

Design of a Tricycle Chassis Using Computer-Aided Design and Finite Element Analysis

by
Elliot Avila

Submitted to the Department of Mechanical Engineering on
May 23, 2014 in partial fulfillment of the requirements for
the degree of

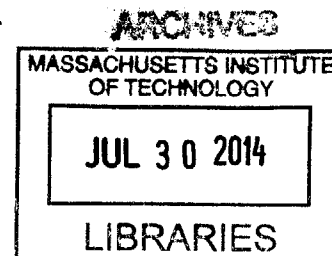
Bachelor of Science in Mechanical Engineering

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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Abstract

Finite element analysis and computer-aided design are powerful tools for modeling complex systems and their responses to external stimuli. This paper explores how these techniques were employed in a highly iterative design process to improve the rear chassis of a pedal-powered tricycle. The tricycle, which is used in Lagos, Nigeria to collect and transport waste materials, is regularly ridden on rough terrain with loads greater than 600 pounds, and thus requires a frame that can be subjected to large loads without failure. The design process resulted in a chassis frame that is stiffer and has a higher safety factor than previous designs, but can still be made from low cost, locally sourced parts.

Thesis Supervisor: Amos Winter

Title: Assistant Professor of Mechanical Engineering

Acknowledgements

There's many, many people that I would like to recognize for their part in this project.

First I would like to thank Gwyn Jones for his superb guidance and mentorship over the course of the semester, as always.

I would also like to thank the many other D-lab staff who helped me out, but especially Kofi and Victor for their diligent work in helping get this project started, and also Eric and Jack for enabling me to travel abroad and continue working on this project in the months ahead.

I owe a lot to Corey and Hannah, for giving up their personal computer (and space) so that I could run my simulations these past few weeks.

And I'd like to acknowledge the help of Billikiss Adebisi-Abiola, founder of WeCyclers, for answering my questions and supporting my upcoming summer travels.

I'd also like to thank my parents, for always supporting both my work and me.

And lastly I'd like to express my gratitude to Professor Amos Winter for sponsoring this research. It would not have been possible otherwise.

Chapter 1

Introduction

The purpose of this project is to use computer-aided design (CAD) and finite element methods to design the rear chassis of a three wheeled, pedal-powered vehicle. The topic choice was motivated by the need of a Nigerian based start-up to have a structurally sound vehicle to collect and transport recyclable materials. This chapter presents background information on this start-up and details the design criteria that guided this project.

1.1 Community Partner

WeCyclers is a company based in Lagos, Nigeria that creates income-generating opportunities by incentivizing the collection of recyclable materials. WeCyclers collects and transports materials using a three wheeled, pedal-powered collection unit called the WeCycle. The WeCycle has two main sections: the rear chassis, and the front bicycle frame, as shown in Figure 1-1. The specs for the current chassis are given in Table 1-1 below, and were selected to accommodate the 200kg of material collected during an average trip.

Table 1-1: Chassis Dimension Specifications

Dimension	Value (inches)
Length	66
Width	24
Height	57



Figure 1-1: An existing WeCycle. The rear chassis is sectioned with canvas bags to hold three different types of materials. Photo credit: Billikiss Adebiyi-Abiola.

1.2 Summary of Design Specifications

Table 1-2: Summary of Design Specifications

Criteria	Value
Stress	Highest Von Mises stress less than 125MPa
Stiffness	Higher torsional stiffness than rickshaw frame
Weight	Minimize weight
Material Use	Use only locally sourced materials
Ease of Fabrication	Fabricate with simple tools – use simple cuts and joints
Ergonomics	Easy to mount and dismount; no collision with chassis
Chain Obstruction	Accommodate for sagging in lower chain

1.2.1 Primary Design Specifications

Stresses in Chassis Due to Loading

The most important consideration in this design was safety and reliability. Component failure can be dangerous to riders, especially when the WeCycle is fully loaded and the rider is riding quickly in high traffic areas. A safety factor is the ratio of yield strength to maximum stress and describes the ability of the system to perform under excessive loads. A safety factor of 2 was chosen for this design.

Criteria: The von Mises stresses should be less than half of the material yield strength.

Stiffness of Chassis

Frame stiffness effects the ease of riding – flexing saps energy from riders and makes steering more difficult.

Criteria: The chassis stiffness should be (higher than that of the bicycle frame.)

1.2.2 Secondary Design Specifications and Considerations

Weight

The weight of the chassis should be minimized to reduce the power required by the rider.

Material Use

The chassis should only use materials that are available on site in Lagos. Common materials include: angle iron, square tubing, circular tubing, and rebar.

Ease of Fabrication

Fabrication of the WeCycles will be done by hand using basic tools (primarily hacksaws and stick welders). Joints should be made to be perpendicular when possible, and otherwise should be made using simple cuts.

Ergonomics

Prior designs caused riders feet to impact the chassis when riding. The chassis design should not cause interference with how the rider would typically mount, dismount, or operate the WeCycle.

Chain Length and Obstruction

The chassis cannot obstruct the chain, and should accommodate for sagging in the lower section of the chain so that there is no chain to chassis contact.

Chapter 2

Designing the Chassis

The chassis was designed in a highly iterative design approach that employed a combination of CAD techniques and finite element analysis (FEA) simulations. The use of these modeling techniques allowed for quick and detailed analyses of the system, which would otherwise be incredibly time-consuming or impossible to do by hand. This chapter discusses the details of these methods and how they contributed to the completion of the final chassis design.

2.1 Using CAD and FEA in the Design Process

The design process used in this project took advantage of two important qualities of CAD and FEA: complex systems are easily modified and quickly solved. The process followed three steps, outlined below.

1. Evaluation of how the current system model meets design criteria
2. Revision of CAD model based on evaluation and previous simulation results
3. Conduct simulation

2.2 Modeling of Bicycle Frame and Chassis

2.2.1 Bicycle Frame

The front end of the WeCycle, referred to as the bicycle frame, was based on a rickshaw frame for the purposes of this analysis. Rickshaw frames evolved from bicycle frames out of the necessity to accommodate passenger loads even greater than the ones acting on the WeCycle. Furthermore, rickshaws have a tricycle configuration and are often used on rough terrain. For these reasons, a rickshaw frame is an appropriate model to be used in the design of the WeCycle. The model's dimensions were found by directly measuring an existing rickshaw frame. Below, Figure 2-1 shows the bicycle frame model.

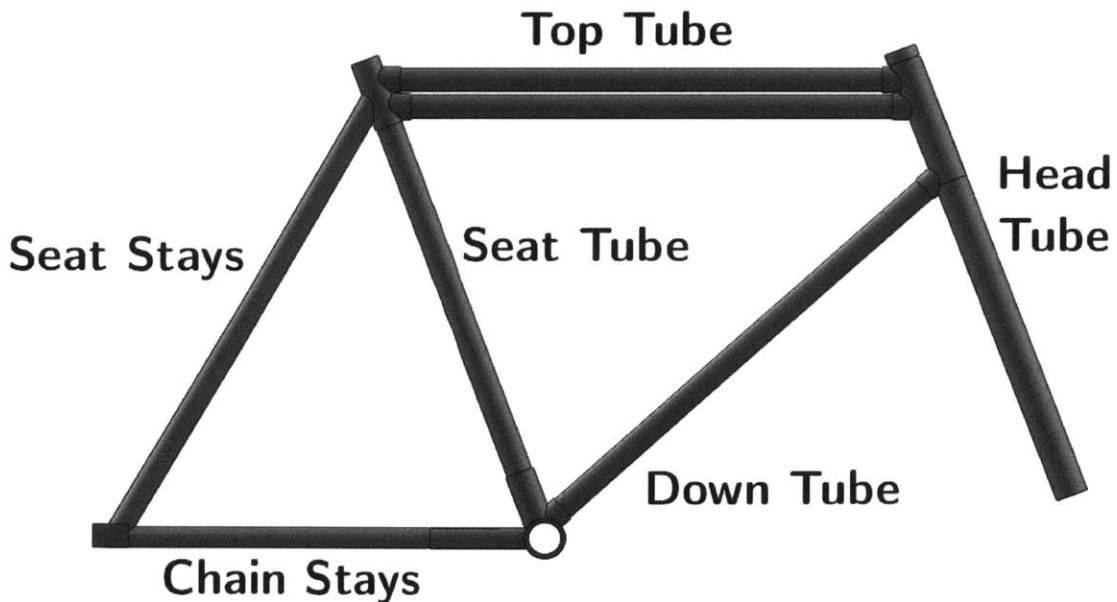


Figure 2-1: The rickshaw frame model, with each component labeled.

