Strength Analysis and Design of Bicycle Frame

MSE 221 Fall 2021

Team Oak

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Abstract

In this report we are conducting a strength and analysis test on a bike frame. In the latter half of the report we also propose new design changes to possibly help improve the performance of the bike.

The bike used for reference is a steel alloy CCM mountain bike. For the first part of the analysis, Finite Element Analysis is used within SolidWorks to calculate the forces and stresses in each beam for the replica frame structure, as shown in the rest of our report. For the second part we changed the material of the bike to aluminum this made it lighter, but slightly less durable.

From this project we can see that even before applying any design changes, the steel frame is more than capable of supporting the weight of the rider even when the rider has jumped onto the bicycle to start. However, by changing the material we can improve the speed and lower the weight at the cost of durability and strength.

This project has given us an overall better and deeper understanding of the subject of statics and strength of materials.

1. Introduction

Bicycles were introduced in the 19th century in Europe, and by the early 21st century, more than 1 billion were in existence; these numbers far exceed the number of cars produced [3]. A bicycle is a human-powered vehicle consisting of two wheels attached to a frame, one behind the other. In this project, we will be breaking down and analyzing the internal forces that act within the frame of a bicycle and we will also be applying some design changes to the frame in an attempt to improve the Factor of Safety for the bicycle that is analyzed.

1.1 - List of Figures and Tables

2. Background Knowledge

2.1 - Bicycle Design

There are multiple different elements that must be considered when designing a bicycle, these elements include power generation, power transmission, aerodynamics, dynamics, strength, mechanisms, and materials [2]. Although bicycles have been around for almost 200 years, they are still far from being considered ‘fully developed’. With an intention of enhancing the riding experience, modern bicycles integrate electronic devices to enhance their performance. For example, many bicycles implement an electronic gear-shifting system which enables riders to shift with electronic switches instead of using conventional control levers and mechanical cables [3]. This enhances the riding experience by allowing faster switching between gears, auto calibration, and may require less maintenance compared to traditional switching methods. Thus, bicycles can gradually become mechatronic devices. With respect to this project, we will be focusing on the strength aspect of bicycles. Fig 2.1 below is a picture of the bicycle that we will be using in this project, the material of the bicycle is steel.

Figure 2.2 - Bicycle

2.2 - Bicycle Frame

Figure 2.2 shown below illustrates the frame of the bicycle, its dimensions, and the names of the different components of the frame. The diameter of the tubes in the bike are approximately 33 mm. In this project the main focus will be towards the frame, specifically the strength and design of the frame.

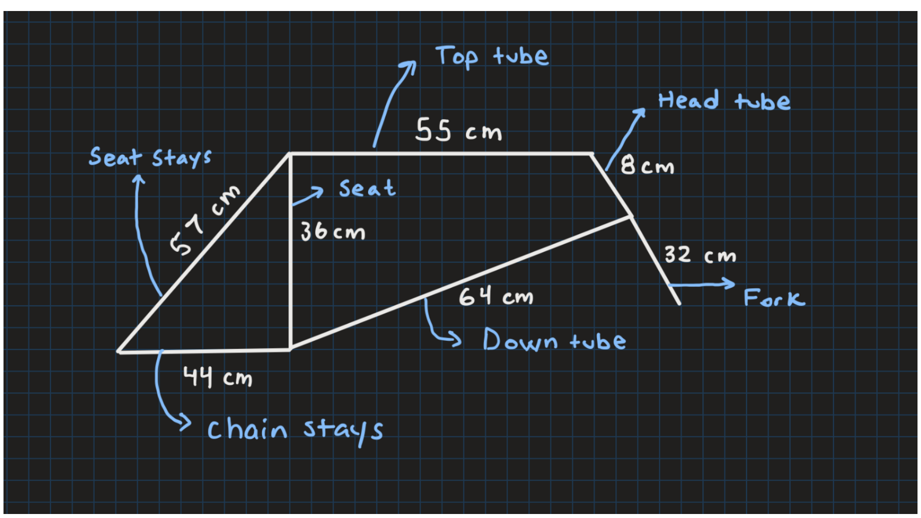


Figure 2.3 - Bicycle dimensions

2.3 - Failure Modes of Bicycle Frames

In this section, we will mention the factors or combination of factors that result in bicycle failure.

