A Technical Seminar report on

Material, Design & Analysis of a Bicycle Frame

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IBRAHIMPATNAM

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Abstract

Paper present the modelling and analysis of the Indian manufactured bicycle frame. The objective was to determine the strength of the frame and its performance under different loading condition. After the analysis it was concluded that large factor of safety have been given which in turn increased the weight of the frame. Reduction in frame tube thickness was feasibility option.

The study was also to point out potent failure areas due to fatigue loading. Optimization techniques were also used to reducing weight of the frame and hence whole bicycle. Comparison check also was made to check with different materials for the frame in aspect of the weight, strength and cost for the commute. For this Finite element analysis was done on the model prepared from the actual frame. Since material selection, heat treatment and geometry of the frame all have significant impact on the performance of the bicycle.

Papers also discussed about various other material section over convention steel frames. Aluminum and titanium frames are beginning to be common these days but due to obvious aren't dominating the market. It was also observed that homogeneous cross section can be dropped out and variation in cross section in high stress region not only saves material but also reduced the frame weight.

Complex shapes are quite difficult with metals but this can be achieved easily by the composites. Composites like carbon fiber made into frame are extremely strong and rigid apart from obvious advantage of low weight.

To have an economical design it was also seen that use of more than one material can be highly beneficial.

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1. Introduction

A bikes frame is the central system to support and locate other components of the bicycle such as Chain-drive system, Handle bar and steering system, pedal assembly, seat. For a good performance of the bicycle various conditions have to be met such as stability, ride quality, ergonomics to rider etc. Bicycle seen today are 100 years old, with very few changes they still are important to many commutes. Now there are more than a billion bicycles worldwide, twice as many as automobiles it's not only a mode of transport but also is a recreational sport, form of physical exercise and the most clean and cheap transport.

The basic shape and configuration of a typical upright, or safety bicycle, has changed little since the first chain-driven model was developed around 1885. But many details have been improved, especially since the advent of modern materials and computer-aided design. These have allowed for a proliferation of specialized designs for many types of cycling.

The bicycle's invention has had an enormous effect on society, both in terms of culture and of advancing modern industrial methods. Several components that eventually played a key role in the development of the automobile were initially invented for use in the bicycle, including ball bearings, pneumatic tires, chain-driven sprockets, and tension-spiked wheels.

The bicycle has undergone continual adaptation and improvement since its inception. These innovations have continued with the advent of modern materials and computer-aided design, allowing for a proliferation of specialized bicycle types.

A bicycle stays upright while moving forward by being steered so as to keep its center of mass over the wheels. This steering is usually provided by the rider, but under certain conditions may be provided by the bicycle itself.

The combined center of mass of a bicycle and its rider must lean into a turn to successfully navigate it. This lean is induced by a method known as counter steering, which can be performed by the rider turning the handlebars directly with the hands or indirectly by leaning the bicycle.

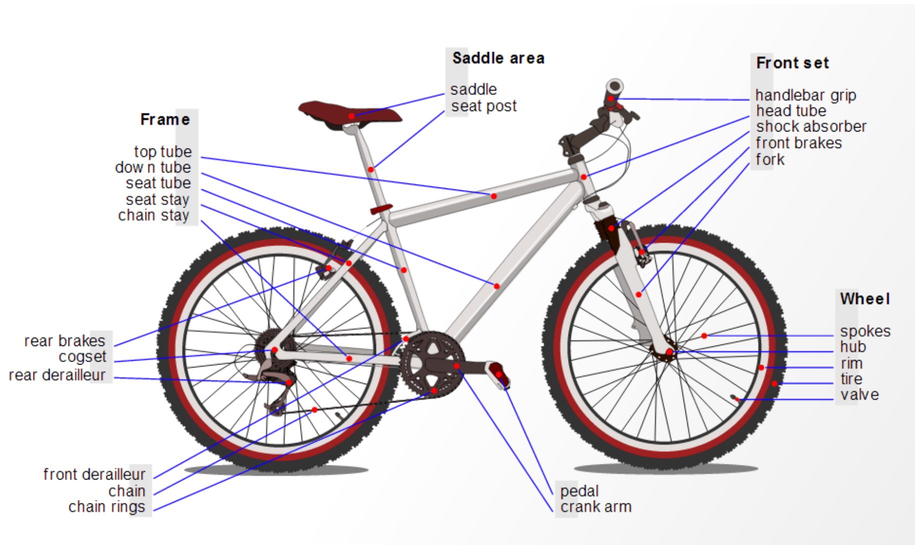


Figure 1.1 Components of a bicycle

2. Literature Review

2.1 Review of Bicycle Frame History

It is believed that people have been thinking about building human powered bicycles sincethe fifteenth century. A sketch named *Codex AtlanticlIs* and attributed 10 Leonardo Da Vinci shows a device resembling a bicycle with pedals. a crank and a chain drive connected to the rear wheel. This bicycle however did not have steering. hence would have been unstable and thus would not have been ridden.

By the beginning of the 18oo's, unsteer able two-wheelers referred to as hobby horses Appeared in England [2]. The problem with these machines is that they could not be balanced going down a hill al high speed as they could not be steered. Thus possibly the most important invention in bicycle frame design was made by the German Karl Von Drais who disco\"ercd (possibly by error) that a front steering hobby horse couId he balanced going down a hill at high speed. In 1817 he built the *Draisienne*

The ensuing evolution in bicycle design was driven by the need to use the legs in an efficient way in order to propel the rider at the highest speed possible. The lack of an appropriate chain drive combined with the road conditions at the time (which would have made a chain drive unusable even if it existed). Led to the appeamnce of the *Ordinary*bicycle (high wheeler)

The driving front wheel was made as large as conformable pedaling would allow in order to provide the maximum distance for each pedaling revolution and hence the highest speed possible. The size of the front wheel was dictated by the length of one's legs. A large *Ordinary* could have arriving wheel in excess of 15m in diameter. The 1870's were the years of dominance of these high wheelers. But severe injuries to those who fell and the impr.ICtÎcaIities that prevented women with dresses and short or athletic people to ride these machine combined with the appearance of suitable chain drives led to the more convcntional *Safery* hicyclc. The *Sakry* hicycle was ealieJ as such he cause it was muchsafer than the *Ordinary.* The liN *S,(/i:ry* hicycle was introduce in 1S69 at the liars! Paris velocipede show hy Andre Guilment [5J. However the Jirect JesccnJants of toJay's bicycles were built and presented in the early 1880's at Britain's Annua! Stanley Bicycle Show by Starley. BC' 1886. these Starlcy *Safery* bicycles had hall baring direct steering. rubber tires and a diamond geometry very close to what we know today. Figure 2... shows the Starlcy *Safery* bicycle [6]. The de cades that followed Ied to refinement in the materials. design. components and construction methods up to what we know today.