Several components of the bicycle frame model were simplified. The biggest simplification was done on the head tube and fork. These were reduced to a single, linear component because the focus of this study was on the rear chassis its connection to the bike frame, and because the finer geometric details of the head tube and fork were thought to have negligible effect on the overall study results. The handlebars were also removed, and any forces on them were instead modeled as acting remotely on the top face of the head tube.

Non-structural components of the rickshaw frame were also not modeled, such as the pedals and seat tube. The front wheel was not included and was instead accounted for by constraints set in the simulation. Similarly, the rear wheels were omitted.

The frame was further simplified through the use of linear members. Chain stays and seat stays on bikes often have slight curvature, but the effects of this curvature were assumed to be negligible.

2.2.2 Chassis

The rear chassis model is based on a simple box frame made of square tubing and flat bar stock. The model is presented below in Figure 2.2. The material was modeled to be ASTM36 structural steel, which has a yield strength of 250MPa. More detailed properties of ASTM36 are given in Appendix D.

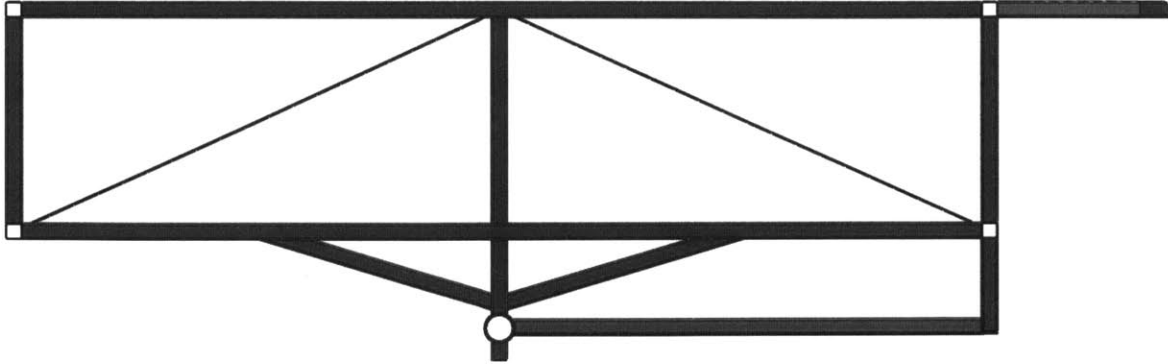


Figure 2.2: A side view of the final chassis design.

The original WeCycle chassis was made primarily of perpendicularly joined beams. My design incorporated many more beams to reinforce sections under high stress. For example, all of the diagonal beams seen from the side face in Figure 2.2 were added to counteract the downward bending caused by the collection load.

The largest simplification of the chassis was that the axle was not incorporated into the model. This was acceptable because of its proximity to the constraints placed on the system during the simulation (detailed in section 2.4.2).

2.2.3 Connection Between Chassis and Frame

The chassis and bike frame connect at two places: connections are made between the top of the seat tube and the top of the chassis, and between the dropouts and the base of the chassis.

Several non-critical simplifications were made at these connection points to overcome some of Solidworks's complexities when joining square and circular tubing together. In a workshop environment, components can still be joined when there are small gaps between them, since small gaps can be either filled with weld filler or closed by deforming components around the gap. This is relatively difficult to do in Solidworks, so the following techniques were instead used to close gaps when necessary:

1. Cuts were made so that components were flush against each other, regardless of fabrication difficulty
2. Plates were placed to intersect with components, and then cut away so that they became flush
3. One component was replaced for a smaller, non-hollow component

Figures 2.3 and 2.4 show the connection points between the chassis and bike frame.

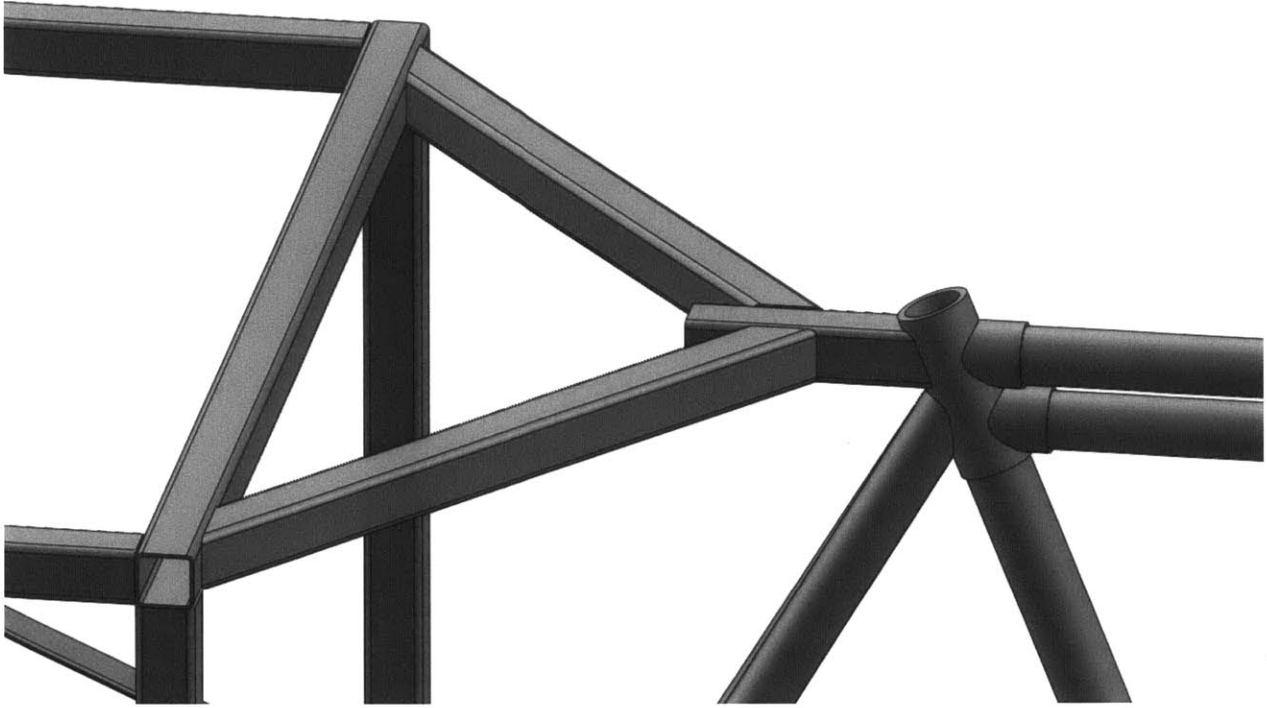


Figure 2.3: The upper-most connection point between the chassis and bike frame. The horizontal member was cut to be flush against the seat tube, despite that being very difficult to do in Lagos.