1) Low-cycle Fatigue (LCF). LCF is defined as fatigue involving 2-50,000 cycles [2]. Surprisingly, the main reason behind bicycle failure is low-cycle fatigue. In this project, we will be defining "σ_{LCF}" as the maximum stress in a specific material which causes failure after 3000 - 6000 cycles.
2) Stress Concentration. Hole and filet stress concentrations can increase stress by a factor of six or more [2].
3) Loads due to impacts (e.g. bumps), start-up, or swerving are far more severe than normal loads encountered in general smooth pedaling [2].

3. Results and Discussion

3.1 - Loading Condition

For this project, we are assuming only one loading condition. The condition is that the rider will jump on the bicycle as he is boarding it. We are assuming that double the rider's total weight is on the seat during impact and a quarter of the rider's weight is on the handlebar. The weight of the rider is assumed to be 180 lbs.

3.2 - Failure Criteria

Finding the exact fatigue strength is very complicated as it depends on many different factors that are not available to be included in our project. Instead, we will assume the number of load cycles (N) = 3000. The equation that relates the number of load cycles to the fatigue strength is: $\mathbf{S(N) = aN^b}$

We can approximate the fatigue at 1000 cycles by substituting N = 10^3 : $\mathbf{S(10^3) = S_m = 0.75\sigma_{ut}}$ where σ_{ut} refers to the ultimate strength in tension.

Since the bicycle that we are using is made of steel, we can approximate the endurance fatigue at $\approx 10^6$ cycles: $\mathbf{S(10^6) \approx S_e \approx \sigma_{ut}}$. In this project, we will be assuming that a safe design will have a safety factor that is greater than 3.0.

3.3 - Final Results

3.3.1 - Truss Structure

Stress is calculated by the formula:

$$\sigma = \frac{F}{A}$$

Where F corresponds to the force subjected on a part, and A is the cross sectional circular area of a part. The diameter of every part was taken to be 33mm.

Safety factor is calculated by the formula:

$$FS = \frac{ultimate\ stress}{allowable\ stress}$$

During the analysis process, the material of the bike frame is “Alloy Steel”. The yield strength of alloy steel is 620.4 MPa, which is 89981.412 psi. Yield strength is a value which represents the amount of stress a material can withstand before permanently deforming. This value of yield strength will be used as the value for ultimate stress in the factor of safety equation and will be divided by the calculated stress in table 3.3.1.

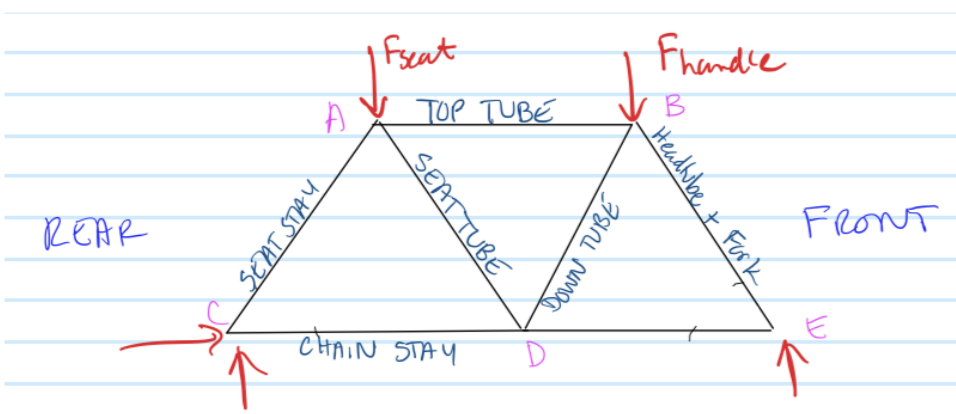


Figure 3.3.1 - All members present

Part	Force, F [lb]	Stress, σ [psi]	Safety Factor
Seat Stay	374.87, Compression	282.43	318.60
Chain Stay	86.66, Tension	65.29	1378.19
Seat Tube	120.85, Compression	91.05	988.28
Top Tube	86.65, Compression	65.28	1378.35
Down Tube	237.33, Tension	178.80	503.24
Head tube + Fork	203.57, Compression	153.37	586.69
Connection from center crank to front wheel	117.60, Compression	88.60	1015.59

