Reverse Engineering of a Bicycle Crank Arm Design

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Abstract

This project aims to use the reverse engineering method to design the crank arm structure of a bicycle and the material used on the component. The crank arm could be determined as the easiest part on a bike that is damaged during usage. As the failure conditions generally require a larger loading scenario, daily use would be hard to reach the design fatigue or breaking state. Bike failure could result in severe health issues for either ordinary people or professional athletes. The changes in material and structure extend the duration of usage or flexibility when facing different road conditions. For instance, older bikes have a round cross-section for the crank arm, then the update to it increases the cross-section area and shape. There are also restrictions on the length of the crank arm; according to studies, the crank arm length has a strong impact on the performance of bike racing as the total revolution per minute is related to it. Generally, two conditions need to be discussed: the first one is the crank length, and the second one is the pedaling rate. The cost function minimum for tall people occurs at longer crank arm lengths and lower pedaling rates than the length and rate for short people. However, this research will only focus on the length of the crank arm in the discussion of the failure.

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Introduction and Background

This bicycle is a Trek-made, 2015 model hybrid bike with an aluminum frame for the daily commute and a bit of exercise, which is not a designed mountain or track racing bike. This bike uses holding breaks for both tires and tires in regular size and shape for common usage. And for the assigned task in this research will first be measuring the bike parameters that include critical parts and online resources for the cross-section's values. Applying the values in a calculation provides the safety factor and total revelation before failing to determine the critical point. In addition to giving supplemental suggestions to improve the bike crank arm's quality, safety, and durability. Also, include the riding conditions and maintenance schedule to prevent the bike crank arm from failure.

Therefore, the discussion of crank arm redesign will focus on the large or extreme loading conditions such as high-speed track cycling in professional competition and downhill racing. Each scenario has specific loading conditions, as the detail will be expressed later in the analysis. The design process goes through the loading and fatigue scenarios with mathematical calculations by applying the relevant material properties. In addition, based on extreme conditions, variables need to be controlled; however, the calculation will be challenging to include the road status that causes inconstant vibration or weather influence on the component, the analysis for mountain downhill racing will remain on the heavy loading. Then, the track cycling will focus on the total available cycles to failure.

Fig 1 [https://cn.depositphotos.com/114648422/stock-illustration-olympics-track-cyclist-bicyclist-athlete.html]

Fig 2 [https://www.bikeperfect.com/features/best-downhill-mountain-bikes]

In summary, the loading scenarios that would be considered are the speed track racing with constant applied force on the pedals for long time rotations that results in crank arm failure

[Fig 1], and the mountain downhill racing with most of the time, the pedal will remain in the same location but change with the direct loading due to inconstant dropping [Fig 2].

Methodology

In the approach to the desired optimal result, the parameters required for the calculation are included below as the rider weight is controlled as 70 kg, which means the force applied on both pedals would be 70*9.81 = 686.7 N.

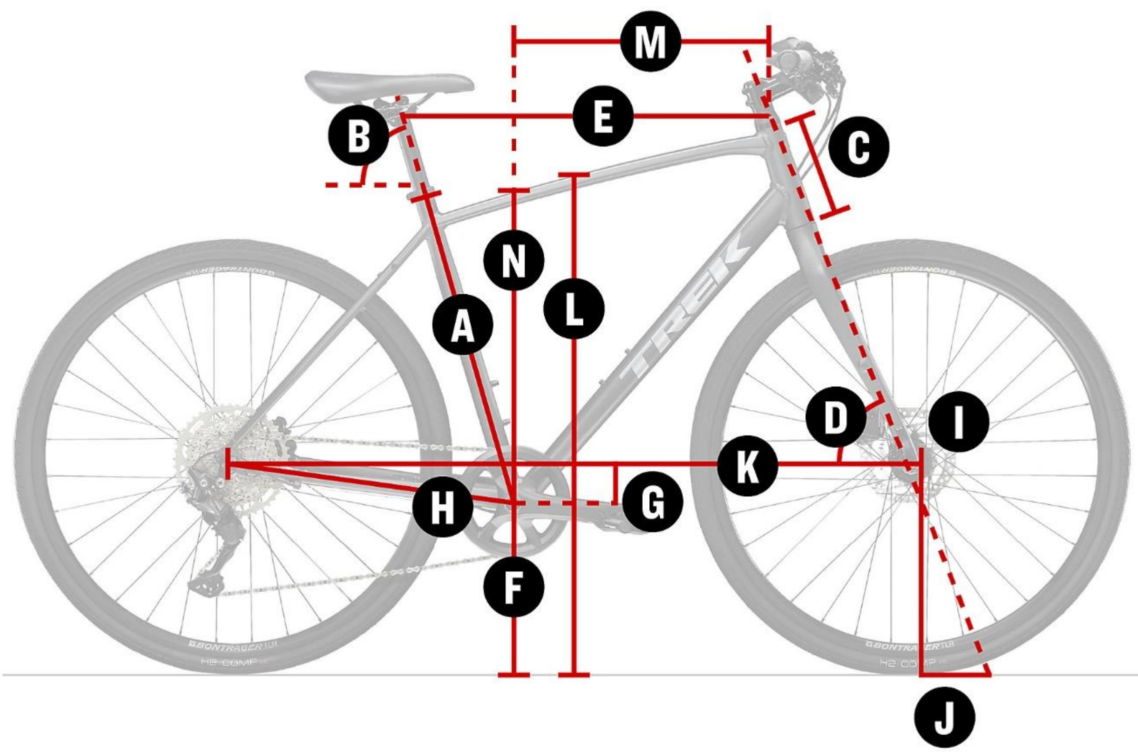
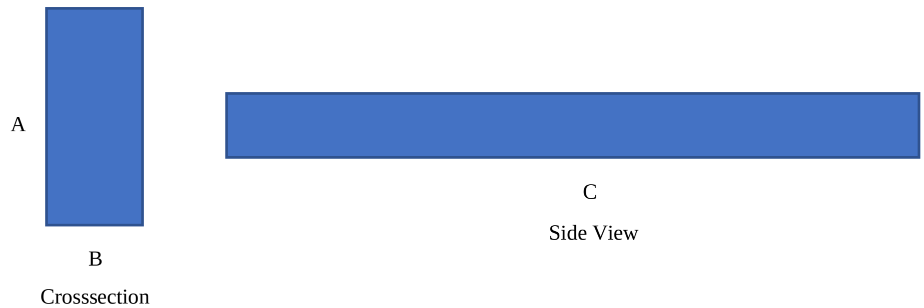