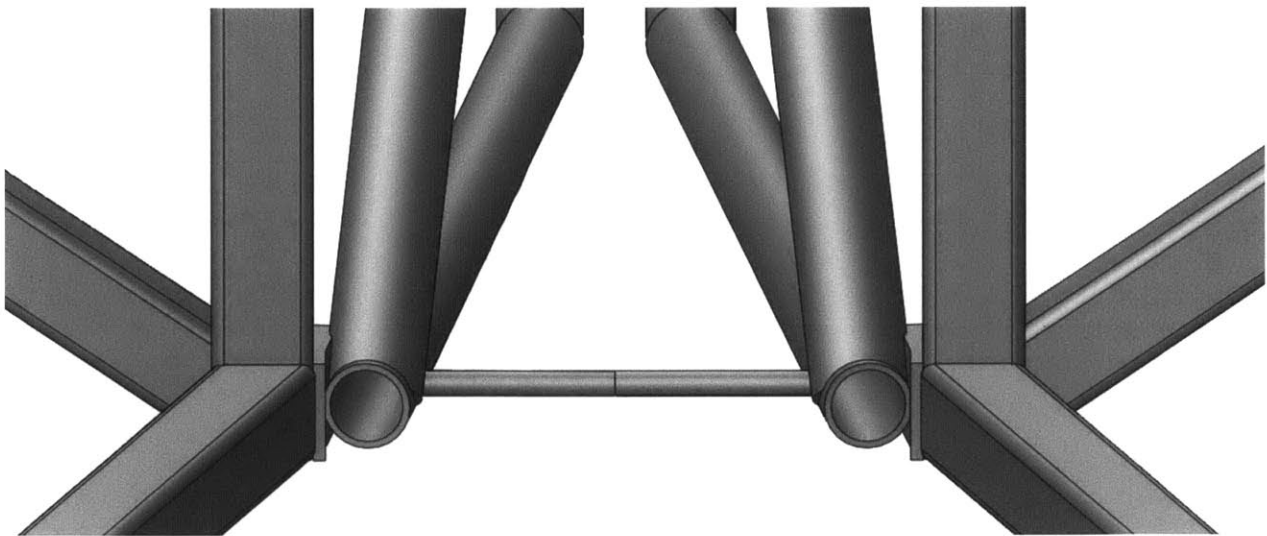


Figure 2.4: The lower connection points. Although it was originally intended that a pipe be placed between the two dropouts, it was replaced with a smaller but solid piece.

2.3 Meshing the Model

Solidworks Simulation was the FEA program used to simulate loads acting on the system and then calculate the resulting von Mises stresses. It does this by subdividing components into smaller, more manageable elements through a process called meshing. Meshing (like most properties set during FEA) can be set globally or locally. After meshing is complete, boundary conditions are applied and the system can be solved.

The first design iterations used meshing parameters set forth in Appendix C. For the final analyses, a finer mesh was applied around areas of highest stress in order to improve the accuracy of the results. Refining the meshing was especially important in this study because thin wall structures, such as tubing, are less accurate unless they are at least two elements thick. Figures 2.5 and 2.6 show how the model's mesh was refined near areas of high stress.

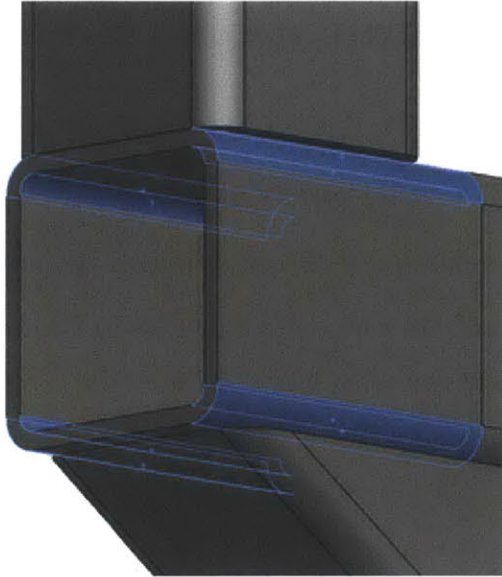


Figure 2.5: The highlighted areas in this figure show the faces that were re-meshed due to high stresses.

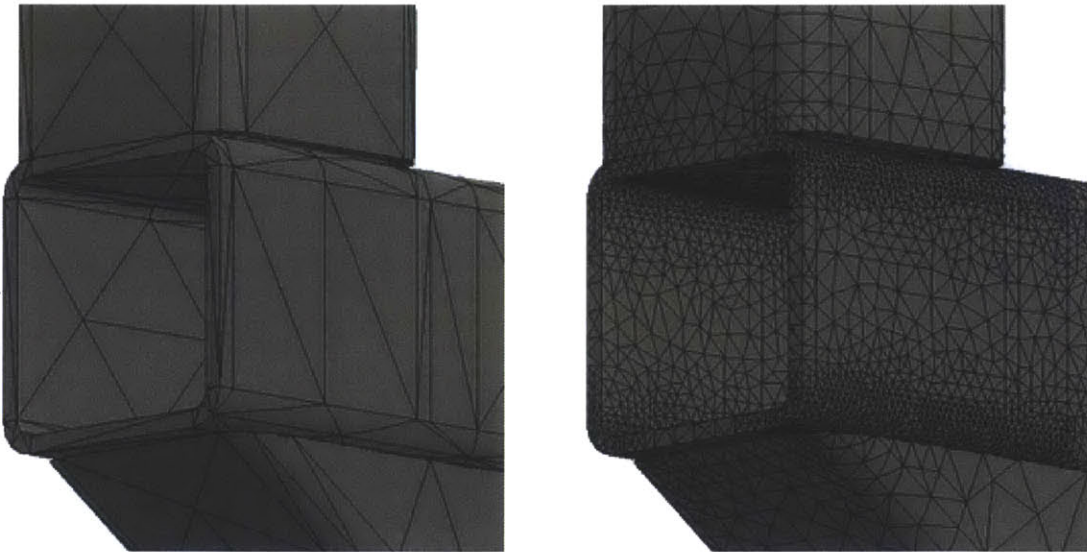


Figure 2.6: Two different mesh sizes are shown. The coarser mesh is useful for first-order simulations, but needs to be made finer before results can be used.

2.4 Setting the Simulation's Boundary Conditions

The boundary conditions in Solidworks fall under three categories: loads, fixtures, and contacts. Defining the boundary conditions is one of the hardest parts of any simulation, as the effects of the system's environment must be isolated and reduced.

2.4.1 System Loads

The loading configuration is presented below in Table 2-1 and shown in Figure 2.7

Table 2-1: System Loads

Value	Component under load	Notes
Force: 200 kg in $-z$ direction	Distributed over lower portion of rear chassis	Represents load on WeCycle from collected material
Force: 90 kg in $-z$ direction	Top of seat tube	Represents weight of rider
Force: 22.5 kg in $\pm z$ direction	Top of head tube	These are remote loads acting ± 6 inches from the head tube. These account for the effects of the rider pushing/pulling the handlebars when leaning into a turn.
Acceleration: 9.81 m/s^2 in $-z$ direction	All components	Represents effects of gravity on system. Component density is determined through material selection.