Table 3.3.1 - Truss Analysis Data for when all Members Present

3.3.2 - Top Tube Removed

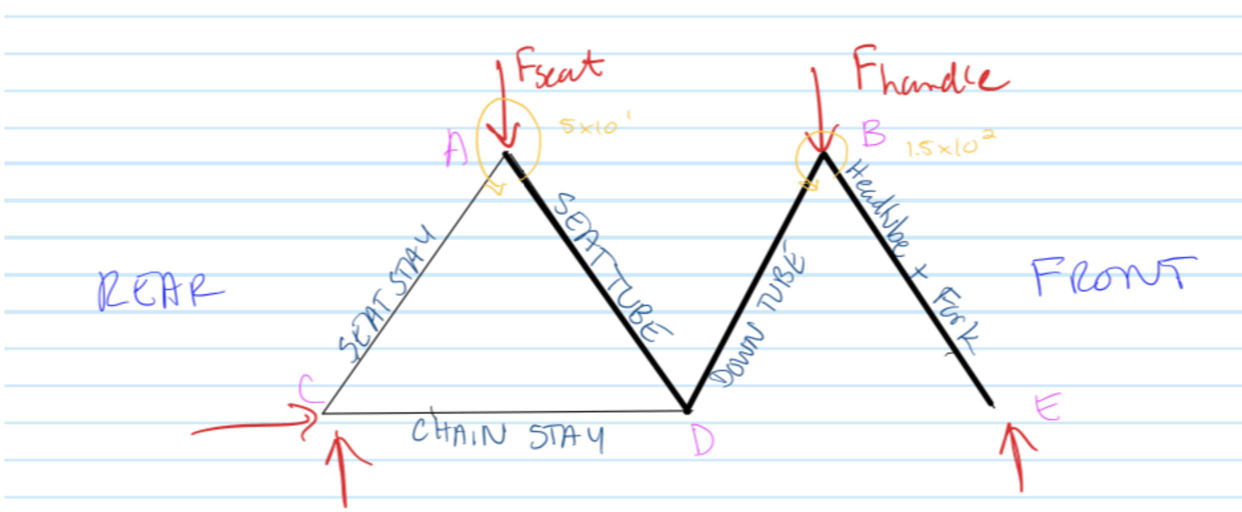


Figure 3.3.2 - Top tube removed

Just as in section 3.3.1, the value of ultimate stress used in the factor of safety equation is 89981.412 psi. This value will be divided by the calculated stress values from table 3.3.2.

Part	Force, F [lb]	Stress, σ [psi]	Safety Factor
Seat Stay	762.60, Compression	574.54	156.61
Chain Stay	204.79, Tension	154.29	583.20
Seat Tube	121.16, Tension	91.28	985.75
Top Tube	- - -	- - -	- - -
Down Tube	237.33, Tension	178.80	503.24
Head tube + Fork	203.57, Compression	153.37	586.69
Connection from center crank to front wheel	- - -	- - -	- - -

Table 3.3.2 - Truss and Beam Analysis Data for when Top Tube Removed

Comparing the data in figure 3.1 to the data in figure 3.2, it can be seen that by removing the top tube from the frame structure, the force subjected on the chain stay and the seat stay increased while the force subjected on the seat tube, down tube, headtube and fork stayed relatively the same. The data concludes that the member which is experiencing the greatest magnitude of stress due to this change is the seat stay.