Fig 3 [https://www.trekbikes.com/us/en_US/bikes/hybrid-bikes/fitness-bikes/fx/fx-1/p/32769/]

Part	Seat Tube	Bottom Bracket Height	Chain Stay	Wheelbase	Bottom Bracket Diameter	Seat-Shaft Distance
	A	F	H	K		
Parameter (cm)	50.8	29.6	45	107	23	66

Crank Arm Dimensions:



A	B	C	Area
2.6 cm	1.2 cm	21 cm	3.12 cm^2

According to the provided website information, this bike uses 6061 Aluminum Alloy [3] for crank arms as described properties in the research from J.R. Davis about the common use location for 6061 Aluminum alloy. In addition, the material properties for crank arm 6061 Aluminum Alloy are included in the below table. [4],[5].

Physical Property	**Value**
Density	2.70 g/cm³
Melting Point	650 °C
Thermal Expansion	23.4 x10^-6 /K
Modulus of Elasticity	70 GPa
Ultimate Tensile Strength	310 MPa
Tensile Yield Strength	276 MPa

Shear Modulus	26 GPa
Shear Strength	207 MPa
Poisson's Ratio	0.33

Furthermore, the assumption also includes that the aluminum is not damaged before the sampling time or calculation; applying the ideal conditions for this trek bike crank arm is the optimal solution for safety measures. In conclusion, the control variables are the rider's weight, the material conditions due to weather or any other objective influence, and the size and shape of the crank arm are in the assumption of a rectangular for easier calculation and measure.

Load Envelopes

This research calculation simplified the crank arm; the cross-section is rectangular instead of the inconstant shape. The crank arm graph is complete through SolidWorks and has the correct dimensions according to the measured value [Fig 4].

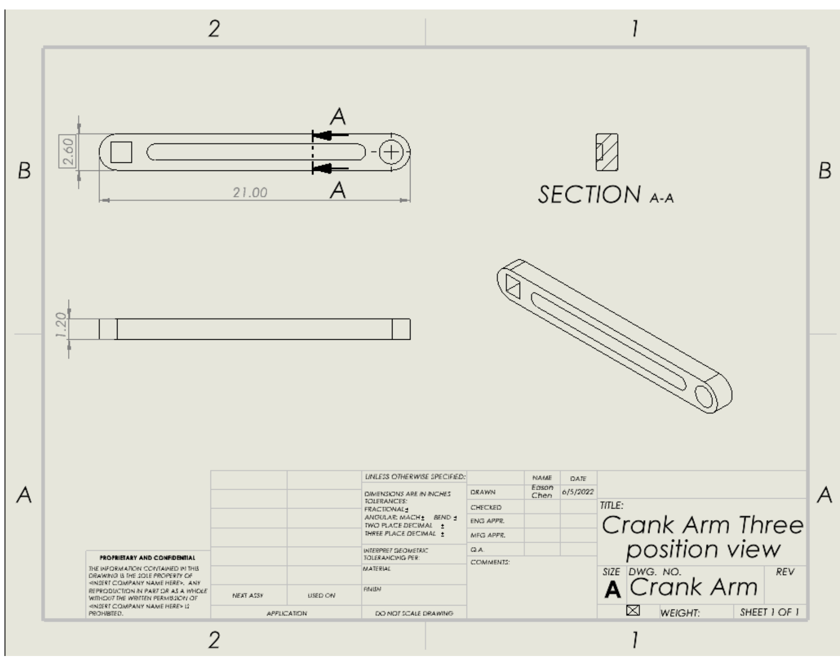


Fig 4

There are differences in the loading time and period in each loading scenario. In the first loading scenario (Track Racing), the load on the crank arm will be periodically according to the available force applied on the pedals, which is shown in [Fig 5]. And for the result that causes the crank arm failure is mainly the repeat forcing and relaxing, and the bending of the material eventually causes the metal to fatigue and fail. The second scenario is about instant heavy loading conditions on the pedals during downhill, especially when the biker jumps down with the bike when both pedals remain in the same position. The instant load is much larger than the athlete's weight [Fig 6].