After the appeurJJ1ce of cars and motorcycles relying on the internal! Combustion engine. bicycle popularity as a means of transportation decreased in some countries. including Canada and the United States. But in the 1960·s. North-America experienced the early signs of a bicycle reVOIUliol". Sport bikes with multiple gearing were introduced into the adult market. Cycling was then promoted as an adult activity and as a legitimate sport that wouId toster cardiovascular health. This revolution gave every indication of being broadbased. deep. and diverse. Millions of people are now riding bikes for exercise and transportation. and the market is alive with inventiveness. Large and small scale manufacturers arc introducing new bicycle f=es. components. and systems at a mpmte. Cilies arc building more and more bicycle paths in order to accommodate the increasing traffic and the sales of bicycles arc ever increasing. We arc thus in the middle of "cycling frenzy" that the word has never experienced before which is favol".label to research into bicycle design.

2.2 Review of Frame Building Materials

Throughout the years. Frame building materials have evolved what we now think as ycry primitive materials to space are materials which were unknown to our society only 30 years ago. It is this improvement in materials which allowed to the greatest extent the evolution in bicycle frame design. This section will view most of the fram4 building materials which have been used in the past. It will show the advantages and disadvantages of the different materials and explain the apparition and disappcar.ll1ce of some of them. This analysis will help to rationalize the use of carbon liber material for use in this project.

Wood

Wood was used in the very first bicycle frames produced. Von Dmis' *Draisienne* and most other hobby horses in the 18oo's were made of wood [7]. Since a minimum stiffness was required in order to prevent enormous bending and potential collapse. hcavy wood was option used resulting in very heavy structures. This combincd with the tremendous work required to shape the wood made designers and builders quickly realize that this material was not the solution. Even though some good wood frame were successfully built. Around the 1870·s. metal construction became dominant. but wood continued to be used spomdically in the construction offrames. rirns. and mudguards even until the 1930·s. At sorne point. bamboo was used in the construction of fr.unes [7]. Figure 2.5 shows a bamboo frame l'rom 1870. However because of the scarcity of this wood in thc cities. and the increasing use and understanding of steel. wood and bamboo fr.lffies have completely disappear

Steel

While the strength is dictated by Metallurgy. Heat treatment. And/or mechanical cold working. The strongest bicycle steel available is the French-made EXCELL. It has a tensile strength of more than 13S0MPa. Among the advantages of using steel includes the fact that it is ideal for custom design. as different tubes~ can be chosen to provide different riding characteristics for each rider. Steel also possesses traditional reality and can in cel1ain cases highlight beautiful craftsmanship. Also. steel has remained relatively inexpensive and readily available over the years. Steel do not fail catastrophically without indication and they possess the attractive progeny of having *fatigue limit. Fatigue limit* is defined as the stress level below which a material will never fail under fatigue loading. It reveal the region close to failure with cracks that widen slowly in order to allow for an early detection of possible failure. If it does break. il is very easily repaired by heating a few joints. Popping out the damaged tube and replacing it with a new one.

Aluminum

The first experimentation with aluminum in the 1891 The early frames were made from cast aluminum. The tubes were joined together with lugs as the welding of aluminum was not well known at that time. tubes arc now brazed. Since aluminum has a modulus lower than steel oversize tubes may be required in order ta provide a rigidity comparable lo a steel. However because of its lower density. even larger diameters and wall thicknesses do not result in a heavier frame. As we increase the diameter of the tube the rigidly increases to the 4th power of the diameter while the weight increases following the square of the Diameter. Hence it is possible to obtain a rigid and light thune with a1uminum. Early Poorly designed aluminum tr.101es helped to build a bad reputation for aluminum frames. The fact that this material does not have a *fatigue limit* requires the frames to be slightly overdesigned in order to compensate for this property of the material.

Aluminum is relatively inexpensive. Light and adequately strong. One of the major

Advantages of a1uminum over steel fr.101es is that it is non-corrosive. If properly designed and built. a1uminum fr.101es can be as stiff and lively as steel fr.101es and are now among the lightest fr.101es on the market.

Titanium

The first use of titanium in frame construction occurred in the early 1970·s. TitaniumOffers bicycle designers a material 62% stiffer than aluminum but 42% lighter than steel. Titanium are amongst the lightest on the market at the present time. Titanium fr.101es are usually made commercially pure titanium (0.2% oxygen added to pure titanium) or from 3A112.5V (3% a1uminum and 2.5% vanadium) a1loy tubes. These. tubes are usually bought from aircraft and chemical company suppliers which sell these tubes usually as corrosion resistant plumbing for these industries. The high cost of titanium comes from the material out of the rutile ore (TiO,) as well as the quality control procedures for components destined for the aircraft industry:'. However. sore tubing manufacturers arc now producing "recreational glade·· titanium a1loy tubes. This grade has only the applicable sufficient for use of the material in bicycles. Another factor which adds to the high price of titanium lr.ll1les is that titanium can only be welded in an atmosphere (typically argon) since molten titanium instantly with oxygen. The Availability of the tubes still being somewhat limited. The designs are limited by the available tubes.

3. Frame tube

The bicycle frames donated for fatigue investigation feature a traditional diamond frame design, consisting of a front and rear triangle. This design has been the industry standard for bicycle frame design for over one hundred years. The frame consists of a top tube, down tube, head tube, seat tube, seat stays, and chain stays. The head tube of the frame holds the steer tube of the fork, which in turn holds the front wheel. The top tube and down tube connect the head tube to the seat tube and bottom bracket. The seat tube holds the seat post, which holds the saddle. The bottom bracket holds the cranks, which hold the pedals. The seat stays and chain stays hold the rear dropouts, which connect the rear wheel to the frame.