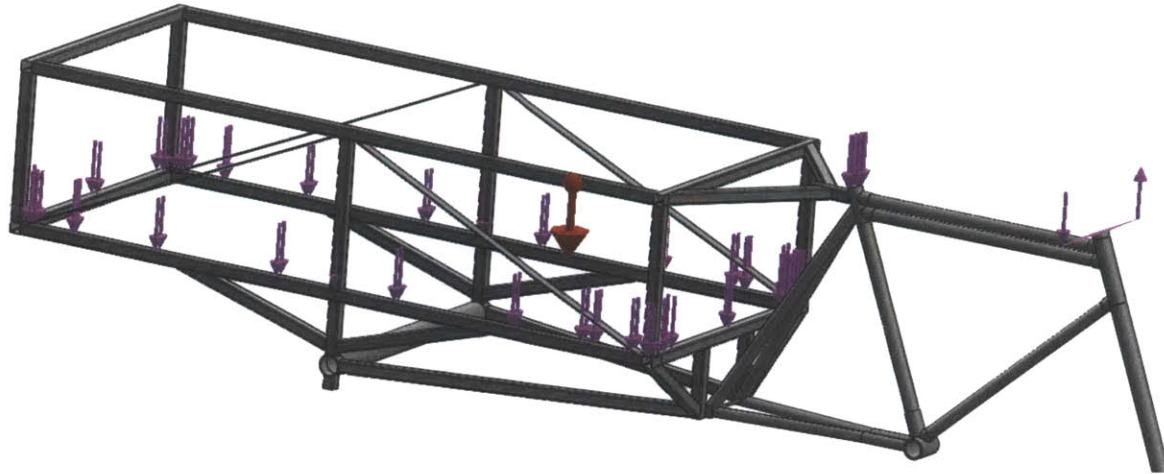


Figure 2.7: Visual representation of the loads acting on the system.

2.4.2 System Fixtures

Fixtures were applied to the system at three areas: the bottom face of the two chassis legs, and the bottom face of the head tube. The fixtures at these points restricted the faces from moving in the vertical direction, to represent the WeCycle's contact with the ground. To make the model stable, additional constraints were also added to the bottom face of one of the chassis legs so that it was completely fixed. The fixtures are shown in Figure 2.8 below.

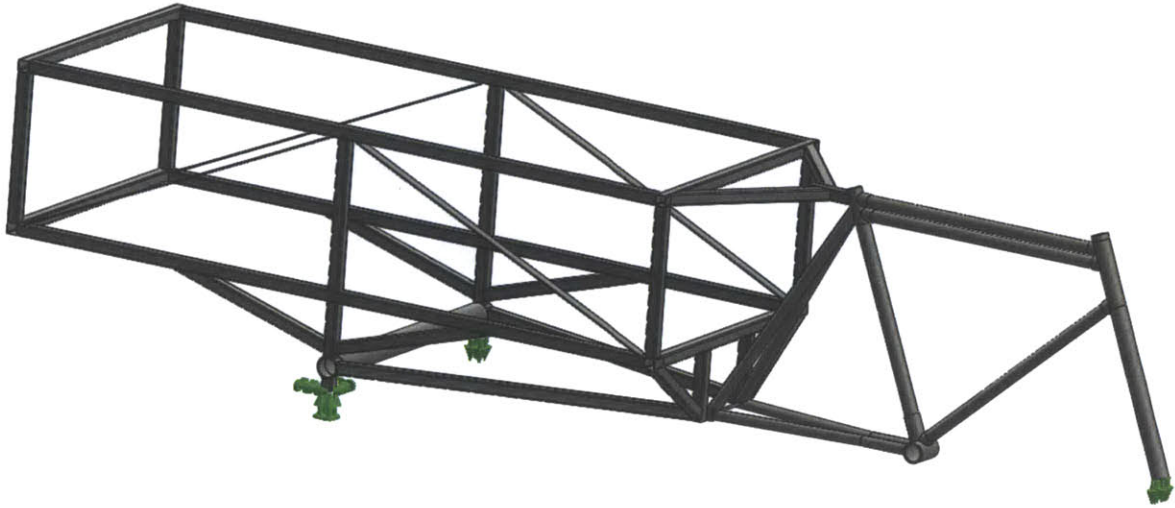


Figure 2.8: Visual representation of the fixtures applied to the system.

2.4.3 Contact Sets Between Components

After defining how components respond to the environment through fixtures and loads, it is necessary to define how components interact with each other. This is done through contact sets, which are simply the areas where multiple components interact with each other. A type of contact set called a component bond as used to simulate the effects of welding on the system.

Chapter 3

Results of the Design Process

Over 25 design iterations were conducted before a final design was produced. A select number of these are presented in Appendix A to demonstrate how models continued to build off of prior results.

3.1 Simulation Results on the Final Design

The results of the final design's simulation are presented below in figures 3.1 through 3.5. The deformation of the system was exaggerated by a ratio 537:1 to visually show the system's response.

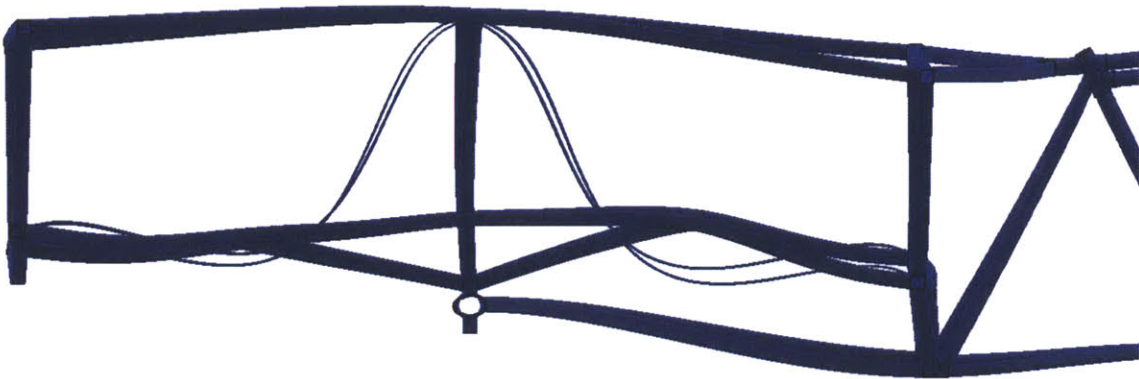


Figure 3.1: A side view of the chassis. The blue color indicates that the majority of the system was not undergoing high stress. The apparent interference between the flat bar and the rest of the chassis is only a visual effect of the deformation scale and did not influence the system response.

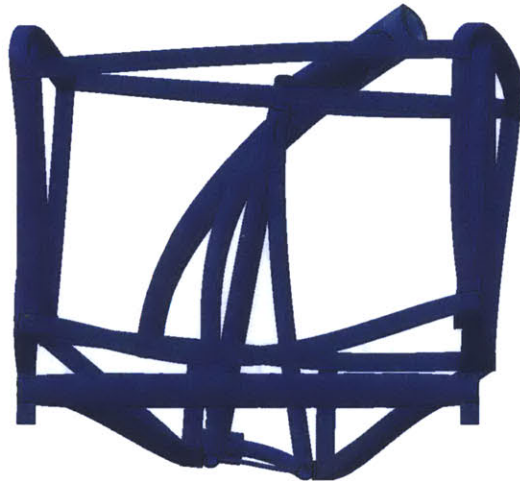


Figure 3.2: Rear view of chassis. From this view, it is easy to observe that the torque on the head tube did not cause large displacements on the chassis, implying that the bike frame is less stiff.

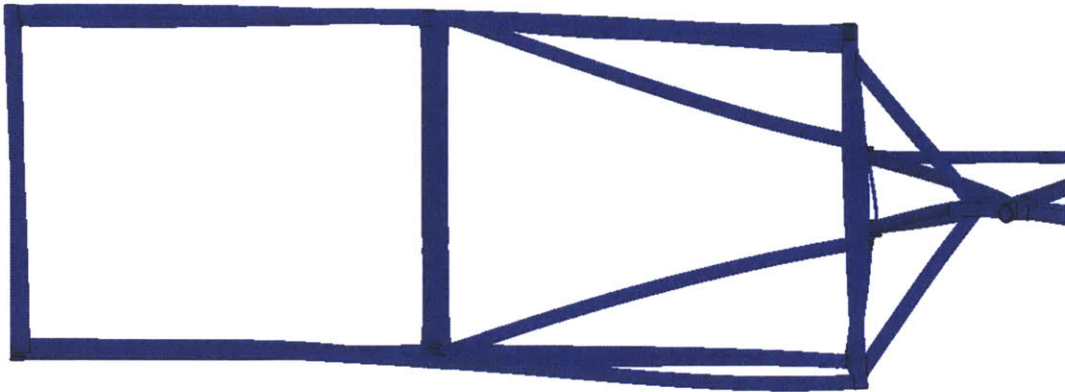


Figure 3.3: A top view of the final chassis design.