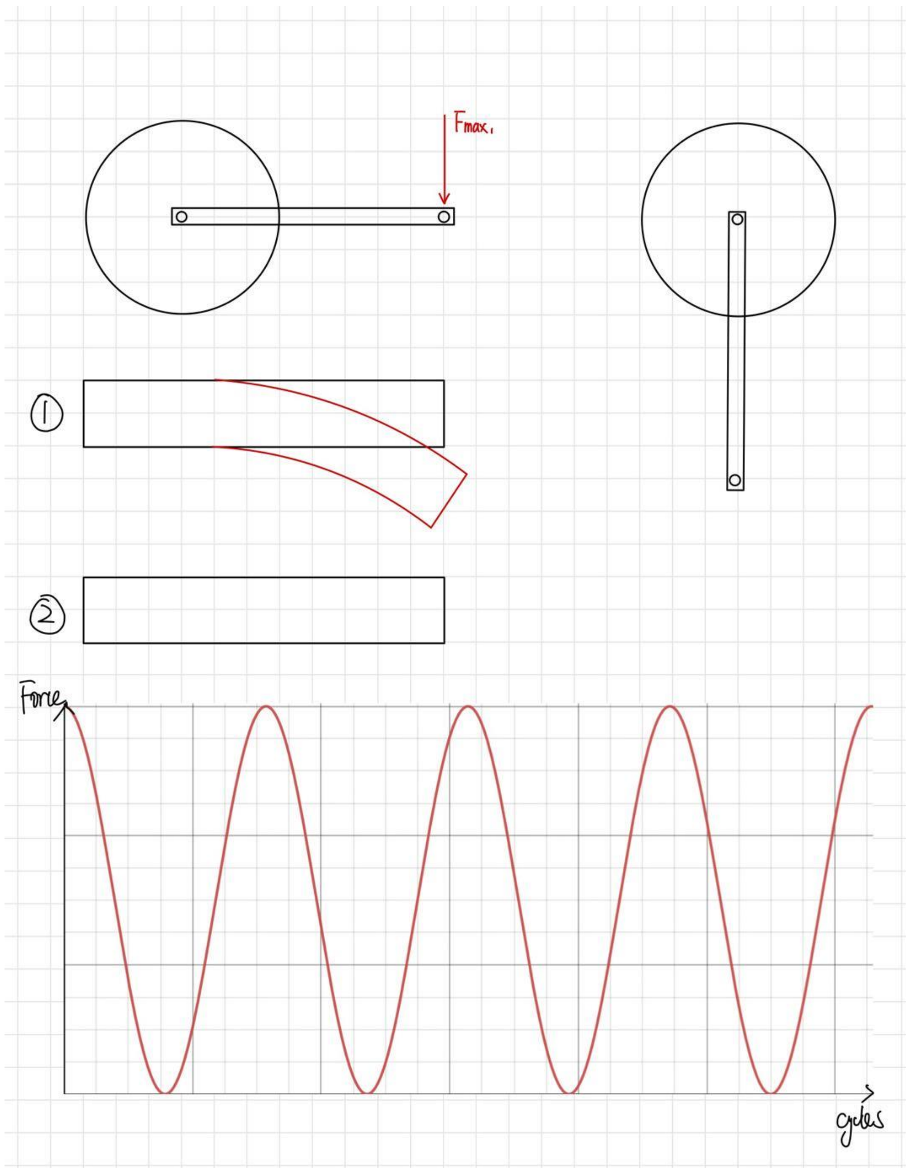


Fig 5

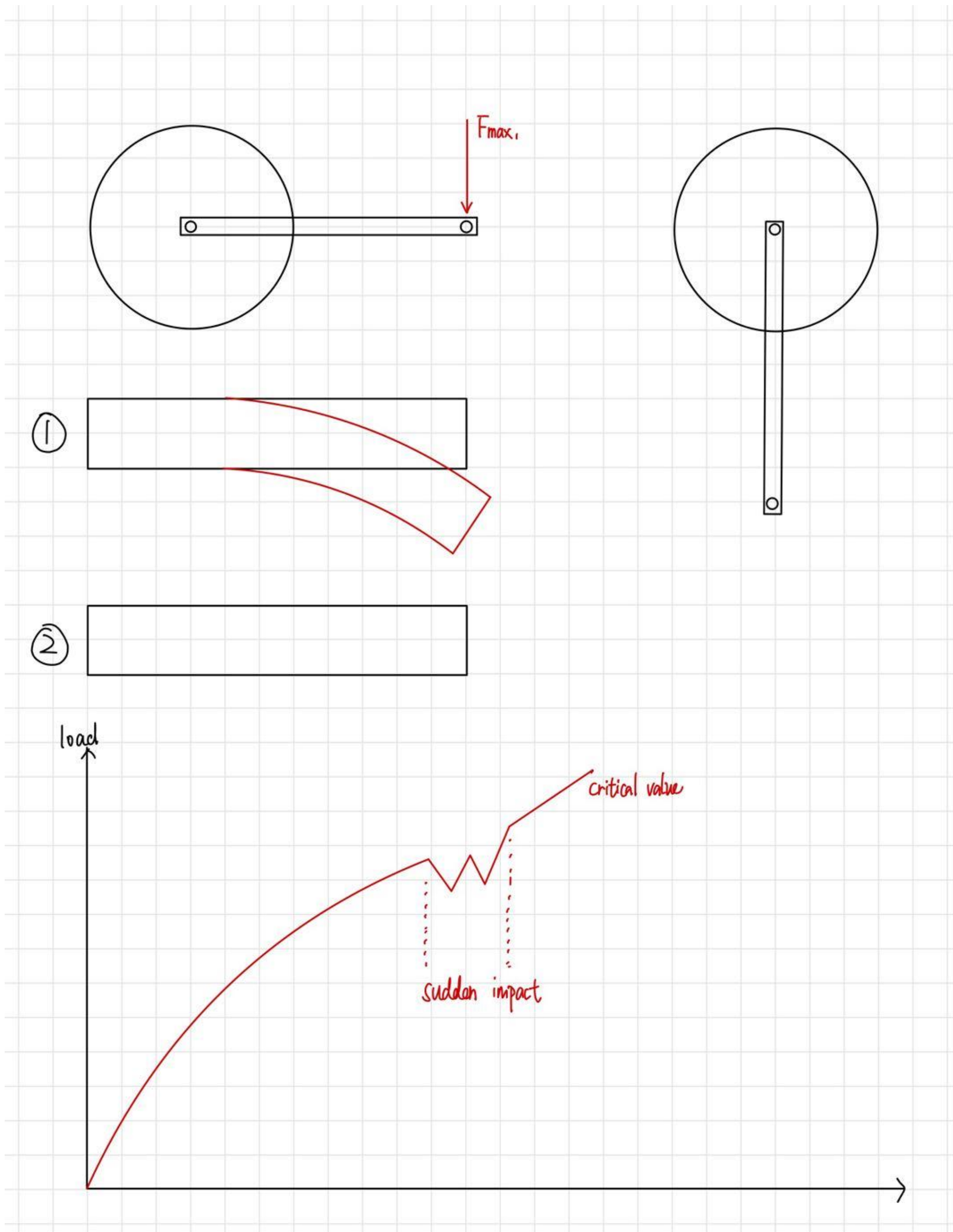


Fig 6

And in the failure scenario, which requires specified control, the breaking point is commonly located close to the center of rotation. Including the Von Mises stresses on the static analysis [Fig 7] and the plot of the total life of the component according to the SolidWorks research by Chetan N Madivalar and Dr. Tony Shay, Shreedhar Kolekar in 2018 [6]. Also, according to most conditions in real life for crank arm failure, the breaking generally starts at the same position, not regarding the arm's material. These are different research, one by actual specimen testing and the other by CAD software simulation.