3.3.3 - Finite Element Analysis

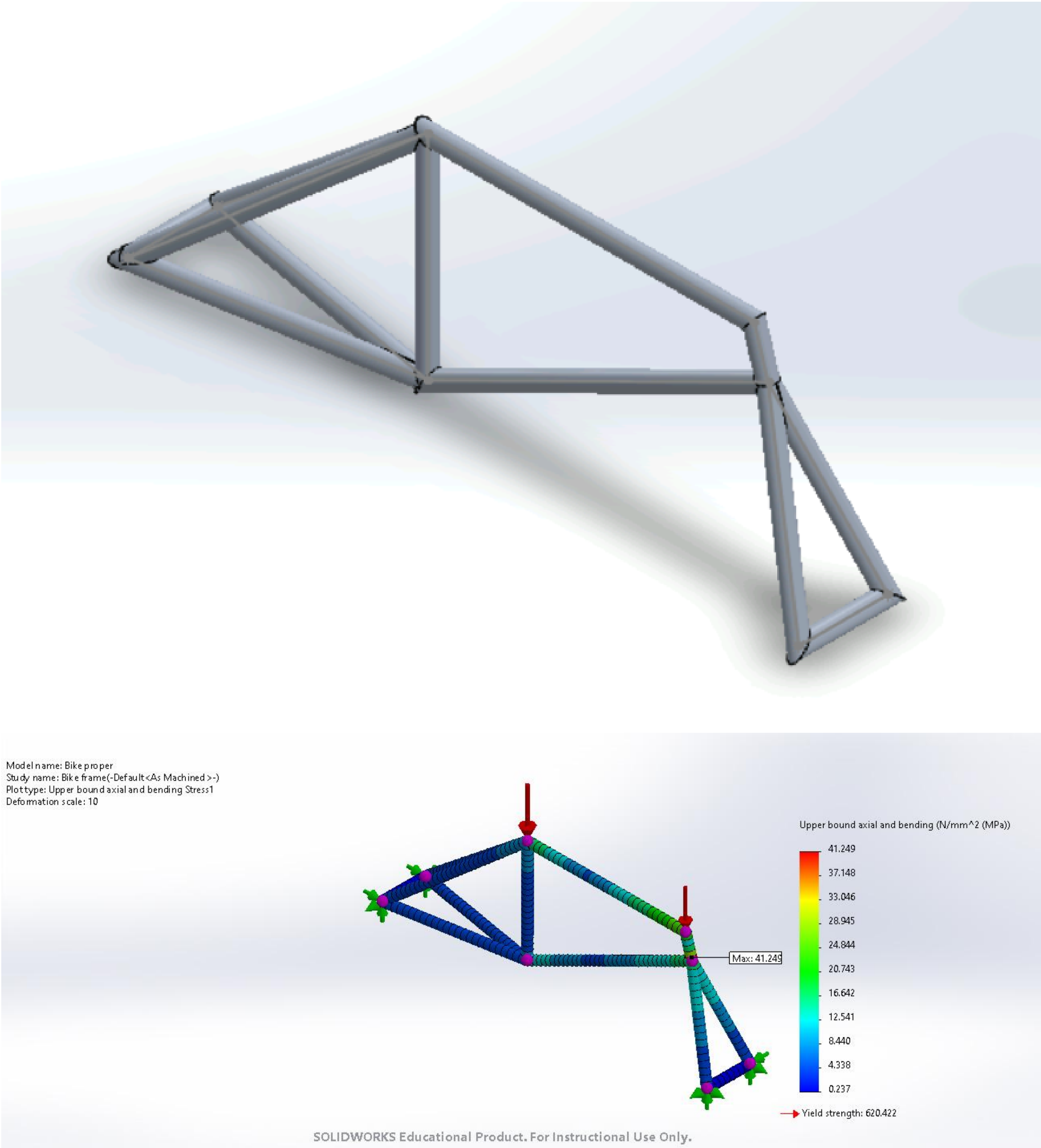


Figure 3.3 - Finite Element Analysis before changes

As shown in the image above we can see that the bike that we used has a frame that is more than capable of supporting the weight of the rider even when the rider has jumped onto the bicycle to start. For the simulation we used a CAD software called SolidWorks. To properly simulate the effects of a rider jumping on the seat of the bike we first had to build a model of the bike frame and then use the weldment feature of the software to properly define the joints and assign the joints as non-moving members so that they stay in place. Next we had to select a material for the bike, the bike that we used as a reference had an alloy steel frame therefore we selected alloy steel on solidworks. Finally it was time to add the loading forces onto the seat and handle, for this we used 360lbs of force for the seat and 45lbs on the handles because the weight of the rider was 180lbs and the rider jumped onto the bicycle at the instant the forces were taken.

3.3.4 - Discussion (A)

a. **Is the frame safe under the given loading conditions?**
   Under the given conditions the frame is safe as shown in the image of the finite system analysis, none of the areas on the frame turn red, red signifies the maximum axial loading and bending. The yield strength as shown in the image above is 620.422. The maximum loading for this frame as calculated by the software is 41.249N/mm^2 the most that is caused by these loading conditions on this frame is approximately 24.844N/mm^2 which is well under the upper limit therefore the frame is safe under the given loading conditions.

b. **Which bar is most risky?**
   The bar that is most risky is the top tube as shown by the finite element analysis. The top tube has the most stress placed upon and is the most at risk to start bending, the second most risky tube is the down tube, which is also green in some spots of the model, this is due to the fact that these two tubes have the most direct contact with the loading forces therefore are most prone to bending.