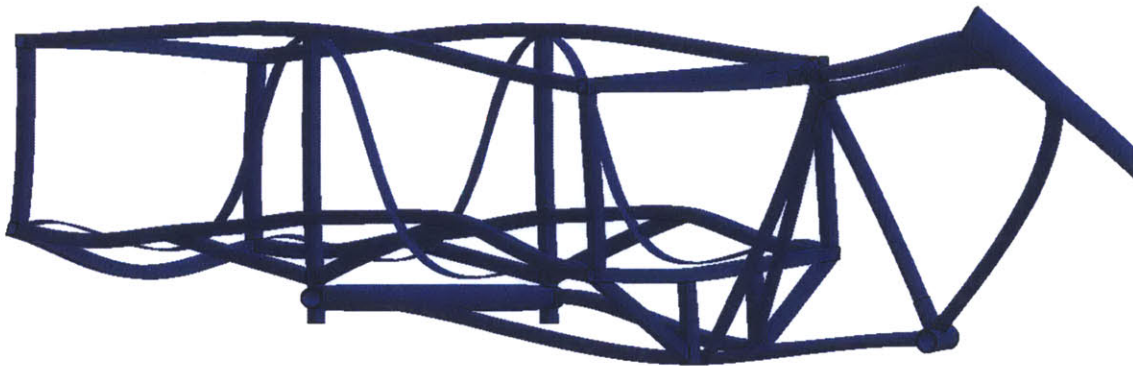


Figure 3.4: An angled view of the chassis.

3.2 Evaluation of Final Model

Following the completion of each simulation, the system was evaluated to see how it met the design criteria. The following sections discuss whether the primary and secondary design criteria were met.

3.2.1 Evaluation by Primary Design Criteria

Stresses in Chassis

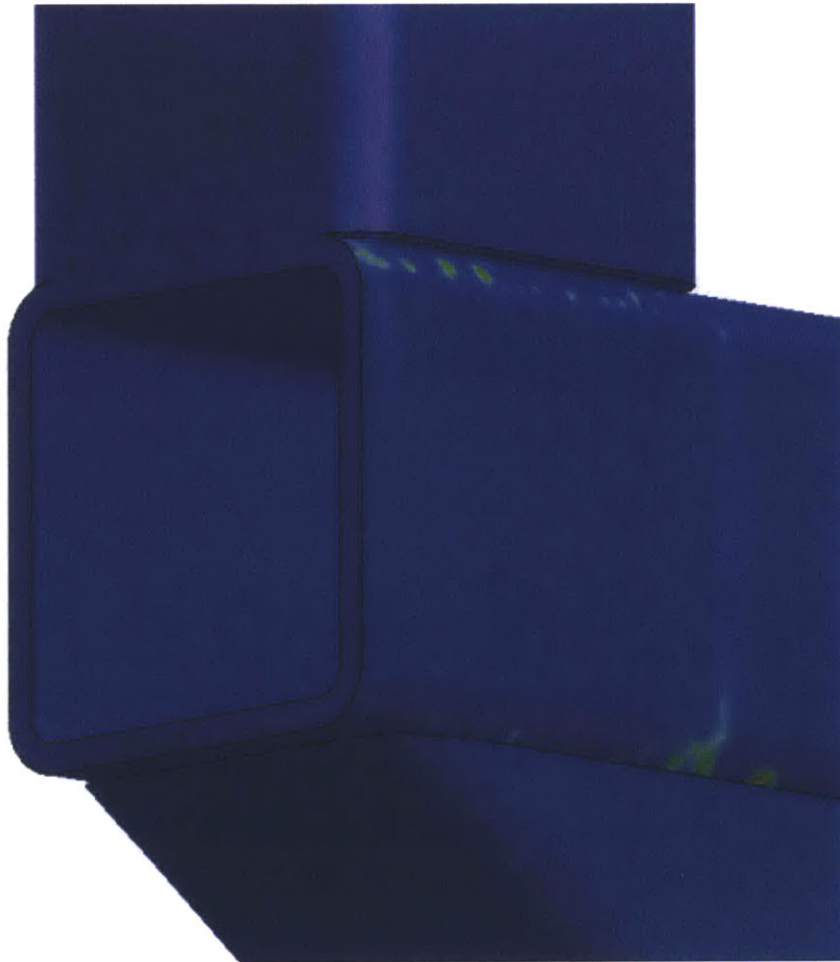


Figure 3-6: A close-up view of a bottom-front corner of the chassis where stress concentrations are visible.

The highest von Mises stress in the chassis was measured to be 122.1 MPa and occurred in one of the bottom-front corner. As shown in figure 3-6, the highest stresses occurred in stress concentrations around the joints.

I expected the stresses to be distributed in a more uniform and gradual way, and believe that improper meshing may have caused the stress concentrations to form. Geometrically irregular element sizes or a coarse mesh are both potential contributing factors. However, since finer meshing tends to reduce the stresses calculated through FEA, and since there is a distribution of stresses between 0 and 122 MPa in such a small area, I believe that refining the mesh would only lower the maximum calculated von Mises stress. From that, I conclude that the strength specification was met and that the system has a safety factor of at least two.

Stiffness in Chassis

The chassis's stiffness was concluded to be higher than that of the rickshaw frame. The moment induced on the head tube did not cause large displacements in the chassis. This can be seen by visual inspection, or by measuring the angle of twist along the body.

The angle of twist was approximated at 4 points, two in the chassis and two in the rickshaw frame, by measuring the projected arc length. The change in angle of twist for a given distance traveled was calculated and found to be greater in the rickshaw frame than in the chassis, implying higher stiffness in the chassis. Figure 3-7 shows these points and the measurements used for calculating the angle of twist, and table 3-1 gives the angle of twists and change in angle of twist per length. While these are very rough approximations, the difference is significant.