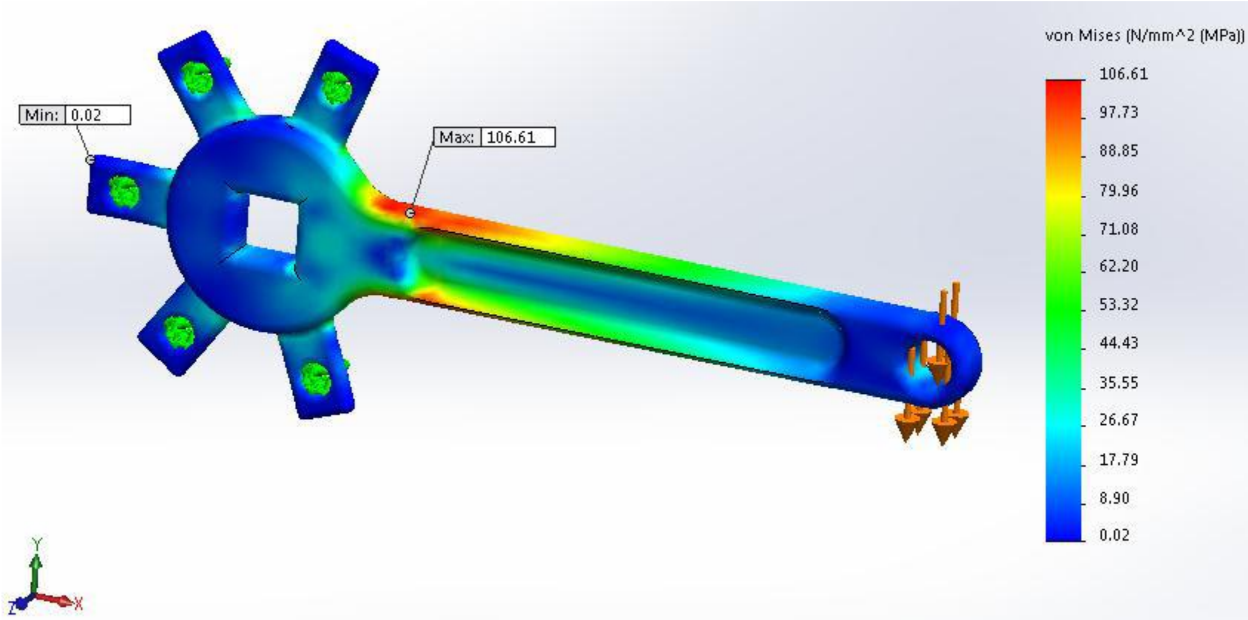


Fig 7

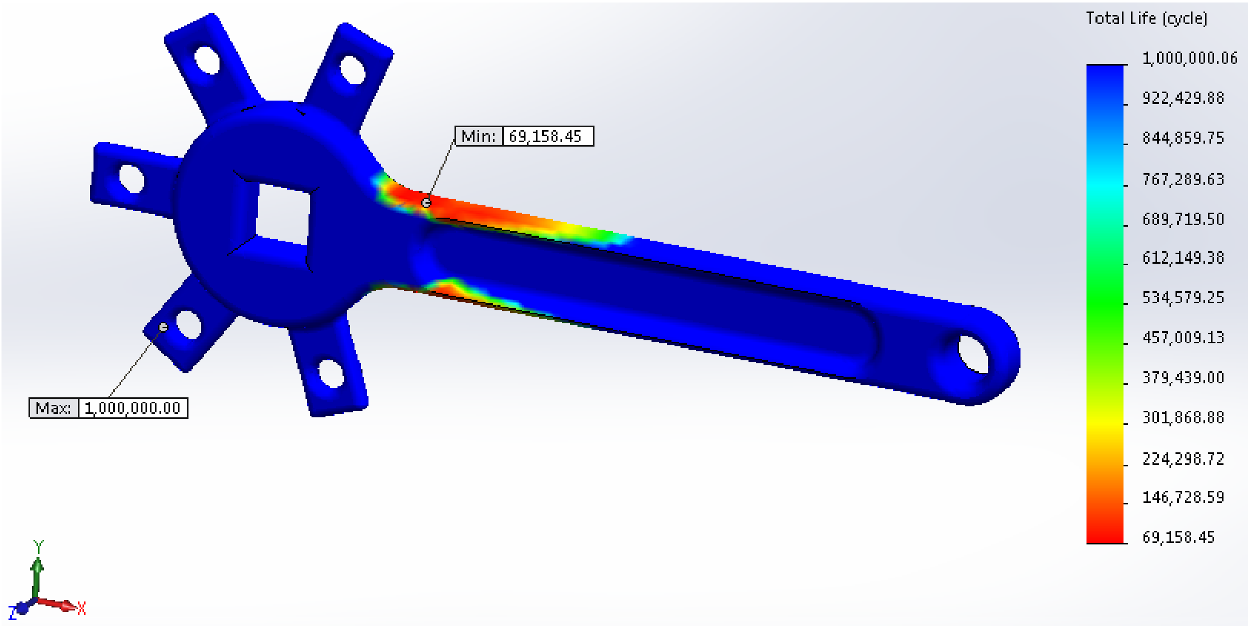


Fig 8

Fig 9

Fig 10

Analysis of Critical Components

The analysis will include the free-body diagrams in the simplified crank arm figure and the equations from book chapters to calculate the safety factors. The failure caused by fatigue in the crank is that the stress applied is lower than the strength over time, under cyclic loadings, and the torsional vibrations add stress. And in relevant to [Fig 10], the surface of breaking indicated that there was a crack initially and started to enlarge over time and eventually triggered the structure to break down. The different color on the surface is called the beach mars, which shows the crack size when reaching the critical level. Generally speaking, the crack started slowly as the speed would increase to an unstable point for an instant break; and the crack also reduced the life of the material that lowered the capacity of holding larger loads.

Before the calculation, according to the real test and SolidWorks simulation, the breakpoints were indicated as A & B in this research. The total distance from the loading point to the point is simplified as 150 mm, which is about 1/5 of the total length of the crank arm. Since the actual crank arm has different cross-area sizes, choosing the minimum material and applying the parameters on the specific point is needed. After measurement, the breaking location tended to be the thinnest bar area, which also matches the assumption at a 150 mm location. In the first part of the calculation, the analysis will focus on the normal riding conditions, which represent the track racing as the applied force will be periodical. The safety factor shows a high number. Therefore, during the normal usage of the bike, the crank arm has good durability to the environment and can withstand more than three times the 70 kg load on pedals. [Section 1 (pg. 11-13)]. After the calculation, we could summarize that point A would be the critical point where the crack will start and later structure failure.

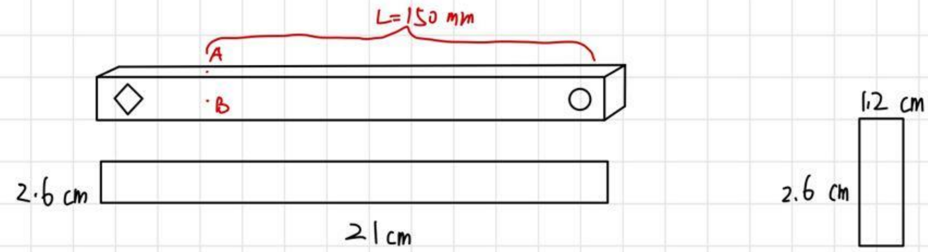