c. **What are your suggestions to improve the current design?**
   A possible design change to improve the current bike frame is to change the material of the frame, as the bike we used is a somewhat old bike it’s frame was made of steel, but through our research we learned that many newer bikes use aluminum frames as they lighter and make the bike faster, but this may come at a cost of a slightly less strong and durable bike.

d. **What if weight is to be reduced, what are your suggestions to change the design?**
   If we reduce the loading weight I would recommend using an aluminum frame as the only downside to using an aluminum one is the reduced strength and durability, but if the load is less the extra strength and durability is not required, therefore a material change is a good change to the design.

3.3.5 - Design Change

Since the frame is already sturdily built and the perfect size for an adult, it would not make sense to change the shape of the truss or any of the dimensions, a change that could be made however is to change the material of the bike to aluminum. As discussed above changing the metal to aluminum would make it lighter and speedier but less durable and strong in theory. To offset the strength losses we can try to make the individual tubes thicker, this should keep the strength the same but lead to a lighter bike. Lets see if this theory holds up in practice once the aluminum frame is put through the finite element analysis.

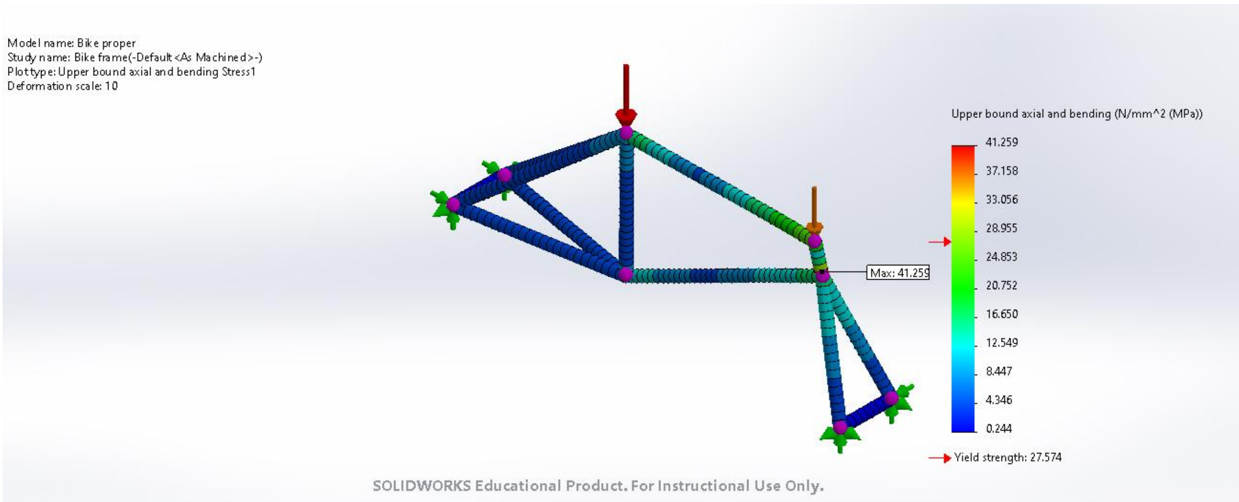


Figure 3.3.5 - Finite Element Analysis after changes

3.3.6 - Discussion (B)

a. **Is the new design better or worse?**
   The new design has both its own set of pros and cons which are addressed in the next part. In my opinion both bikes are fine for day to day use for the average person.

b. **In which way is it better or worse?**
   As shown in the FEA above the aluminum is less durable than steel but due to this we made the diameter of the tubes wider and thicker, this resulted in a similar strength as before but an overall lighter bike, the bike is slightly less durable with a yield strength of 27.574and it now has max bending of 41.259N/mm^2 which is slightly different from the earlier 41.249N/mm^2 . Overall the differences between the two designs are almost negligible although it is important to note that steel is generally more cost efficient than aluminum which gives a slight edge to steel for the average cyclist who does not need an overly fast bike.

c. **If you are asked to design it again, what are the changes that you plan to try?**
   Some other changes that would be worth making could be changing the dimensions of the bike, I do not think that this would make a huge difference in terms of the actual strength of the bike but, it would be a fun aspect to play around with for the sake of research it would also help in deepening our understanding of the topics that we have been taught. Another thing that I would like to to do is to make an even more detailed model of the bike frame as the one we made now while was good enough to get the job done is not

what a real bike frame would look like, this is due to our relative inexperience with CAD software, but now that we have more experience I am sure we could make a more detailed model on SolidWorks