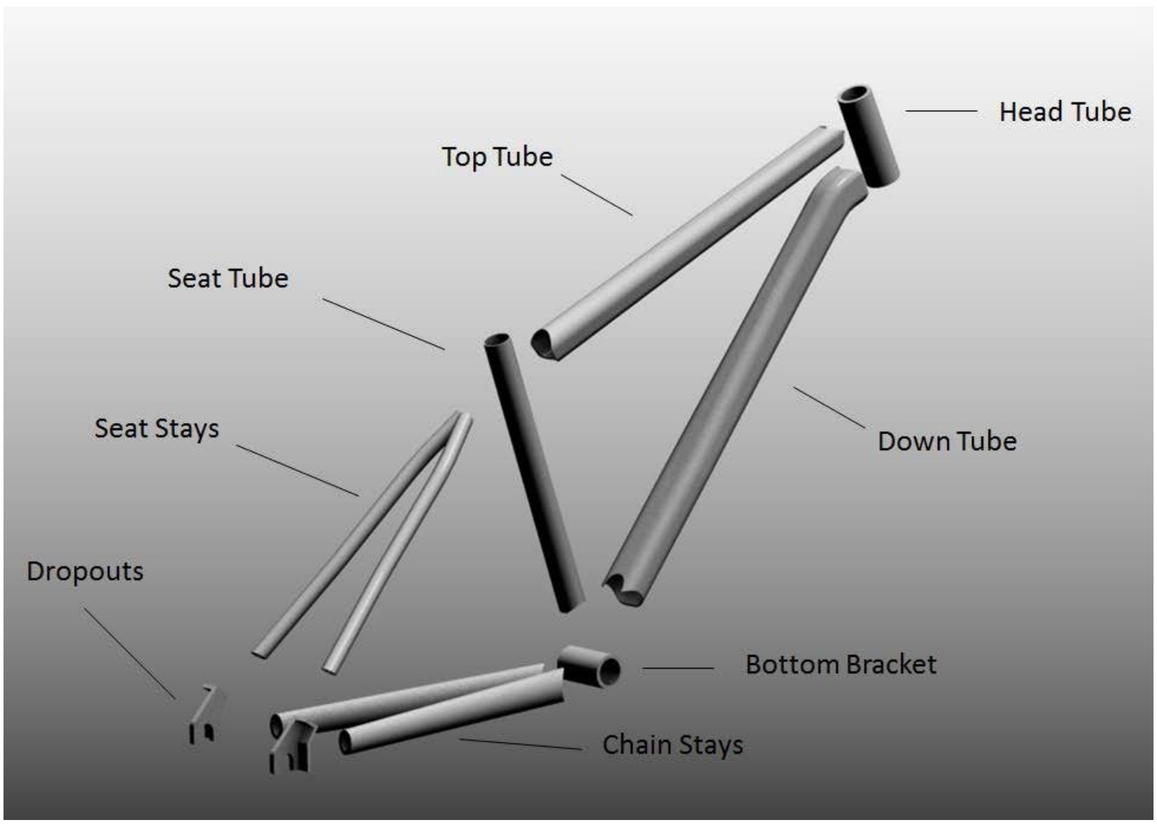


Figure 3.1: Tubing diagram of the donated bicycle frames.

4. Common materials for frame

There are a wide variety of materials used in bicycle frames. Bike frames were originally made from wood, but modern frames are made primarily from aluminum, steel, titanium and carbon fiber. Some of the less common materials used in creating frames include bamboo, thermoplastics and magnesium. Bicycle frames constructed from the more common frame materials can be seen in Figure 2.

Figure 4.1: Common bicycle frame materials

The materials used for mountain bicycle frames have a wide range of mechanical properties. These properties can be seen in Table 1. There is not one material in the table that has advantageous properties in each category, which explains why manufacturers continue to fabricate frames from several different materials.

	Modulus of Elasticity (GPa)	Yield Strength (MPa)	Tensile Strength (MPa)	Fatigue Strength at 50,000 Cycles (MPa)	Density (kg/m3)	Weldability and Machinability	Cost (rupess per kg)
Aluminum – 6061-T6	72	193-290	241-320	75	2,700	Excellent	280
Steel - 4130	205	800-1,000	650	250	7,800	Excellent	170
Titanium – Grade 9	91-95	483-620	621-750	250	4,480	Fair	4000
Carbon Fiber	275-415	Varies	Varies	Varies	1,800	Fair	Varies

Table1: Specifications of materials for frame

5. Manufacturing of frame

Welding is the method of choice for most manufacturers to join frame tubes, as it provides high joint strength and is also affordable. TIG welding is the most common type of welding for 6061 bicycle frames, and was the joining method used for the donated frames. TIG Welding is an arc welding process in which heat is produced between a non-consumable tungsten electrode and the work metal. TIG welding utilizes the inert gas, argon, to keep the weld area clean which prevents the metal from oxidizing during the welding process. TIG welding is commonly chosen as the welding method for thin tubes and is desirable for the bicycle industry since it provides a high quality finish on the weld surface.

6. Methodology

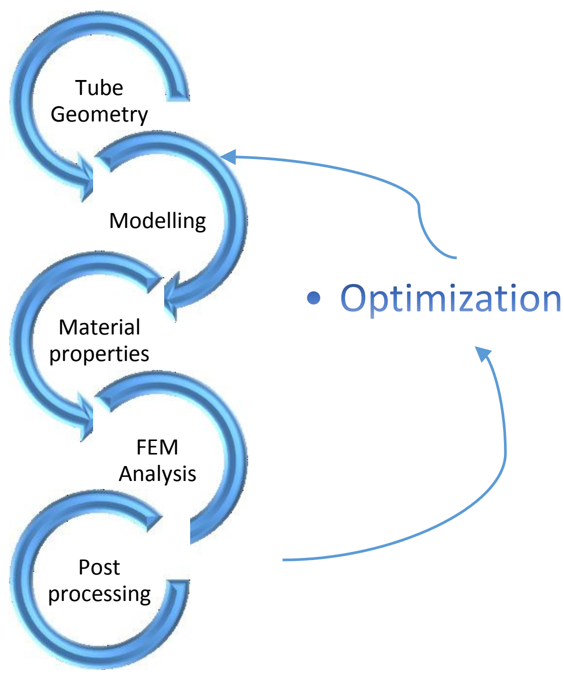


Figure 6.1 Methodology of project

7. Geometry

The geometry of frame was taken by considering the view. Since it was easier to take the plot the coordinates, it was modeled by taking the reference datum at bottom tube. Also the angles were also easily accommodated in such approach.

Figure 7.1 Frame under study

The measurement and spacial arrangement of seat stay and chain stay were a bit complicated due to their existing in different plane from front. There were simplified by talking the smaller and larger breadth of the trazepiziod.