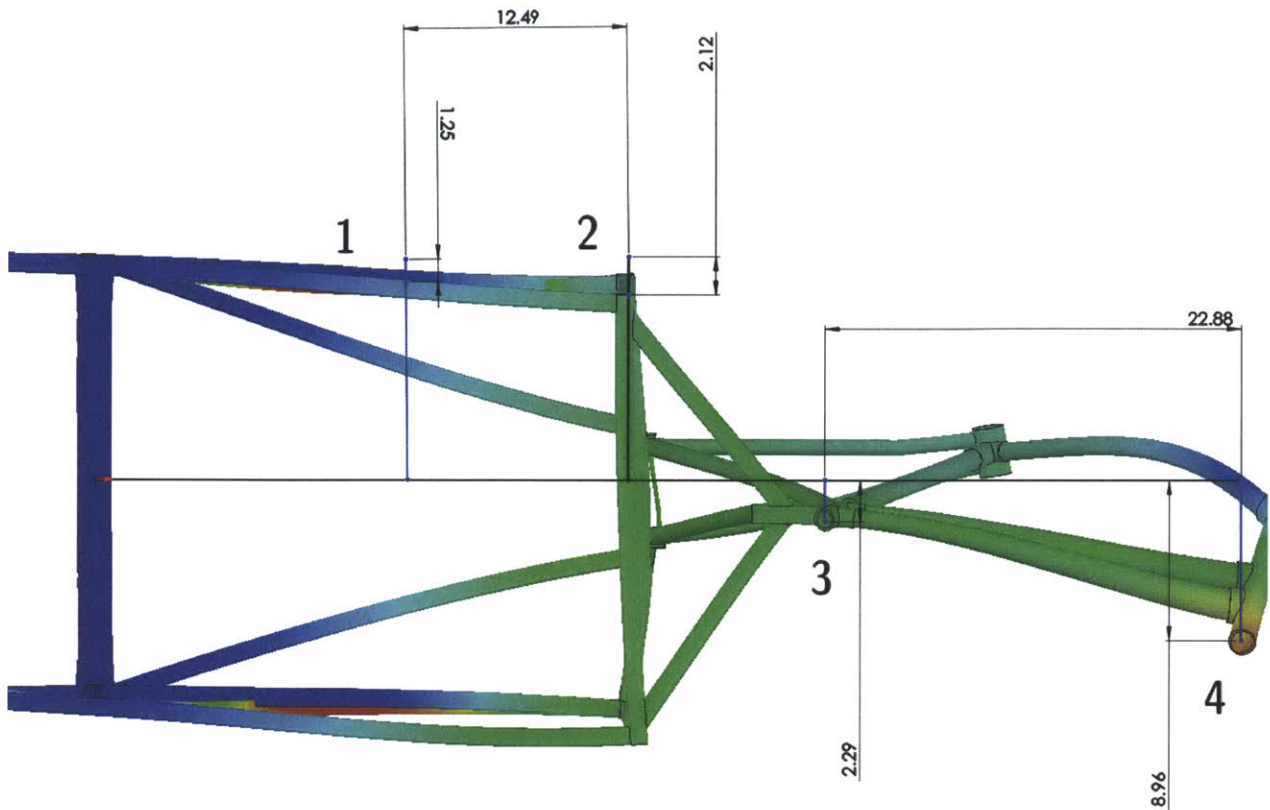


Figure 3-7: Points used to calculate angle of twist at different points in the system. In a system with a uniform cross-section undergoing pure torsion, the angle of twist would decrease linearly from one end to the other.

Table 3-1 – Calculated Angles of Twist

Point	Angle of Twist	Angle of Twist per length
1	5.28 degrees	0.28 degrees/inch
2	8.83 degrees	
3	9.95 degrees	1.20 degrees/inch
4	37.34 degrees	

Note: These approximations were taken on the system after the deformations were exaggerated and are therefore are scaled 537 times higher than normal.

3.2.2 Evaluation by Secondary Design Criteria

Weight

The weight of the chassis is 47.8 lbs. The overall weight was kept low by the use of relatively small size of square tubing, at the cost of decreased strength.

Material Usage

All of the materials used in this design are available in Lagos, at relatively low-cost. One inch square tubing and flat bar are some of the most commonly available structural steel pieces in the developing world, giving WeCyclers the option to fabricate the chassis in other locations if they ever decided to expand.

Chain Length and Clearance

The chain loops around one of the lower beams. This removes the potential for any collisions due to sagging, however it does require the chain to be disassembled before being removed or installed.

Ergonomics

The design is more difficult for short people to mount than previous designs were, as the top tube on the rickshaw frame is higher up and the chassis prevents mounting from behind. This could be addressed by changing the front bike frame.

Ease of Fabrication

Most beams in the chassis require only simple vertical cuts to be made before being welded. The two most complex joints are the upper connection point (where the chassis connects to the seat tube) and the connection of the lower beam to the axle housing. In the model, both of these joints have a piece of square tubing cut so that it sits flush against a piece of round tubing. This would be very difficult for WeCyclers to do, however the details of these joints are yet to be worked out, as the upper connection will depend on the style of bike frame that WeCyclers decides to use and the lower will depend on pending revisions to the axle.

3.3 Conclusions and Future Work

CAD and FEA were successfully incorporated into the design process, which allowed a large number of designs to be constructed and tested over a relatively short period of time. The use of these methods ultimately produced a chassis design that addresses many of WeCyclers' needs. The design provides an adequate margin of safety and is stiff enough to give riders a responsive and comfortable ride, in addition to being easily fabricated from locally available materials.

3.3.1 Follow-up Work in Lagos

Many other components of the WeCycle need improvement before it can be considered truly finished. In one month, I will be travelling to Lagos for three weeks to visit WeCyclers and work with them on these issues. Some of the components that I will be working on while in Nigeria are detailed below.

Bike Frame

As mentioned earlier, a rickshaw frame addresses the structural needs of the WeCycle but does not meet the ergonomic requirements for the rider. In the upcoming months I will be working with WeCyclers to either:

- develop a reinforced bike frame that has similar strength of a rickshaw frame
- modify a rickshaw frame so that it is easier to mount and dismount
- design a new bike frame that WeCyclers can fabricate

Wheel and Axle Reinforcements

A video of the WeCyclers' facilities showed that bent wheels were an extremely common problem, suggesting that there is a major problem with the rear axle and wheels. I plan on investigating how to strengthen the wheels to prevent future occurrences of this problem.

Aesthetic and Functional Design

The focus of my work was on the structural mechanics of the rear chassis, and did not go include work on the aesthetics or functionality of the WeCycle. While in Lagos, I plan to discuss with WeCyclers how the current WeCycle design can be modified so that it looks better, is a more effective communication of the WeCycle brand, and is easier to load and unload.

In addition to the above, I hope to test a physical prototype of the new WeCycle and then use the results of that testing to make any necessary revisions to the chassis design.

