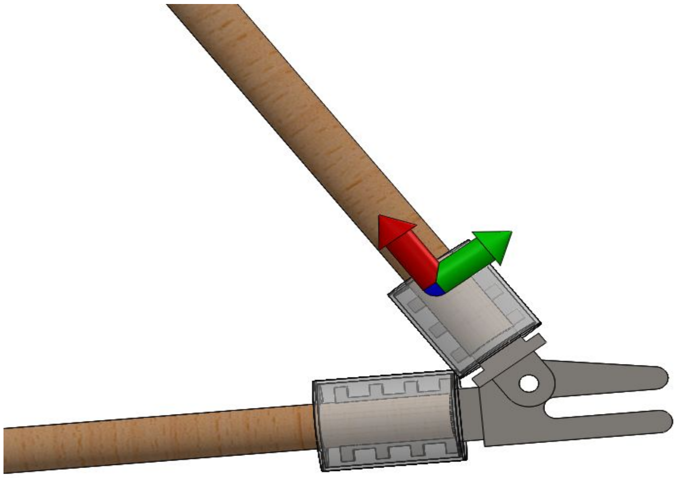


Figure 21: seat stay-dropout connection

Down tube-bottom bracket connection:

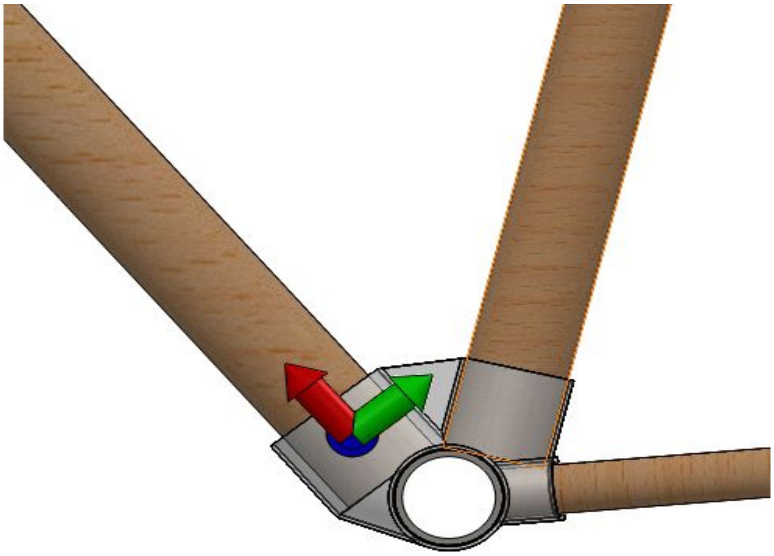


Figure 22: Down tube-bottom bracket connection

Down tube-head tube connection:

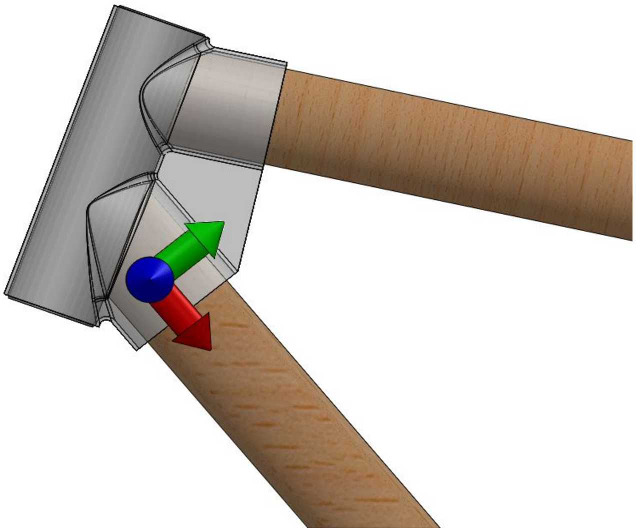


Figure 23: Down tube-head tube connection

Chain stay-seat post connection:

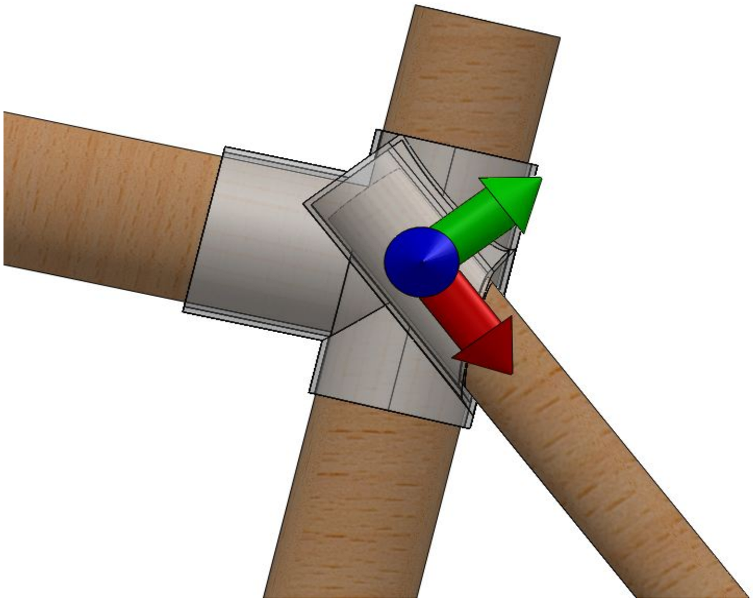


Figure 24: Chain stay-seat post connection

Chain stay-bottom bracket connection:

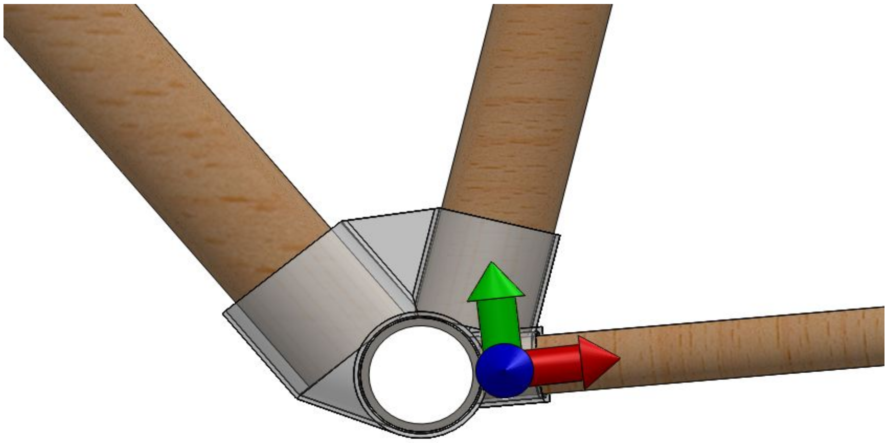


Figure 25: Chain stay-bottom bracket connection

Chain stay-dropout connection:

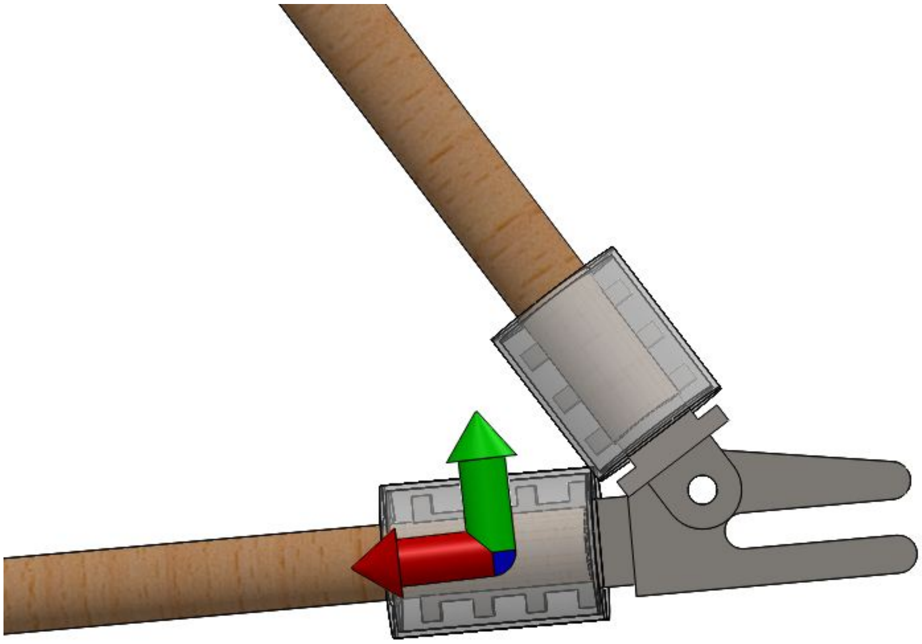


Figure 26: Chain stay-dropout connection

Appendix 6: Physical integration diagram

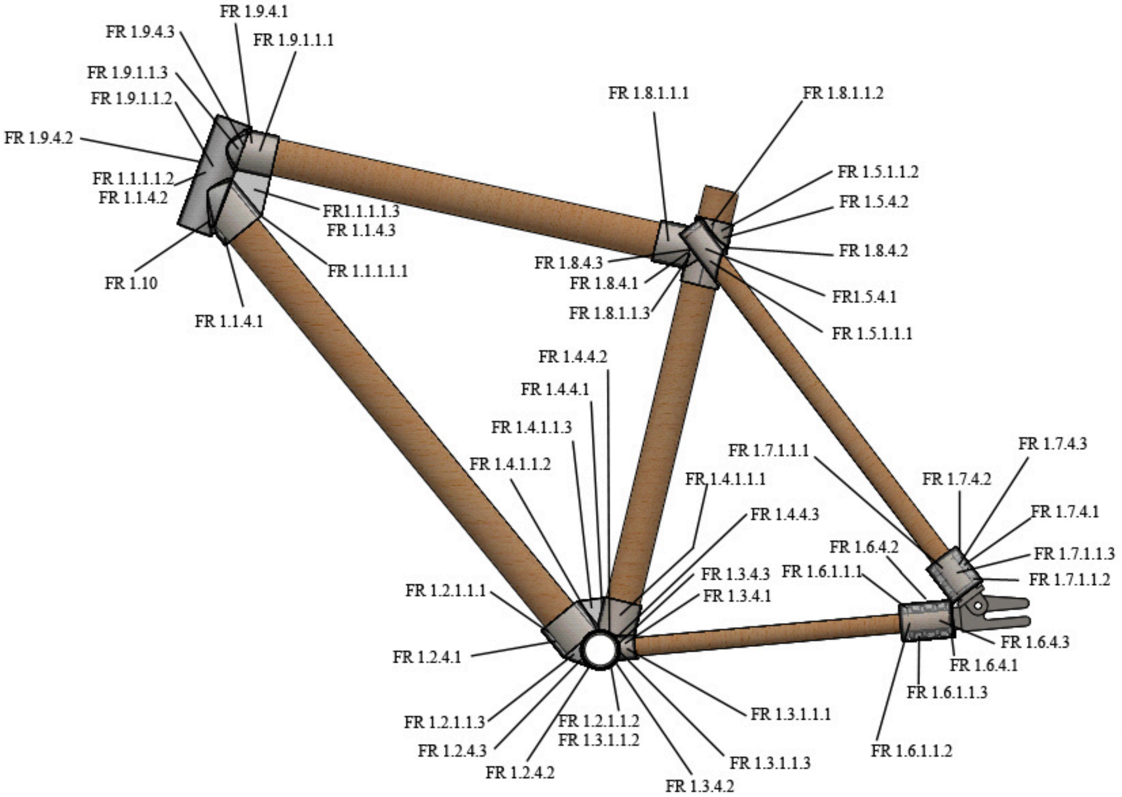


Figure 27: Physical integration diagram

Appendix 7: Research on bicycle loading

The University of Manchester Institute of Science and Technology in Manchester, England conducted a study on bicycle loading during normal riding (Soden, Adeyefa, 1978). Forces on the bicycle were recorded when the rider was starting off, riding uphill, and riding on flat ground. See the free body diagrams below for forces acting on the bicycle.