4. Conclusion

Although the strength analysis of a bicycle frame is a relatively small portion of the total analysis required when designing a bicycle, it is an element that cannot be left aside. The quality of the material and design also depend on the intended purpose of the bicycle. From this project we can see that even before applying any design changes, the steel frame is more than capable of supporting the weight of the rider even when the rider has jumped onto the bicycle to start. However, by changing the material we can improve the speed and lower the weight at the cost of durability and strength. To conclude, bicycles will certainly remain as a useful and practical tool for mankind and one can only wait to see what exciting new innovations can/will be added to it in the attempt to increase the bicycles overall performance.

5. References

[1] F. Beer, R. T. Johnston Jr., and D. F. Mazurek, “Analysis of Structures,” in *Statics and Strength of Materials* , New York, NY: Mc Graw Hill, 2017

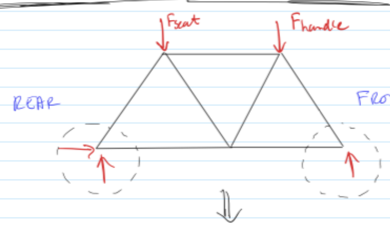
[2] Bailey, Helen, ‘Strength Analysis and Design of Bicycle Frame’, Simon Fraser University, Fall 2021.

[3] Wikipedia Foundation. (2021, November 29). *Bicycle*. Wikipedia. Retrieved December 9, 2021, from https://en.wikipedia.org/wiki/Bicycle.

6. Appendix

6.1 - Calculations for Section 3.3.

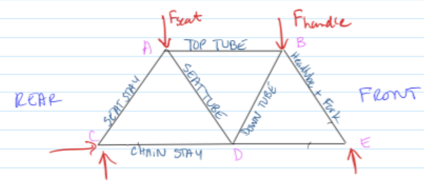
- TRUSS ANALYSIS, ALL TUBES PRESENT



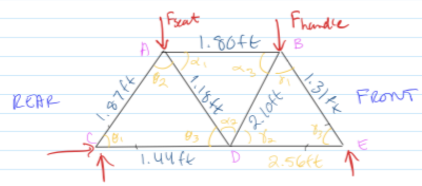
- Mass of Rider = 180lbs
- Force on seat when rider jumps on bike =

  (2)×(weight) = (2)(180) = 360lbs = Fseat
- Force on handle bar when rider jumps on bike =

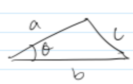
  $\left(\frac{1}{4}\right)(180)$ = 45lbs = Fhandle



- Seat stay = 0.57m = 1.87ft
- Chain stay = 0.44m = 1.44ft
- Seat tube = 0.36m = 1.18 ft
- Top tube = 0.55m = 1.80ft
- Down tube = 0.64m = 2.10 ft
- Headtube + Fork = 8+32 = 40cm = 0.4 m ≈ 1.31ft



By cosine law, I will determine the Angle between the members:



$$\theta = \cos^{-1}\left(\frac{a^2+b^2-c^2}{2ab}\right)$$

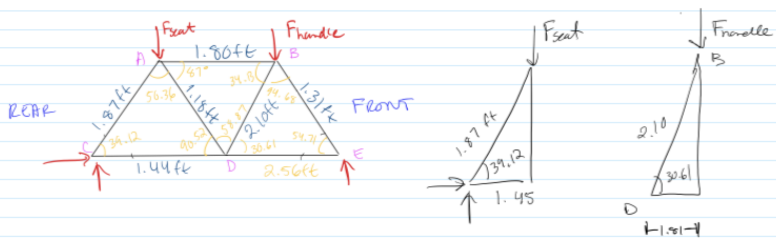
$\theta_1 = 39.12°$ $\alpha_1 = 87°$ $\gamma_1 = 94.68$

$\theta_2 = 50.36$ $\alpha_2 = 58.87$ $\gamma_2 = 30.61$

$\theta_3 = 90.52$ $\alpha_3 = 34.13$ $\gamma_3 = 54.71°$

From sin law, we can find the distance from D to E.