The diameter of each tube were taken in consideration also thickness. To measure the thickness the approach of referencing with standards were used.

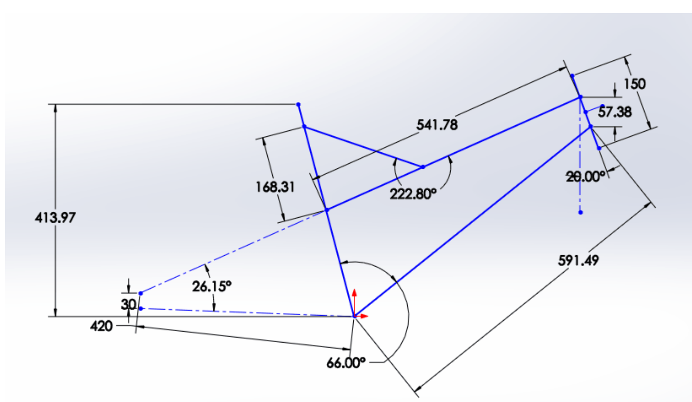


Figure 7.2.Front view dimensions

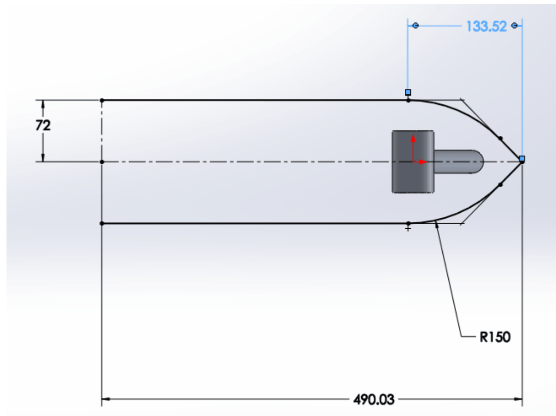


Figure 7.3 seat stay dimensions

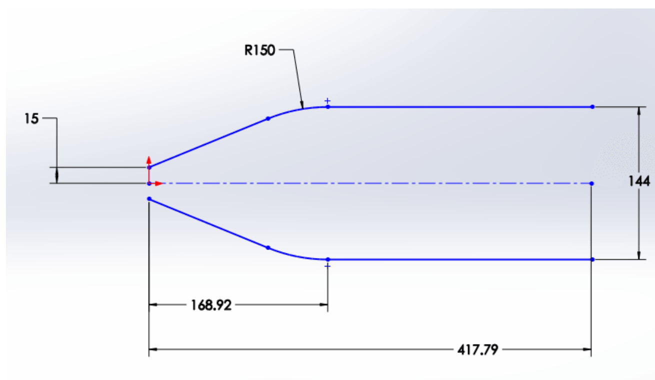


Figure 7.4 Chain stay tube dime

When all the required dimension were drafted to respective planes. The next step was to model the tube around them.

According to STEEL TUBES IS: 3601-1984 Appendix A (Clauses 1.1,9.1,21.1.1)

Outer Diameter	Thickness	Weight per length (Kg/m)
mm	mm	kg/m
21.3	2.6	1.56
26.9	3.2	1.87
33.7	4.0	2.93
42.4	5.0	4.61
48.3	5.0	5.34
60.3	5.0	6.82

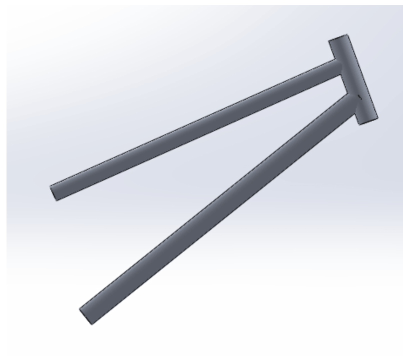
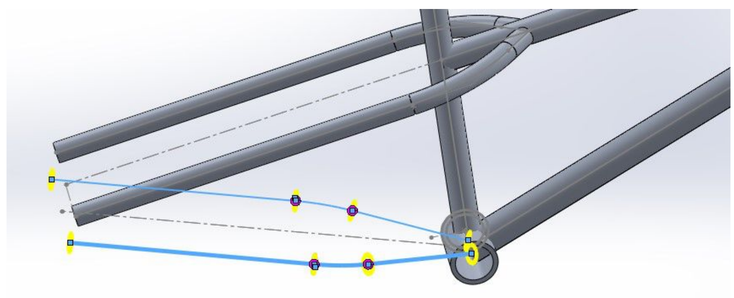
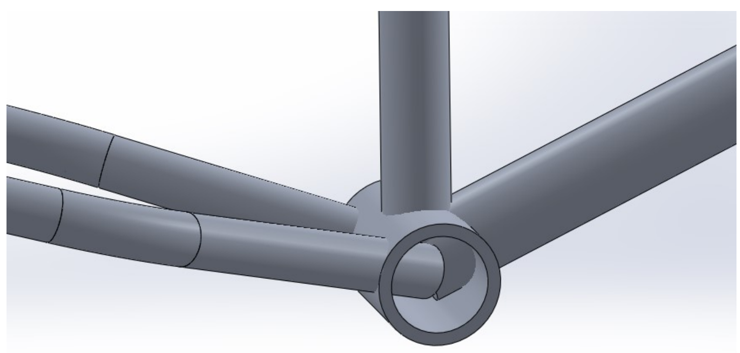
From the above information the dimensions for the tubes in frame are such