In [section 2 (pg. 14-15)], calculation, the total available cycles for the aluminum 6061 before failure is collected from a research paper by G.T. Yahr [7]. Which have 200,000 cycles before starting the crack, and based on my calculation, the total rotation for each crank arm is around 2.14*10^5 cycles. And It provides information for track bicycling that after a total of 200,000 cycles, the crank arm better be changed for health considerations. Future calculations [Section 3 (pg. 16-17)] will analyze the heavy load that occurs during mountain downhill biking. The assumption is the same as the 70kg rider but in the crease to an instant load of 110 kg in assumption. By calculating the safety factor, we will be able to determine if this bike is safe for the sport.

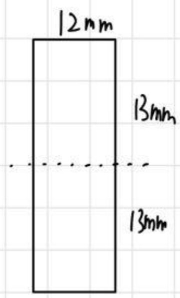
Section 1

Analysis: $E = 70$ GPa $\quad v = 0.33 \quad S_{ut} = 310$ MPa $\quad S_y = 276$ MPa $\quad L = 150$ mm

Point A & B stress and strain.

Setting that weight as 70 kg, the $F = 70 \cdot 9.81$ N/kg $= 686.7$ N





$I = I_c = \frac{bd^3}{12}$

$A = 1.2 \cdot 2.6 = 3.12 \text{ cm}^2 = 312 \text{ mm}^2$

$I = I_c = \frac{12 \text{ mm} \cdot 26^3 \text{ mm}}{12}$

For point A: $y_A = 13$ mm

For point B: $y_B = 0$ mm

$I = I_c = 17576 \text{ mm}^4$

$L = 150$ mm

$\sigma_A = \frac{F \cdot 150 \cdot 13}{17576} = 76.1871$ MPa

$\sigma_B = 0$

For torsional moment $\frac{T}{J} = \frac{\tau}{r} \Rightarrow \tau = \frac{Tr}{J}$ as $J = \frac{bd^3}{3} = \frac{12 \cdot 26^3}{3} = 70304 \text{ mm}^4$

At point A $r_A = 12$ mm at point B $r_B = 0$

$\tau_A = \frac{F \cdot 12}{J} = 0.117211$ MPa $\qquad \tau_B = 0 \text{ N/mm}^2$

$G = \frac{E}{2(1+v)} = \frac{70}{2(1+0.33)} = 26.3158$ GPa

1

Then for strain formula [Chapter 3 equations & concepts]

$$\varepsilon_x = \frac{\sigma_b}{E} - \nu\left[\frac{\tau_T + \tau_s}{G}\right] \quad \gamma_{zy} = \frac{\tau_T}{G} - \nu\left[\frac{\sigma_b}{E} + \frac{\tau_s}{G}\right] \quad \gamma_{zx} = \frac{\tau_s}{G} - \nu\left[\frac{\sigma_b}{E} + \frac{\tau_T}{G}\right]$$

For point A: $\sigma_{ba} = 76.1871$ MPa
$\tau_{TA} = 0.117211$ MPa
$\tau_s = \frac{686.7}{312\ mm^2} = 2.201$ MPa