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<http://vimeo.com/91442240>

Appendix A: Evolution of Design

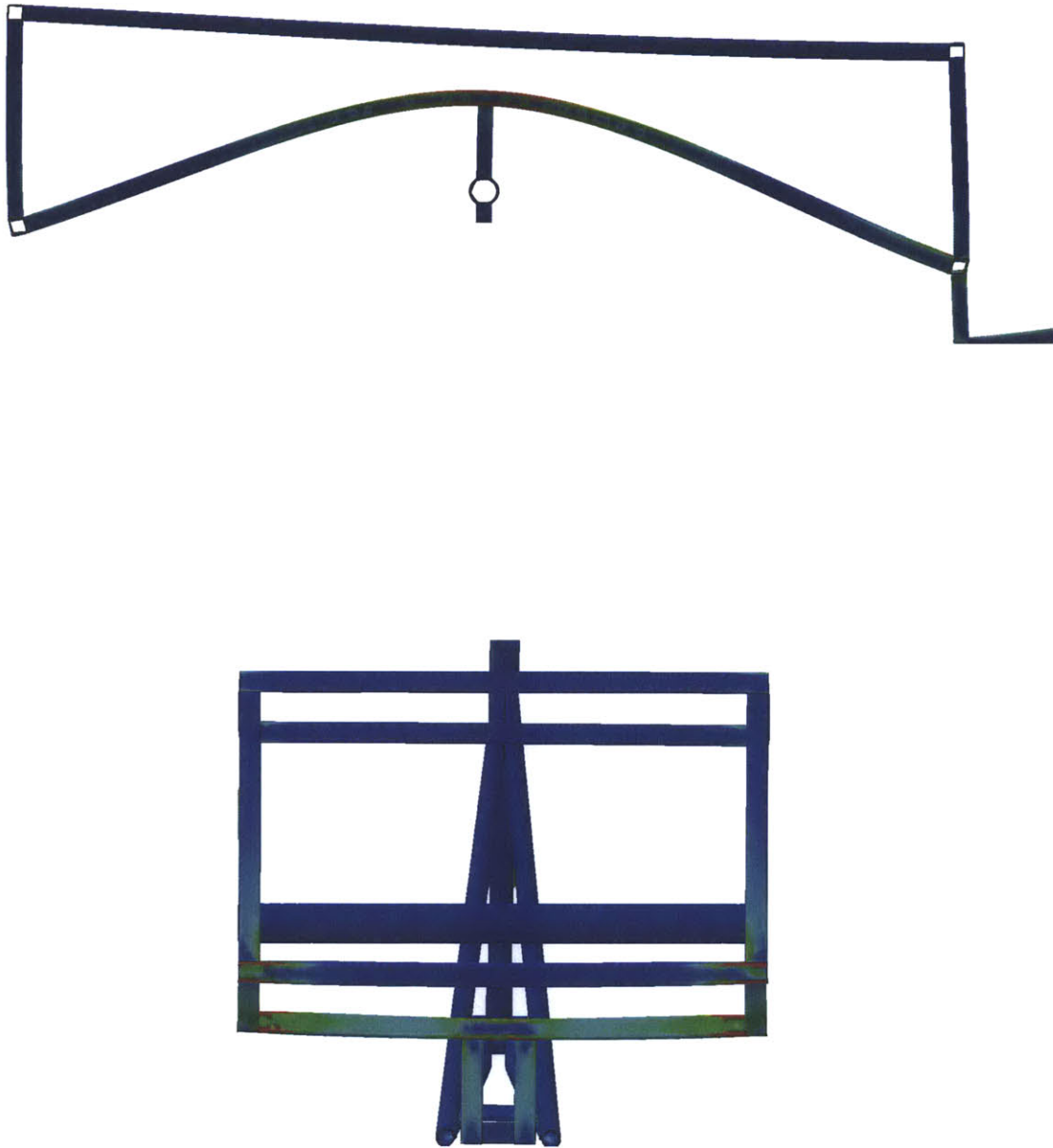


Figure A-1: Two views of the preliminary chassis model that served as a launch point for the rest of the study. The stresses are noticeably higher through, as are the deformations (Deformation scale: 14.2:1).

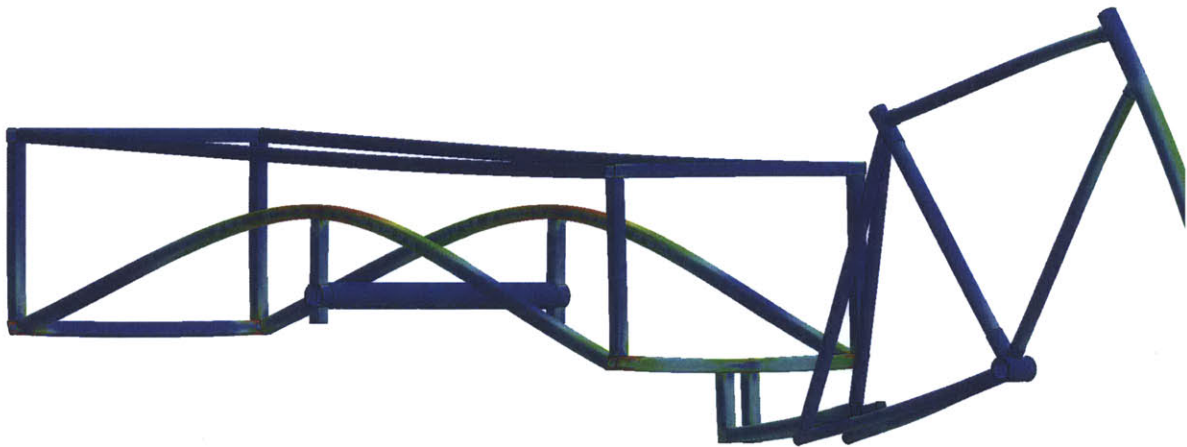
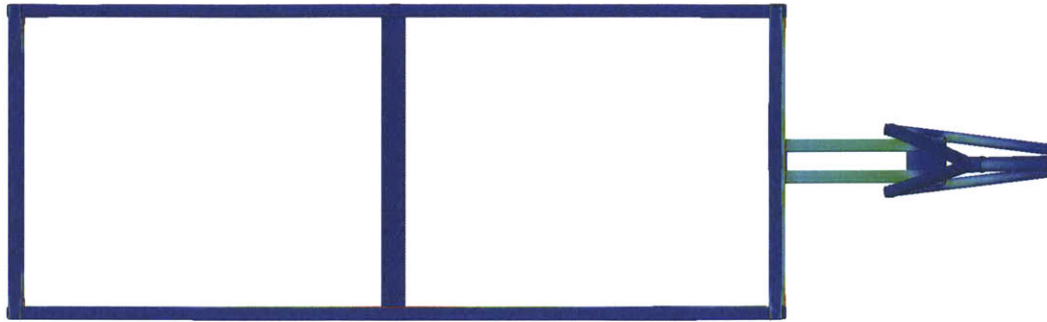


Figure A-2: More views of the preliminary chassis.

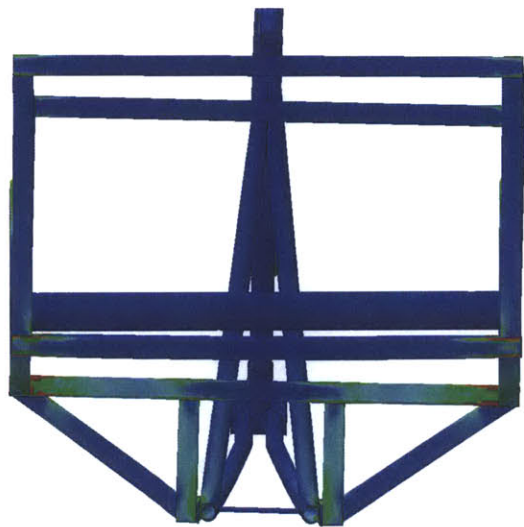


Figure A-3: Only a slight change as made from the first chassis design: the dropouts were moved closer to the chassis so that the joints between the two became vertical. This produced only a slightly better performance, but opened up many better options for connecting the chassis to the bike frame. (Deformation scale: 18.4:1)

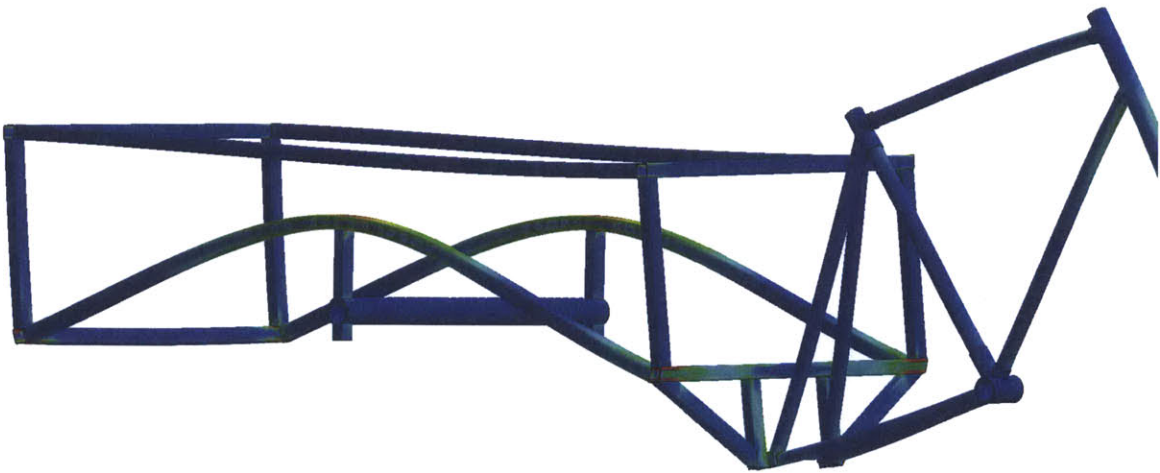
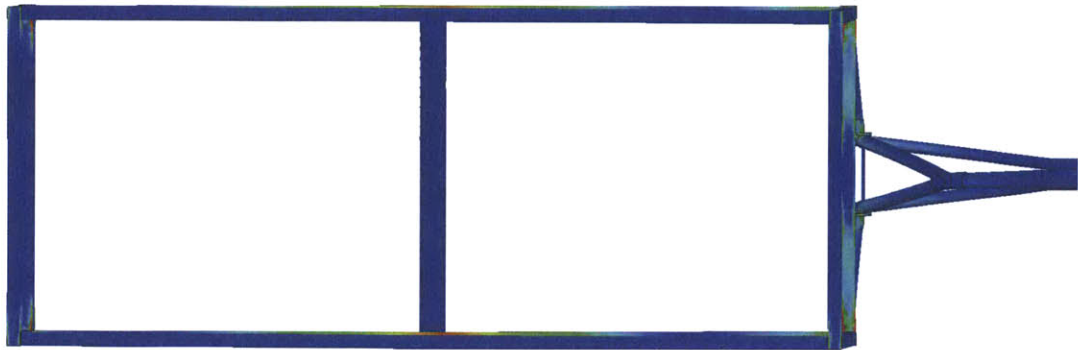


Figure A-4: Two additional views are presented of the chassis from A-3.