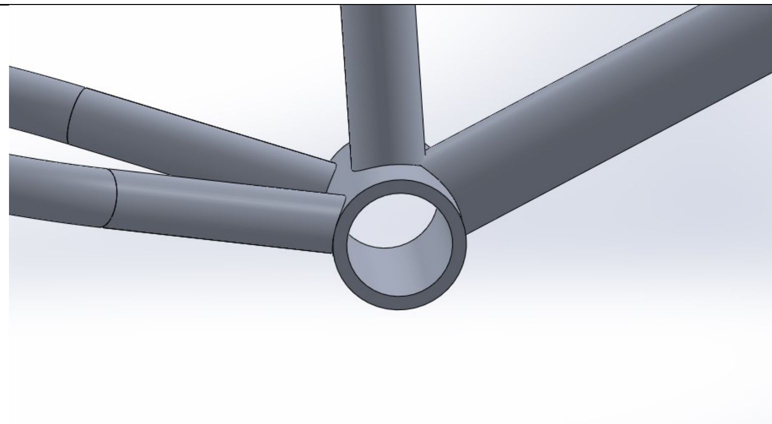
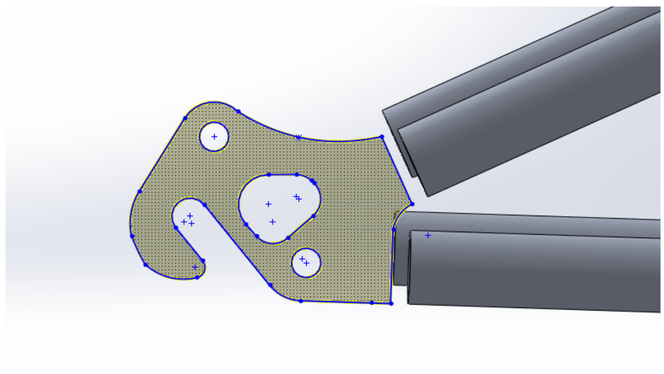
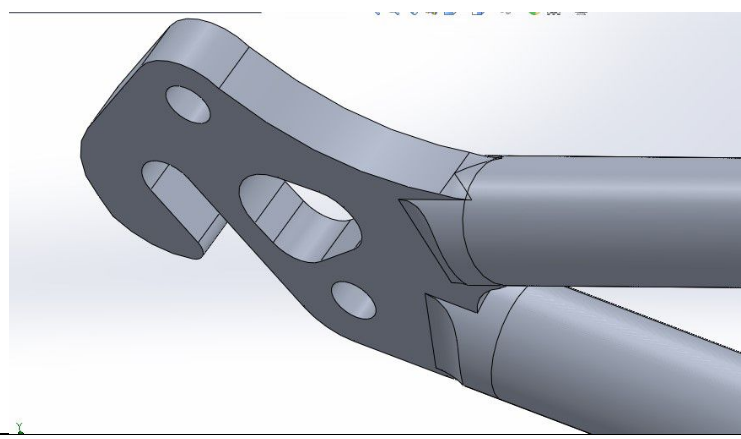
Tube	Cross-sectional Dimensions	Length (mm)
Head tube	33.7 x 4	150
Down tube	33.7 x 4	591
Top tube	26.9 x 3.2	541
Seat tube	26.9 x 3.2	428
Bracing tube	21.3 x 2.3	244
Bottom bracket	48.5 x 5	72
Seat stay	21.3 x 2.3	952
Chain stay	21.3 x 2.3	858

Few were also verified by measuring the thickness taken at the end caps of the tubes.

8. Modelling

Modelling is done in following steps.

Weldment command is used to create the tube cross section. Availability of such a command is very helpful for any frame design. Conventional CAD used Sweep command making it tedious to make separate planes for cross-section	
Each individual tube is selected as different tubes have different cross section.	
The interference of tube aren't appropriate as they extend beyond the intersecting tube	

<table>
<tr><td>Tubes are mittered by using trim/extend command. Also un mittered ends interfere with analysis.</td><td></td></tr>
<tr><td>Drop-outs are sketched accordingly.
It can be complex to join a tube end and a plate</td><td></td></tr>
<tr><td>The contact of drop outs and tube are done by fillet welding and providing a circular plate.</td><td></td></tr>
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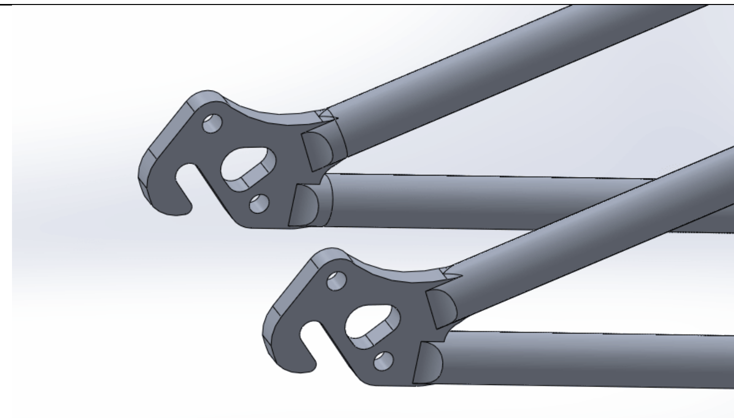
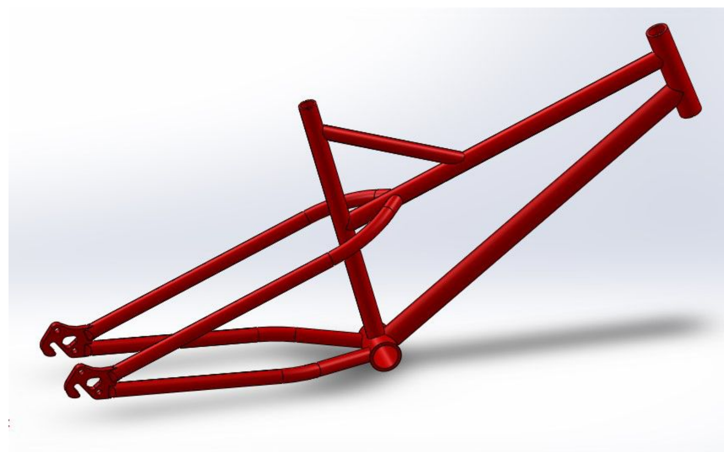
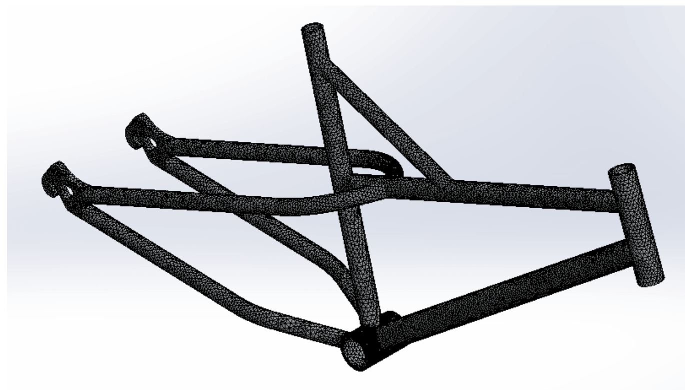
The sharp edges are filleted. The body is then mirrored.	
Colored to match the parent frame from the Hercules bicycle. Complete of model	