For poin B: $\sigma_{bb} = 0$
$\tau_{Tb} = 0$
$\tau_s = 2.201$ MPa

In summary: $E = 70$ GPa, $\nu = 0.33$, $G = 36.3158$ GPa

For A: $\varepsilon_{xA} = \frac{76.1871}{70\cdot10^3} - 0.33\left[\frac{0.117211 + 2.201}{36.3158\cdot10^3}\right] \Rightarrow \varepsilon_{xA} = 1.07\cdot10^{-3}$ mm

$\gamma_{zy} = \frac{0.117211}{36.3158\cdot10^3} - 0.33\left[\frac{76.1871}{70\cdot10^3} + \frac{2.201}{36.3158\cdot10^3}\right] \Rightarrow \gamma_{zy} = -3.76\cdot10^{-4}$ mm

$\gamma_{zx} = \frac{2.201}{36.3158\cdot10^3} - 0.33\left[\frac{76.1871}{70\cdot10^3} + \frac{0.117211}{36.3158\cdot10^3}\right] \Rightarrow \gamma_{zx} = -2.99\cdot10^{-4}$ mm

For B: $\varepsilon_{xB} = 0 - 0.33\left(\frac{2.201}{36.3158\cdot10^3}\right) = -2\cdot10^{-5}$ mm

$\gamma_{zy_B} = 0 - 0.33\left(\frac{2.201}{36.3158\cdot10^3}\right) = -2\cdot10^{-5}$ mm

$\gamma_{zx_B} = \frac{2.201}{36.3158\cdot10^3} - 0 = 6.06\cdot10^{-5}$ mm

To find Von Mises stress : $F = 686.7\ N$ $L = 150\ mm$

$\sigma_A = 76.1871\ MPa$ $\tau_A = 0.117211\ MPa$

Equations for Chapter 5:

$$\sigma' = \left[\frac{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2}{2}\right]^{\frac{1}{2}}$$

① $\Rightarrow \sigma' = (\sigma_x^2 - \sigma_x\sigma_y + \sigma_y^2 + 3\tau_{xy}^2)^{\frac{1}{2}}$

$\sigma' = \frac{S_y}{n}$

② Coulomb-Mohr : $\frac{\sigma_1}{S_t} - \frac{\sigma_3}{S_c} = \frac{1}{n}$

Modified Mohr : $\sigma_A = \frac{S_{ut}}{n}$

$\sigma' = \sqrt{\sigma_A^2 + 3\tau_A^2} = 76.1874$ $\sigma' = 76.1874\ MPa$

Thus for Factor of Safty $\Rightarrow n = \frac{S_y}{\sigma_{max}} = \frac{276\ MPa}{76.1874\ MPa} = 3.62$

Section 2

Attemption for calculating total avaliable cycles crank arm can with stand.

Applying chapter 6 equations:

$$\sigma_a' = \left\{ \left[k_{f\,bending}\,\sigma_{a\,bending} + k_{f\,axial}\,\frac{\sigma_{a\,axial}}{0.85} \right]^2 + 3\left[k_{fs\,torsion}\,\tau_{a\,torsion} \right]^2 \right\}^{\frac{1}{2}}$$

$$\frac{1}{n_f} = \frac{\sigma_a'}{S_e} + \frac{\sigma_m'}{S_{ut}} \qquad N = \left(\frac{\sigma_{rev}/n}{a}\right)^{\frac{1}{b}} \quad \text{as} \quad \begin{cases} a = (f S_{ut})^2 / S_e \\ b = -\frac{1}{3}\log\left[\frac{f S_{ut}}{S_e}\right] \end{cases}$$

$$k_f = 1 + \frac{k_t - 1}{1 + \sqrt{\frac{a}{r}}} \qquad S_e = k_a k_b k_c k_d k_e k_f S_e'$$

$n = 3.62$

As from previous calculation that $\sigma_A = 76.1871\ MPa = \sigma_x$

$\tau_A = 0.117211\ MPa = \tau_{xy}$

To find minimum & maximum principle stress

$$\sigma_{max} = \left(\frac{\sigma_x + \sigma_y}{2}\right) + \sqrt{\frac{(\sigma_x - \sigma_y)^2}{2} + (\tau_{xy})^2} \Rightarrow \sigma_{max} = \frac{76.1871}{2} + \sqrt{\frac{76.1871^2}{2} + 0.117211^2}$$

$$\sigma_{min} = \left(\frac{\sigma_x + \sigma_y}{2}\right) + \sqrt{\frac{(\sigma_x - \sigma_y)^2}{2} + (\tau_{xy})^2} \Rightarrow \sigma_{min} = \frac{76.1871}{2} - \sqrt{\frac{76.1871^2}{2} + 0.117211^2}$$

$$\Rightarrow \begin{cases} \sigma_{max} = 91.9661\ MPa \\ \sigma_{min} = -15.779\ MPa \end{cases}$$

assuming that $f = 0.9$ $\quad S_e = 96.5\ MPa$ [research value]

$S_{ut} = 310\ MPa$

$$\sigma_a = \left|\frac{\sigma_{max} - \sigma_{min}}{2}\right| = \frac{91.97 + 15.78}{2} = 53.875\ MPa$$

$$\sigma_m = \left|\frac{\sigma_{max} + \sigma_{min}}{2}\right| = \frac{91.97 + (-15.78)}{2} = 38.055\ MPa$$

$$a = \frac{(f S_{ut})^2}{S_e} = \frac{(0.9 \cdot 310)^2}{96.5} = 806.64 \qquad b = -\frac{1}{3}\log\frac{f S_{ut}}{S_e} = -\frac{1}{3}\log\frac{0.9 \cdot 310}{96.5} = -0.154$$

$$N = \left(\frac{\sigma_a}{a}\right)^{\frac{1}{b}} = \left(\frac{53.875}{806.64}\right)^{-\frac{1}{0.154}} = 4.28 \cdot 10^5 \text{ cycles.}$$

So total rotation for both pedals $= \frac{N}{2} = 2.14 \cdot 10^5$ cycles.