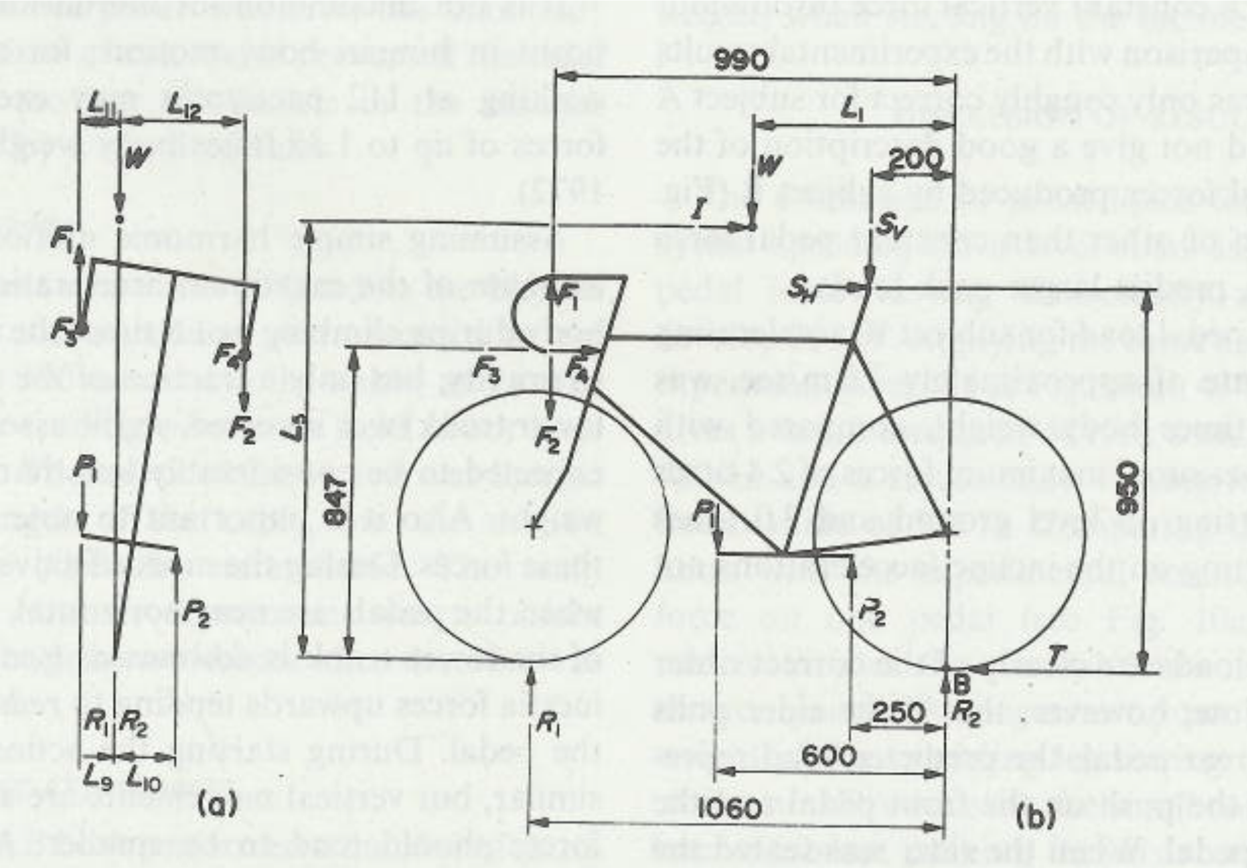


Figure 28: Front (left) and side right) view of the loading on a bicycle during normal riding

Appendix 8: Bamboo material, physical, fracture, and chemical properties

8.1 Mechanical properties:

According to CES Edupack the Young's modulus of bamboo ranges from 2.18 to 2.9 $*10^6$ psi. See table in Appendix 1. The yield strength ranges from 5.98 to 6.38 ksi and the tensile strength is 5.22 to 6.53 ksi. The elongation is 2.88 to 5.08 % strain and the hardness (Vickers) ranges from 2 to 12 HV. Although bamboo is anisotropic, this source did not list a direction in which the properties were found. The data was corroborated with K.F. Chung's and W.K. Yu's publication *Mechanical properties of structural bamboo for bamboo scaffoldings* (Chung & Yu, 2001) which, along with showing that their tests were done lengthwise along the bamboo culms, stated that their tests were done on three separate bamboo culms per species and each culm was at least three years old. The age of the bamboo affects the hardness. See Appendix 2. Other important factors such as moment of inertia of area and nondimensional stress can be found in Fiber texture and mechanical graded structure of bamboo (Amada, Ichikawa, Munekata, Nagase, Shimizu, 1997)

8.2 Physical properties:

Bamboos specific gravity ranges between .4 and .8 (Li, 2002) and it's density varies from 37.5 to 49.9 lb/ft^3 (CES Edupack, 2011). Generally the outer diameter of a bamboo culm is inversely proportional to its height from the ground and the longest intermodal lengths occur in the middle of the culms, their lengths lessening towards the ends (Amada, Ichikawa, Munekata, Nagase, Shimizu, 1997). Other physical properties, such as node thickness and bundle sheath number also rely on the intermodal number, or how high up on the culm the tested piece of bamboo came from (Amada, Ichikawa, Munekata, Nagase, Shimizu, 1997).