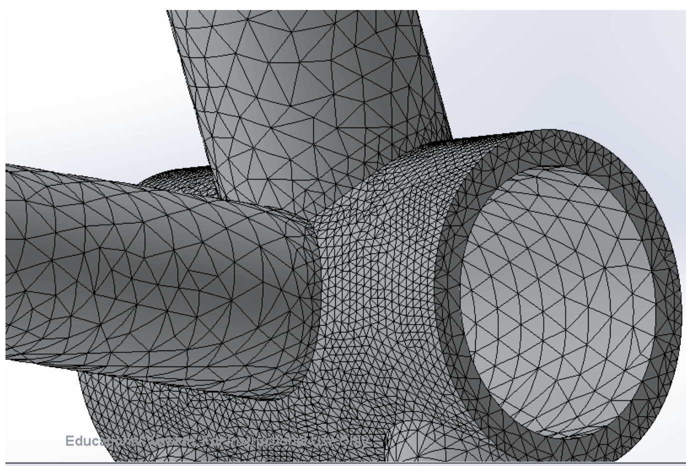
9. Preprocessing

Once the solid model of the donated frame and the test fork were created, an FEA was conducted with COSMOL using the solid model. An FEA is a computer based numerical method which models an object with a mesh of separate elements connected by nodes to determine stress, strain and a number of other properties 37

The decision was made to use Solid works Cosmos due to its ability to import solid models created in Solid works, and the software's ability to simulate fatigue loading on the frame. The procedure for setting up the model in ANSYS is described in the following sections.

Meshing for the model was done using the automated meshing refinement feature. Added resolution was used for the head tube, weld zones, and upper top and down tubes. This added resolution decreased the element size, and increased the total number of elements in these areas. This allowed for more accurate understanding of the behavior in this area since this area is predicted to fatigue fail based on the frame. Larger element sizes were used in the rear triangle of the frame, and in the fork due to the reduced need for these areas to be accurate since these areas were predicted to fail with higher loads and higher cycles. Tetrahedron mesh was used heavily due to complex curvature at tube endings.





10. Constrains

The drop out is where the bearing is place they are constrained as rigid. Also the stability of shaft rotation is turned out to not to conflict with the output.

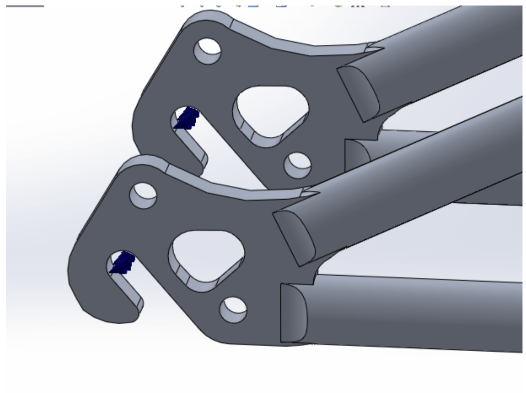


Figure 10.1 Constrain 1

The lower face of the head tube was constrained by elastic support which acts as a tire deflection.

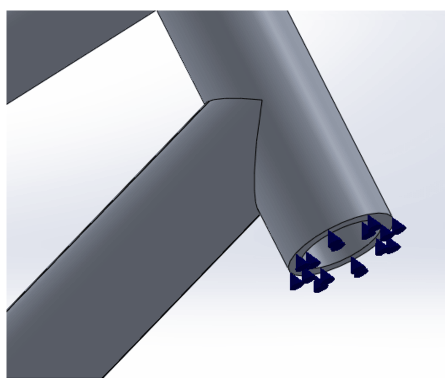


Figure 10.2 Constrain 2

11. Loading Scenarios

Steering Handle

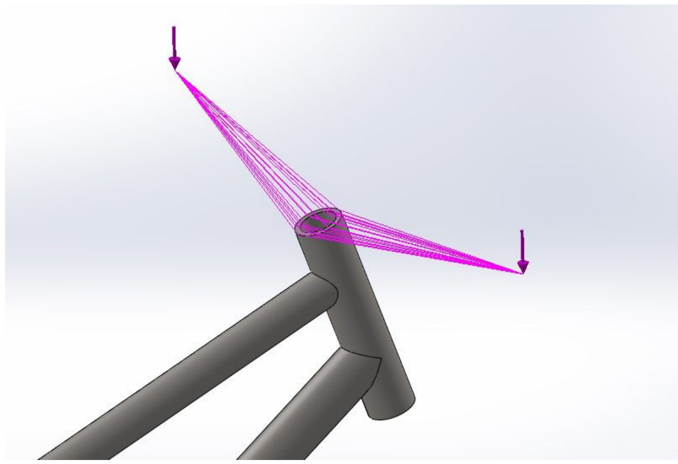


Figure 11.1 Loading 1

Remote loading at a distance of 250 mm away from hear tube on both sides was added. This replicates the eccentric loading of the handle.

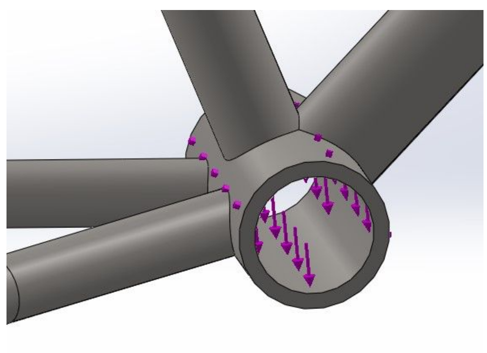


Figure 11.2 Loading 2

Since the pedal bearing take 60% of the loading, it is loaded by bearing load in radial direction.

Effect of inertia was also added.

Impact loading

This test try to replicate stress produced when the bicycle falls from a certain height. To obtain the impact load on the hubs,

Assuming the bicycle falls from the height (h),

$$h = 1\ m$$

The impact velocity (v) of the bicycle is,

From kinematic relation for rectilinear motion

$$v\ = \sqrt{(2 * g * h) - u^2}$$

whereas,

g = acceleration due to gravity (9.8 m/s^2)

u = Initial velocity of the bicycle before the fall (0 m/s)

Substituting the above value,

$$v\ = 4.42\ m/s$$

And now for calculating the impact force (F)

From Work-Energy Principle,

Change in Kinetic Energy of the object = Work done on the object

$$\frac{1}{2}\, m\ (\ v^2 - u^2) = F * d$$

whereas,

d = the compression of the shock springs (0.15 m)

Thus,

$$F_{shock} \approx 7000\ N$$

Pedaling/ Cruising

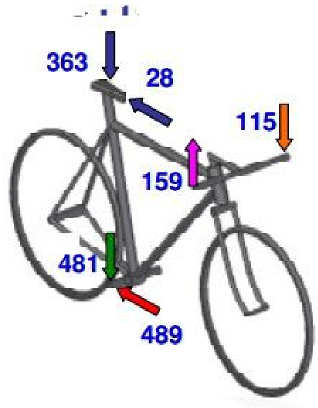


Figure 11.3 Pedaling

Since in the posture of pedaling one hand tends to pull up while other goes down this being respect of the same side of feet going down.

