Bike Frame Finite Element Analysis Under Varying Load Distributions

Calla Taylor

Abstract

Finite element analysis (FEA) is often utilized to predict the behavior of components or systems subjected to various forces, vibrations, and other physical effects. Static structural analysis in ANSYS was used to analyze the deformation, stresses, and safety factors of a bike frame subjected to multiple load distributions of a 100kg person. The objective of this project is to redesign the original bike frame for the load distribution with the most deformation to reduce the residual stresses and increase the factor of safety. The result of the original bike frame simulation, under 8g loading, with structural steel shows significant plastic deformation due to the residual stresses exceeding the yield strength of the material. Titanium has a higher yield strength leading to a reduction in stresses throughout the component. The static structural analysis for both materials determined the critical case to be the load distribution with 50% of the weight on the seat and pedals, and 50% of weight on the handlebars as it exhibited the highest stresses. To redesign the frame for a minimum factor of safety of 2.0 based upon the previously mentioned applied loads, many factors must be evaluated to achieve an improved design. The iterative nature of mechanical design includes geometric optimization along with material choice. The use of optimal angles, chamfers, and relief notches resulted in a final design with a minimum factor of safety of 2.2 for a frame constructed of structural steel and a factor of safety of 7.8 if it is crafted from a titanium alloy (Ti6Al4V).

Introduction

Bike frames are typically constructed from drawn metal tubes to ensure that they are seamless. These tubes are then assembled by brazing or welding, depending on the material, to form the desired frame. The two most common frame types are mountain bikes and road bikes which have drastic variations in design criteria. Road bikes are intended for speed requiring an aerodynamic configuration, whereas mountain bikes rely on stability to handle intense vibrations and fluctuating load patterns. They are often crafted from metal alloys, some of the most common being steel, aluminum, and titanium. Each material has distinct properties, providing different benefits and drawbacks. Steel alloys provide bike riders with a good balance between strength, wear, and affordability; however, these alloys are relatively heavy. Aluminum is a prominent choice for bike frames as it is lightweight, affordable, and has decent strength. The main drawback of aluminum is its high ductility, making aluminum frames more prone to dents, scratches, and fatigue failure. Titanium is another common choice for bike frames due to its high strength to weight ratio and fatigue resistance although these frames tend to be more expensive. Recently, certain polymers such as carbon fiber are becoming a popular alternative to metal alloys due to the light weight, shock absorption, and relatively high yield strength of the material. [1]

Bike frames are subjected to complex load distributions during the duration of a ride prompting the need for a comprehensive finite element analysis. This project utilizes linear elastic analysis to predict the behavior of the frame under various load distributions to determine the deformation and stress patterns that occur throughout the original design. The preliminary simulation of a 100kg rider, performed under 8g loading, considers two load distributions and materials. This simulation shows a decrease in the factor of safety and increase in residual stresses for the load distribution with 50% of the weight on the seat and pedals, and 50% of weight on the handlebars. The goal of this project is to geometrically redesign the most critical case to mitigate the residual stresses and prevent failure.

Method

The mesh for all cases was created with an element size of 7.5mm, resulting in only one element through the thickness of the model as shown below in figures 1 and 2. This mesh results in 101,610 nodes and 48,050 elements. Generating more mesh elements through the thickness of the component would ensure that the bending stresses across the wall are accurately captured, leading to more accurate results. However, this is limited by the student license as it prevents the user from exceeding 128,000 nodes and elements.