8.3 Fracture properties:

Bamboo is anisotropic, meaning that its fracture properties differ depending on where in the bamboo they occur. The fracture toughness according to Amada and Untao was. The fatigue strength at 10^7 cycles is between 3.63 to 5.08 ksi and the fracture toughness is 4.55 to 6.37 ksi*in^5 (CES Edupack, 2011). A journal article written by Sigeyasu Amada and Sun Untao called *Fracture properties of bamboo* corroborated the bamboo fracture properties. Their tests were completed on two-year-old dried Mousou bamboo culms.

8.4 Chemical properties:

According to *Bamboo in the laboratory* written by Wolfram Schott, bamboo is composed of "50-70% cellulose, [and] 20-30% lignin, depending on the species," (Schott, 2006). It also contains hemicellulose and pectin.

Appendix 9: Bicycle tube tolerances

Table 5: Bicycle tube tolerances

Bamboo Tube	Min Diameter (inches)	Max Diameter (inches)
Seat Tube	2.677165352	1.57480315
Top Tube	1.338582676	1.653543305
Down Tube	1.574803148	1.889763778
Chain Stays	0.708661417	0.866141731
Seat Stays	0.669291338	0.944881889

Appendix 10: Bicycle frame elements

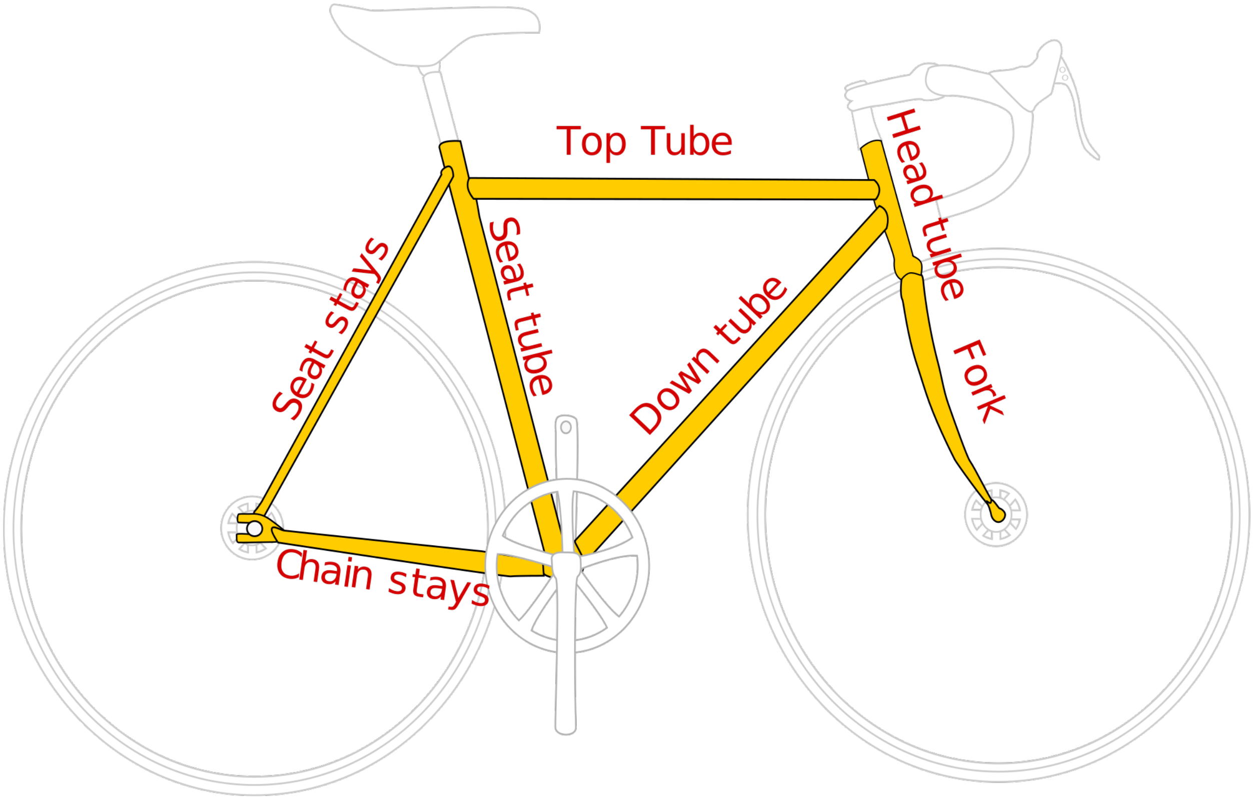


Figure 29: Bicycle frame elements