Standing Pedaling

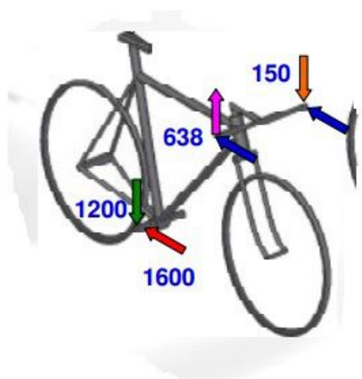


Figure 11.4 Standing Pedaling

Since whole of weight falls on pedals and handle, no load is taken on seat.

Braking

During the heavy braking whole of the drivers shifts on handle.

Figure 11.4 Braking

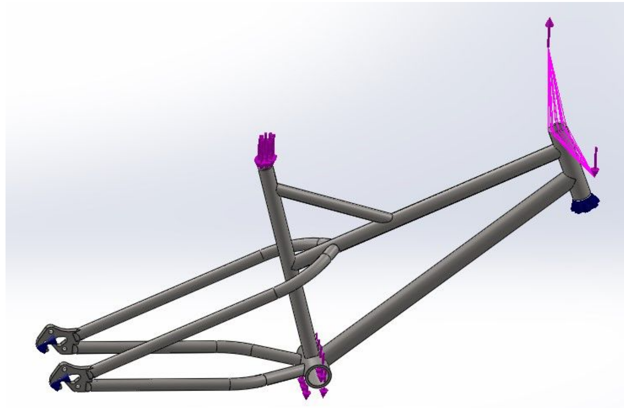
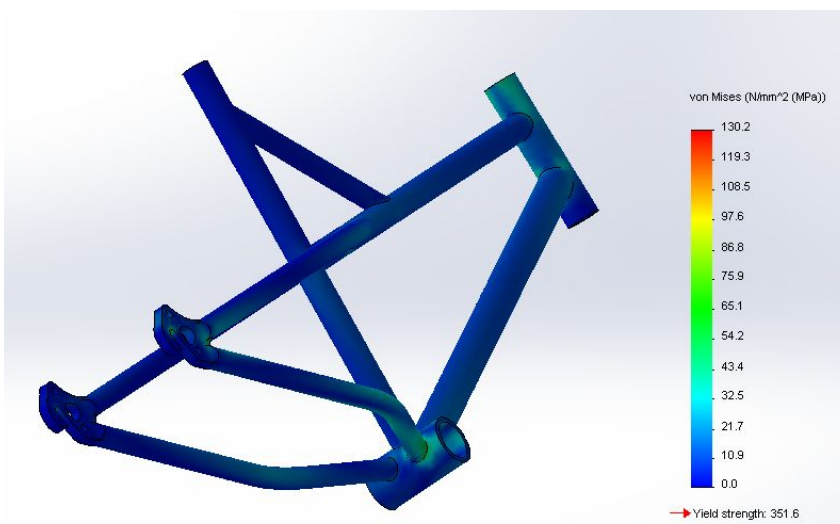


Figure 11.5 Loading on frame

Shown is the loading and constrains of the frame.

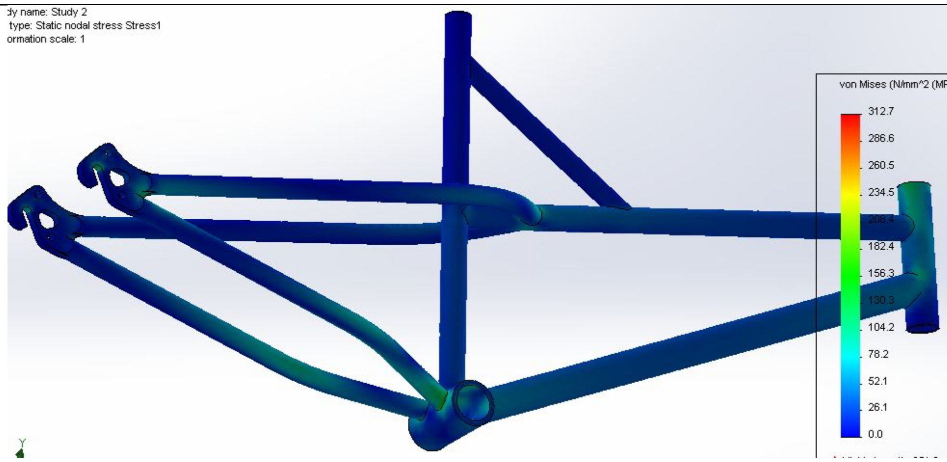
12. Analyzing

Following table will have the analysis of the scenarios correspondingly to their post processing values.

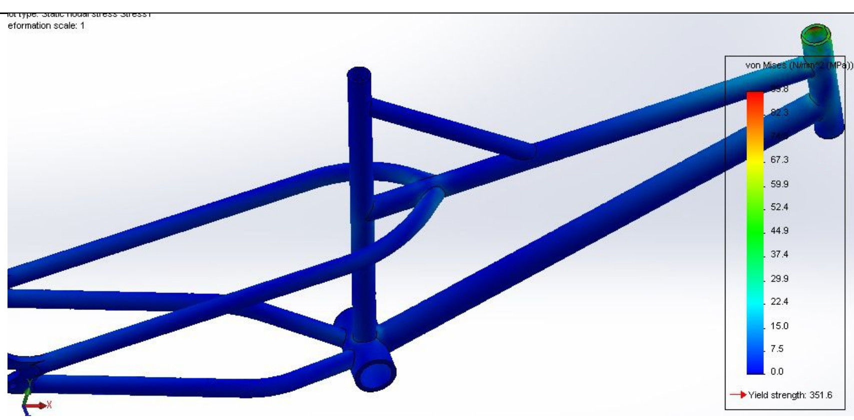


Scenario	Sitting Pedaling
Maximum Stress	130 MPa

Maximum Deflection	1.45 mm
Factor of safety	2.45



Scenario	Standing Pedaling
Maximum Stress	260 MPa
Maximum Deflection	4 mm
Factor of safety	1.45