$\text{Distance}_{DE} = 2.56\text{ft}$



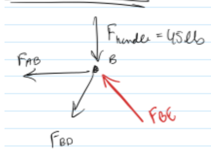
$$\overset{+}{\circlearrowleft} M_E = (-F_{seat})(1.44) - (F_{handle})(1.44+1.81) + F_E(1.44+2.56) = 0$$

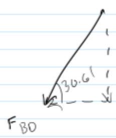
$$F_E = \frac{(F_{seat})(1.44) + (F_{handle})(1.44+1.81)}{(1.44+2.56)}$$

$$= \frac{(360)(1.44) + (45)(3.25)}{(4)}$$

$$F_E = 166.16\ \text{lb}$$

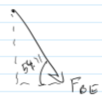
Forces at B





$F_{BDx} = F_{BE}\cos(30.61)$

$F_{BDy} = F_{BE}\sin(30.61)$



$F_{BEx} = F_{BE}\cos(54.71)$

$F_{BEy} = F_{BE}\sin(54.71)$

$F_{BE} = 203.57$

$F_{BD} = 237.33\ lb$

$\sum F_y = 0 = -F_{handle} + F_{BEy} - F_{BDy} = F_{BD} = \frac{-45 + F_{BE}\sin(54.71)}{\sin(30.61)} = -88.38 + 1.60F_{BE} \Rightarrow 237.33\ lb$

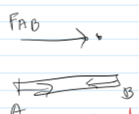
MEMBER BD feels Tension

$\sum F_x = 0 = -F_{AB} - F_{BEx} - F_{BDx} = F_{AB} = F_{BE}\cos(54.71) - F_{BD}\cos(30.61)$

$= (203.57)\cos(54.71) - (237.33)\cos(30.61)$

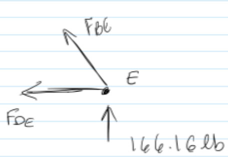
$F_{AB} = -86.65\ lb$

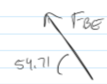
Assumed Wrong Direction



Member AB feels COMPRESSION

Forces @ E





$F_{BEx} = F_{BE}\cos(54.71)$

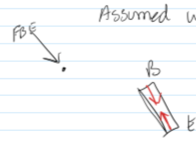
$F_{BEy} = F_{BE}\sin(54.71)$

like

$\sum F_y = 0 = 166.16 + F_{BE}\sin(54.71)$

$F_{BE} = \frac{-166.16}{\sin(54.71)} = -203.57\ lb = F_{BE}$

Assumed wrong Direction.



member BE feels 203.57 lb Compression

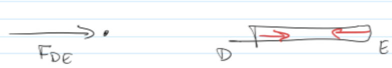
$\sum F_x = 0 = -F_{DE} - F_{BE}\cos(54.71)$

$F_{DE} = -F_{BE}\cos(54.71)$

$= -(203.57)\cos(54.71)$

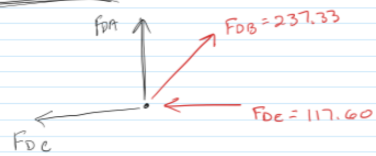
$F_{DE} = -117.60$

Assumed wrong direction.