Apply research paper value. $2 \cdot 10^5$ cycles

the Mansion's method would give $2.08 \cdot 10^5$ cycles.

Section 3

Bring all avaliable values from previous calculations: F in this case increase to 110/g · 9.81

$\Rightarrow F = 1079.1\ N$

$I = I_c = 17576\ mm^4$

$$\sigma_A = \frac{F \cdot 150 \cdot 13}{17576} = \frac{1079.1 \cdot 150 \cdot 13}{17576} = 119.723\ MPa$$

$\sigma_B = 0$

$$\frac{T}{J} = \frac{\tau}{r} \Rightarrow \tau = \frac{Tr}{J} \quad \text{as } J = \frac{bd^3}{3} = \frac{12 \cdot 26^3}{3} = 70304\ mm^4$$

$$\tau_A = \frac{F \cdot 12}{J} = 0.184\ MPa$$

$$G = \frac{E}{2(1+\nu)} = \frac{70}{2(1+0.33)} = 26.3158\ GPa$$

To find Von Mises stress : $F = 1079.1\,N$ $\quad L = 150\ mm$

$\sigma_A = 119.723\ MPa$ $\qquad \tau_A = 0.184\ MPa$

Equations for Chapter 5:

1

$$\sigma' = \left[\frac{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2}{2}\right]^{\frac{1}{2}}$$

$$\Rightarrow \sigma' = (\sigma_x^2 - \sigma_x\sigma_y + \sigma_y^2 + 3\tau_{xy}^2)^{\frac{1}{2}}$$

$$\sigma' = \frac{S_y}{n}$$

2 Coulomb-Mohr : $\frac{\sigma_1}{S_t} - \frac{\sigma_3}{S_c} = \frac{1}{n}$

Modified Mohr : $\sigma_A = \frac{S_{ut}}{n}$

$$\sigma' = \sqrt{\sigma_A^2 + 3\tau_A^2} = 119.723\ MPa \qquad \sigma' = 119.723\ MPa$$

Thus for Factor of Safty $\Rightarrow n = \frac{S_y}{\sigma_{max}} = \frac{276\ MPa}{119.723} = 2.3$

For when n lower than 1 , $\sigma_{max} = 276$ MPa

The reverse calculation would suggest that $\sigma_A \approx 275$ MPa

Which $\sigma_A = \dfrac{F \cdot 150 \cdot 13}{17576} \Rightarrow F = \dfrac{17576 \cdot \sigma_A}{150 \cdot 13}$

$\Rightarrow F = 2478.67\ N \Rightarrow W = 252.667\ kg$

Thus, from the reverse calculation of the maximum instant load on the crank arm, the allowable range is 252.67 kg. That represents the athlete's weight, which is around 70 kg; the total load due to acceleration or road conditions could not go over 252.67-70 = 182.67 kg (subject to change due to the different weights of people). And according to Newton's law, 182.67 kg = 1791.99 N, which could be calculated through F= ma. And that will give the result for distance D = ½ at^2 for t close to 0, the distance for dropping a bike with a rider on it should not go over 90 m.

Suggested Design Modifications

According to the calculations, the suggestion for redesigning the crank arm would be to increase the cross-section area, especially by strengthening the thinnest area used for calculation. With a safety factor of 3.62, this bike can withstand most road conditions during normal usage or track racing. To be able to carry a heavier load, such as a compact bicycle traveling with heavy luggage, the maximum load is determined as 182.67 kg, including the rider's weight. The other construction suggestion would be to attach high tensile strength material to the top of the crank arm to prevent the initial crack process, which often occurs close to point A. Also, from previous discussions about the length of the crank arm, the rider's body, including weight and height, are the principles to determine efficient riding. As the taller the rider, the crank arm length should be increased, which will cause the maximum strength to decrease. Therefore, taller riders should consider the safety factor when customizing their bikes, such as applying better crank arm material or clearly determining the purpose of the usage.

In different riding environments, fatigue could occur easier due to the temperature, acidic water, or physical damage. During the extreme condition discussion about the mountain speed dropping competition, normal bikes like this one should not be used for such purposes, and this also applies to heavy loading and unstable road condition. The calculation also suggests that the crank arm suppose to be switched to a new one after roughly 200,000 rotations; both the research paper about 6061 Aluminum properties and the cycling math agree [7]. And for the use years before, maintenance should be determined with more complicated calculations and storage conditions. Like most metals, aluminum would have better performance if stored correctly in the desired environment. An incorrect storing method could reduce the life of the crank arm as well as other components on the bike.

Conclusions

Two of them are for loading and the other for fatigue in three different scenarios. The analysis went through the principle stress calculation and the strain for the crank arm cross-section in the thinnest area. With the calculation regarding the total cycles before failure and the maximum instant load on the crank arm, we can determine that this specimen is good relativity amount the ordinary market crank arms. Although Trek designs this bike for daily commute purposes, it still uses quality crank arms similar to their mountain bikes. The finding in the first loading scenario, the track speed racing, could be comprehended as regular usage of the bike since it only relates to the total cycles of the crank arm with periodically loading. The founding shows the good quality of the crank arm with a safety factor of 3.62, showing that the axial loading and the torsion are in the safety range before exceeding the suggested maintenance crank swap. By applying the concepts and equations from chapters 3 and 5 and the reverse process, we are also able to indicate the maximum loading weight on the bike pedal for the crank arm.