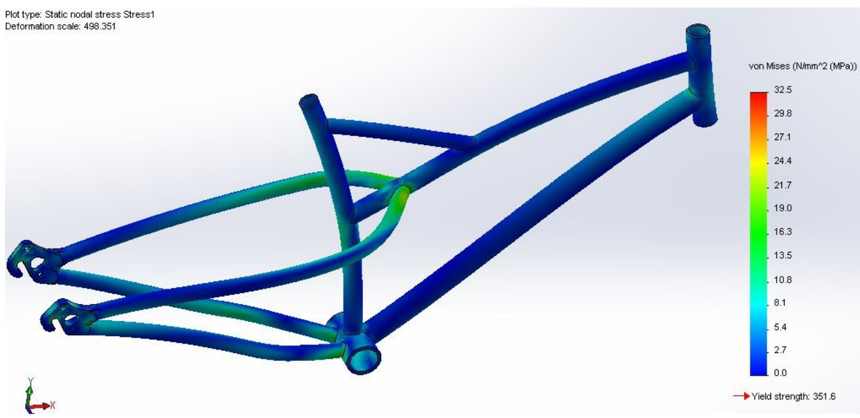


Scenario	Braking
Maximum Stress	89 MPa
Maximum Deflection	0.3 mm
Factor of safety	3.6

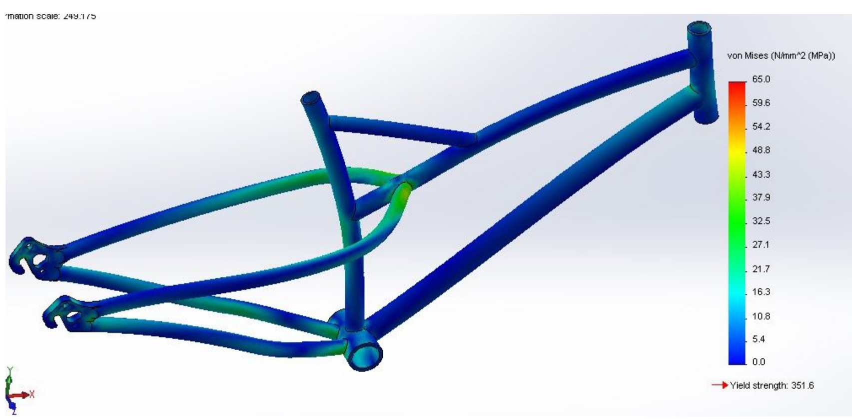
Checking the strength of the frame

Iteration

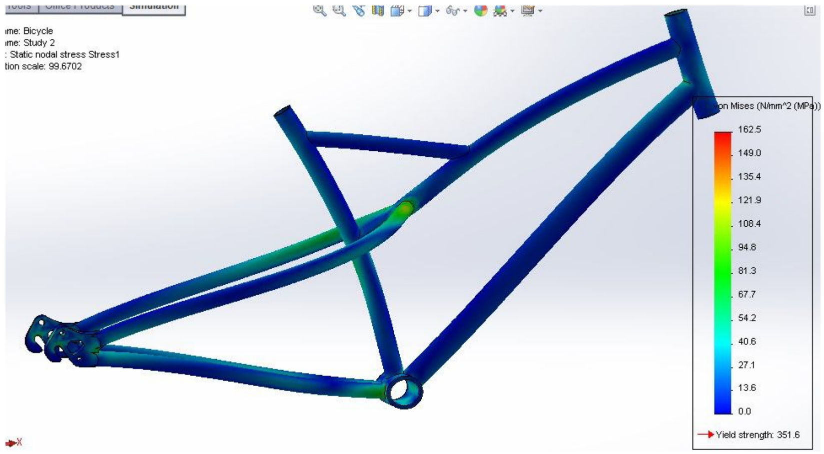
1. 1000 N- 600N on the pedal 200 N on the either handle sides



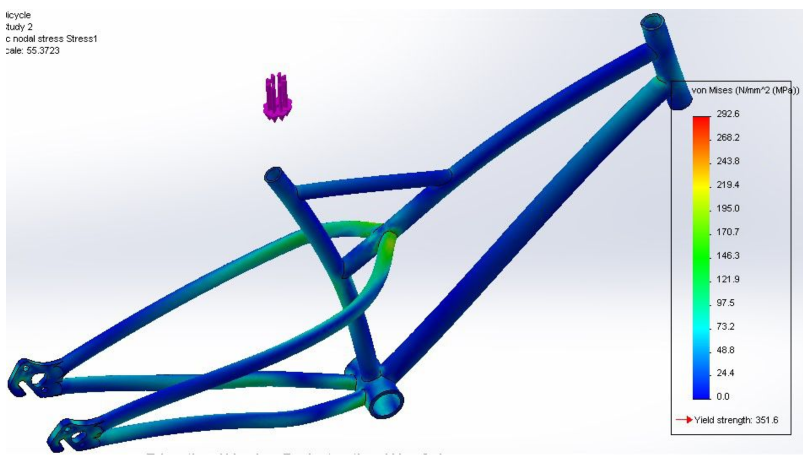
2. 2000 N- 1200N on the pedal 400 N on the either handle sides



3. 5000 N- 3000N on the pedal 1000 N on the either handle sides



4. 9000 N- 5400N on pedals 1800N on handles



Going any further would not yield any appropriate results as the Heat effected zones have reduced strength if not heat treated they fail way before than yield strength.

13. Inference

1. Since steel was used, alternative materials like aluminum and titanium alloys can be used to bring down the weight. Current model weights 9 Kg with steel, the same can be made 2.4 Kgs with aluminum.
2. Low weight greatly reduces the fatigue of the driver.
3. Many locations of low stress regions were observed suggesting a non-homogenous designs could yield a reduced weigh and added strength
4. Complicated cross sections can be easily be optioned by the use of composites by making dies.
5. Weld radius can be increased to reduce the notch sensitivity
6. Maximum stress were found at welded joints.
7. Strength of the given frame was analyzed to take up vertical load up to 9000N.