member DE feels 117.60 lb COMPRESSION

Forces @ D

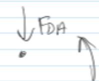


$F_{DBx} = 237.33\cos(30.61) = 204.26$ lb

$F_{DBy} = 237.33\sin(30.61) = 126.85$ lb

$\Sigma F_y = F_{DA} + 120.85 = 0 \Rightarrow F_{DA} = -120.85$

Assumed wrong Direction $\Rightarrow$



member DA is in COMPRESSION

$\Sigma F_x = 0 = 204.26 - 117.60 - F_{DC}$

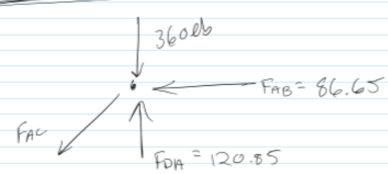
$\downarrow$

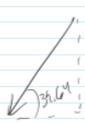
$F_{DC} = 46.66$ lb

$\downarrow$

Member DC is in Tension

Forces @ A





$F_{ACx} = F_{AC}\cos 39.64$

$F_{ACy} = F_{AC}\sin 39.64$

$\Sigma F_y = 0 = 120.85 - 360 - F_{AC}\sin 39.64$

$\downarrow$

$$F_{AC} = \frac{120.85 - 360}{\sin 39.64}$$

$F_{AC} = -374.87$ lb

Assumed wrong Direction

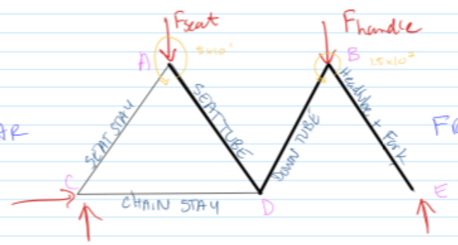
$\downarrow$

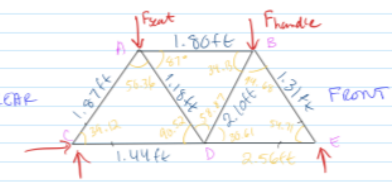
$F_{AC} = 374.87$ lb, AC in Compression

$F_{DE} = 117.60\ lb$, DE = compression
$F_{BE} = 203.57\ lb$, BE = Compression
$F_{AB} = 86.65\ lb$, AB = Compression
$F_{BD} = 237.33\ lb$, BD = Tension

$F_{DA} = 120.85\ lb$ DA = Compression
$F_{DC} = 86.66\ lb$, DC = Tension
$F_{AC} = 374.87\ lb$, AC = Compression.

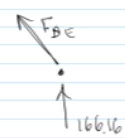
6.2 - Calculations for Section 3.3.2





$F_E = 166.16\ lb$

Joint At E



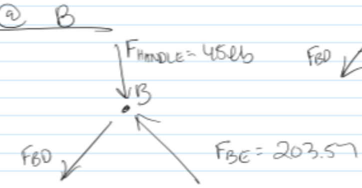
$F_{BE}\cos 54.71 = F_{BEx}$
$F_{BE}\sin 54.71 = F_{BEy}$

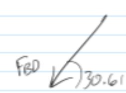
$\Sigma F_y = 0 = 166.16 + F_{BE}\sin 54.71$

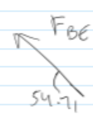
$F_{BE} = \dfrac{166.16}{\sin 54.71} = 203.57\ lb$

$F_{BE} = 203.57$, BE = COMPRESSION

Joint @ B







$F_{BDx} = F_{BD}\cos 30.61$
$F_{BDy} = F_{BD}\sin 30.61$

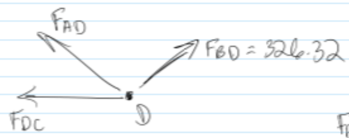
$\Sigma F_y = 0 = 166.16 - F_{BD}\sin 30.61 - 45$

$F_{BEx} = 117.61$
$F_{BEy} = 166.16$

$F_{BD} = \dfrac{166.16 - 45}{\sin 30.61}$

$F_{BD} = 237.45\ lb$, BD = TENSION

Joint @ D



$F_{BDx} = 204.79$ lb
$F_{BDy} = 121.16$ lb

~~F_{ADx}~~
$F_{ADy} = \checkmark$

$\Sigma F_y = 0 = F_{AD} - 121.16$ lb

$\downarrow$

$F_{AD} = 121.16$ lb

$\Sigma F_x = 0 = -F_{DC} + 204.79$

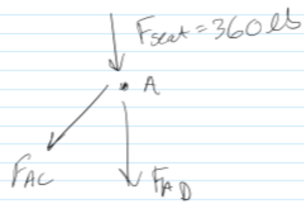
$\downarrow$

$F_{DC} = 204.79$

$F_{AD} = 121.16$ lb , AD = TENSION

$F_{DC} = 204.79$, DC = Tension

Joint @ A



$F_{AC} \cos 39.12 = F_{ACx}$

$F_{AC} \sin 39.12 = F_{ACy}$

$\Sigma F_y = 0 = -360 - 121.16 - F_{AC} \sin 39.12$

$\downarrow$

$$F_{AC} = \frac{-360 - 121.16}{\sin 39.12} = -762.6 \text{ lb}$$

$F_{AC} = 762.6$ lb , AC = COMPRESSION

$F_{AC} = 762.6$ lb, AC = Compression

$F_{DC} = 204.79$ lb, DC = Tension

$F_{AD} = 121.16$ lb, AD = Tension

$F_{BD} = 237.95$ lb, BD = Tension

$F_{BE} = 203.57$ lb, BE = Compression