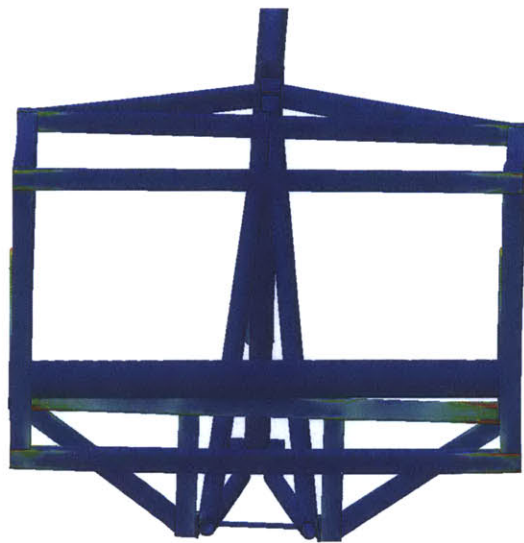


Figure A-5: A connection is made between the seat tube and the top of the chassis, decreasing the displacement between the lower connections. The stresses do not change very much from the previous chassis, but the system becomes more stable overall. (Deformation scale: 18.0:1)

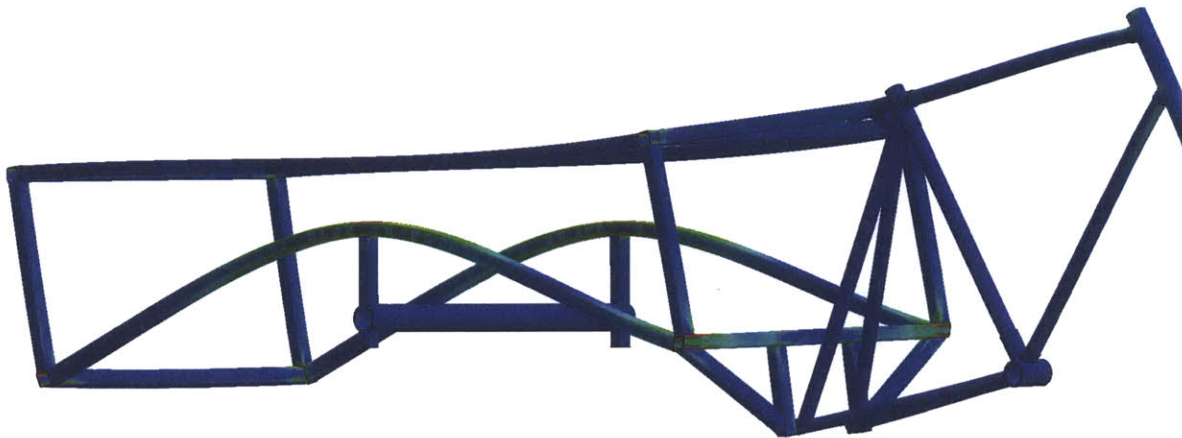
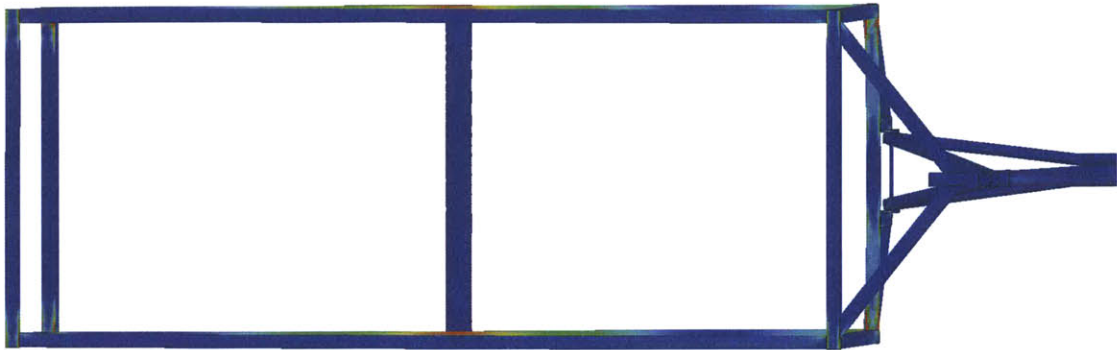


Figure A-6: Additional views of the chassis from A-5.

Appendix B – Weldment Profile Dimensions

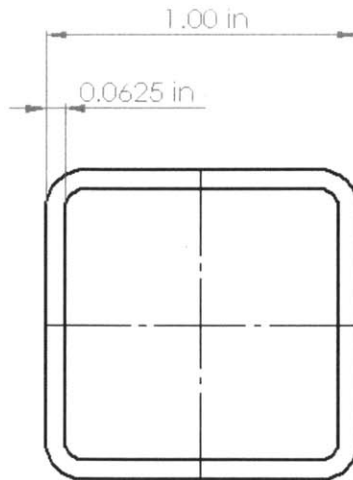


Figure B-1: Cross-section from a one-inch square tube.

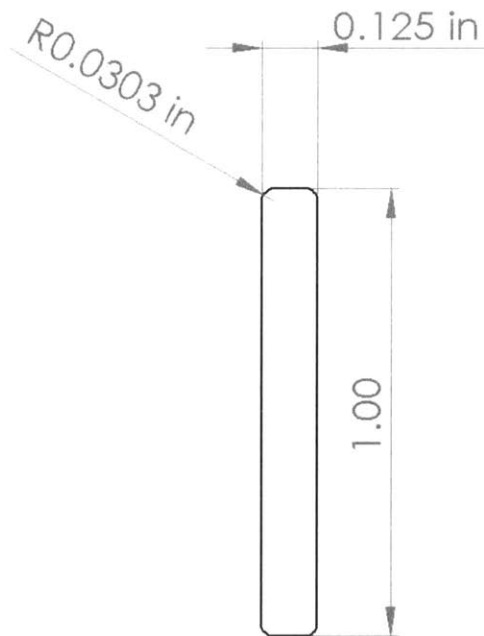


Figure B-2: Cross-section from a one-inch piece of flat stock.

Appendix C – Meshing Parameters

Table C-1: Coarse Meshing Parameters

Maximum element width	2.65 in
Minimum element width	0.53 in
Minimum number of elements in a circle	8
Element size growth ratio	1.6

Table C-2: Fine Meshing Parameters

Maximum element width	0.03125 in
Ratio	1.5

Appendix D – Properties of ASTM A36 Steel

Table D-1 – Material Properties of ASTM A36 Steel

Property	Value
Elastic Modulus	2×10^5 MPa
Poisson's Ratio	0.26
Shear Modulus	79.3×10^3 MPa
Mass Density	7850 kg/m^3
Tensile Strength	400 MPa
Yield Strength	250 MPa