In the second loading scenario, extreme instant loading conditions occur during the downhill competition. With a body weight of 70 kg, the athletes could be safe in a low distance drop. But these are based on the ideal circumstances when the crank arm is also in ideal conditions with no weather damage or cycling fatigue, including physical damage such as a crack. Therefore, it would be a negative suggestion to use this bike for downhill competition as it could result in severe injury if the crank arm breaks.

These two loading scenarios brought up the fatigue scenario that could result from both long-time cycling and instant heavy loading. The causes of the failure are different, but the result is similar, commonly represented by the same breaking location. The breaking point makes sense to most people, as the shape of the crank arm narrows or gets thin when close to the center of rotation for either design-looking measures or lightweight purposes. According to the research and mathematical result, the breaking starts with a small crack that eventually lowers the material's strength. So, the suggestion would be to apply regular maintenance and provide good storage conditions for better performance in daily commute or light exercise that would use this bike to prevent the failure of the crank arm. Although the total cycling before failure seems a lot, that indicates the dangerous duration of use and the need to change the part immediately. And to use this bike safely, follow the instructions from Trek's official website about the maximum load and lifetime of this bike.

In conclusion, the result from the calculation is relatively moderate due to many assumptions and a lack of critical data. The research and official documentation for Aluminum 6061 are not all using the bicycle crank arm, which causes inconstancy in certain values. In order to increase the accuracy of calculations, a similar shape specimen should be tested in a lab to find the corresponding values. The SolidWorks drawing shows that the part’s shape changes could cause inaccurate measurements, eventually increasing the error. The methods to improve the test results include testing different periods of used Trek FX1 crank arm compared to the brand new arm and applying load on the actual bike to test the crank arm performance when constructed into the bike body for real-life safety measures.

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EME 150A Course Project Grading Rubric

					Score
Cover Page Contains your name, title of the project, and a picture of your bicycle.	**3 pts** All elements are included with no errors.		**1 pts** Not all elements of this criterion are included OR there are errors.		
Abstract	**5 pts** All elements are included with no errors. **(4-6 sentences)**		**3 pts** Less than 4 sentences		
Introduction and Background Clearly states 1. description of your bicycle 2. the assigned task and objective 3. the loading and fatigue failure scenarios you are going to consider	**10 pts** All elements are included with no errors.		**7 pts** Not all elements of this criterion are included OR there are errors.		
Methodology or Approach Must include: 1. Assumptions 2. Tables that include the parameters, critical cross section values (areas and perimeter), and material characteristics of the bicycle	**10 pts** All elements of this criterion are included with no errors and no missing information.	**8 pts** All elements of this criterion are included but with minor errors OR minor amounts of missing information.	**6 pts** All elements of this criterion are included but with significant errors OR significant amounts of missing information.	**4 pts** Not all elements of this criterion are included OR there are significant errors AND there are significant amounts of missing information.	
Load Envelopes (3) 1. Loading Scenario 2. Loading Scenario 3. Fatigue and Failure Scenario (Include detailed engineering drawings of the parts involved)	**10 pts** All elements of this criterion are included with no errors and no missing information.	**8 pts** All elements of this criterion are included but with minor errors OR minor amounts of missing information.	**6 pts** All elements of this criterion are included but with significant errors OR significant amounts of missing information.	**4 pts** Not all elements of this criterion are included OR there are significant errors AND there are significant amounts of missing information.	
Analysis of Critical Components The analysis for the scenarios must include: 1. Free Body Diagrams. 2. Equations and concepts from at least three chapters of the book. The three required chapters must be Chapter 3 (load and stress analysis), Chapter 5 (failures resulting from static loading, the factor of safety), and Chapter 6 (fatigue failure resulting from variable loading). 3. Calculations (using different theories)	**30 pts** All elements of this criterion are included with **no errors and no missing information**.	**24-27 pts** All elements of this criterion are included but with minor errors OR minor amounts of missing information. One error -3 pts Two errors -5 pts	**18-23 pts** All elements of this criterion are included but with significant errors OR significant amounts of missing information.	**15 pts** Not all elements of this criterion are included OR there are significant errors AND there are significant amounts of missing information.	
Suggested Design Modifications Discuss: 1. Replacing and modifying parts to improve safety	**10 pts** All elements of this criterion are included with no errors and no missing information.	**8 pts** All elements of this criterion are included but with minor errors OR minor amounts of missing information.	**6 pts** All elements of this criterion are included but with significant errors OR significant amounts of missing information.	**4 pts** Not all elements of this criterion are included OR there are significant errors AND there are significant	

2. Riding conditions (loading conditions, surfaces, weather, etc.) 3. Maintenance schedule (number of cycles and years in operation)			amounts of missing information.	
Conclusions and Recommendations 1. Summarize the main findings from the 3 scenarios. 2. Reiterate the results and list recommendations. 3. Discuss whether the results make sense and how you could improve the results	**10 pts** The conclusion is complete and accurate.	**8 pts** The conclusion is almost complete (Missed one point or one inaccuracy).	**5 pts** The conclusion is not quite complete and does not cover the all of the points in the criterion.	
References Provides bibliographical information for any material that is not original and which is cited in the report.	**5 pts** Adequate references are provided.	**2.5 pts** Adequate references are only partially provided.		
Attach this rubric	**2 pts** All elements are included with no errors.	**N/A**		
Overall Writing	**5 pts** The writing is clear. There are no spelling or grammar mistakes.	**3 pts** The writing is clear. There are a few spelling and grammar mistakes.	**1 pt** The writing is not clear. There are many spelling and grammar mistakes.	

If any sections are not present, then the scores for these sections are zero. **TOTAL SCORE:** _____________

Note: If you are missing a scenario, you will be deducted 33% for each missing scenario in the both the load envelopes and analysis of critical components sections.

The project is due on Friday, June 3 at 11:59pm. A late penalty of 25% per day will be applied for every 24 hour period.