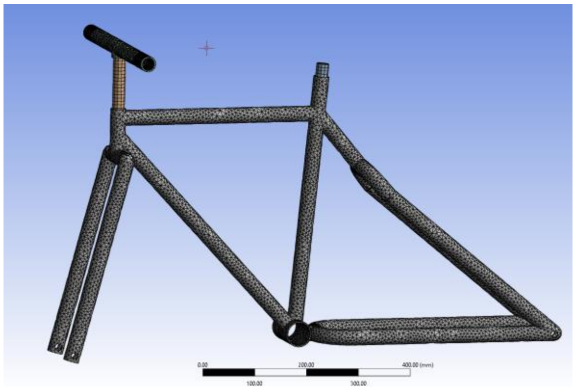


Figure 1 Bike Frame Mesh

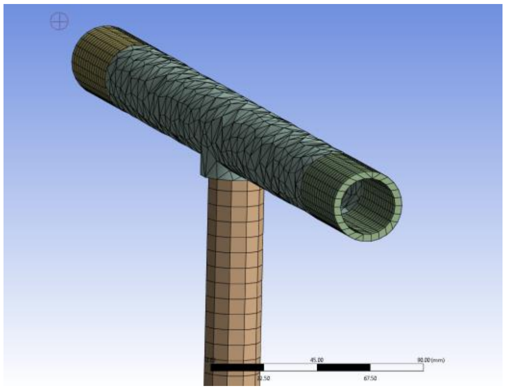


Figure 2 Mesh elements through thickness

The first two cases, (Scenario 1a and 1b, Figure 3) assume the mass of a person is 100kg, with 70% of the weight distribution on the seat and pedals and 30% on handlebars. The next two cases, (Scenario 2a and 2b, Figure 4) assume 50% of the weight distribution is on the seat and pedals and 50% on handlebars. All cases were conducted for 8g loading, with a displacement support at point A preventing movement in the Y and Z directions and a fixed support at point B as shown below in figures 3 and 4.

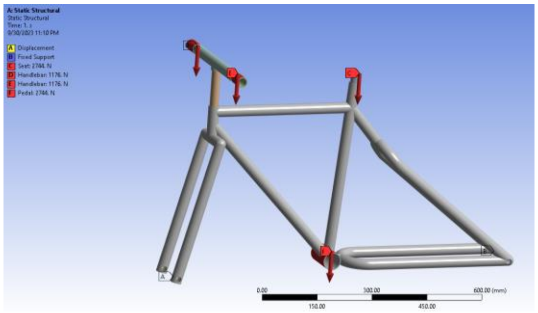


Figure 3 Scenarios 1a and 1b load distribution and boundary conditions

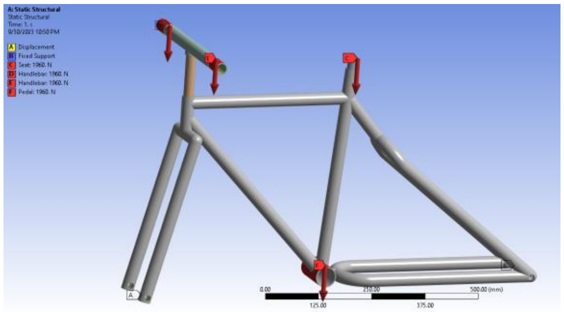


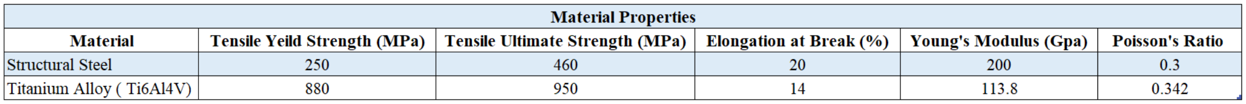
Figure 4 Scenarios 2a and 2b load distribution and boundary conditions

Yield strength is a critical parameter in design and finite element analysis. It is used to determine if the system undergoes any plastic deformation under applied loads. Two failure theories that predict permanent damage are the maximum distortion energy theory, also known as Von Mises theory, and maximum shear stress theory, referred to Tresca theory. The FEA for all cases was conducted using these theories as structural steel and Grade 5 Titanium (Ti6Al4V) have elongations of 20% and 14%, respectively, making them more ductile materials. [2] The maximum equivalent stress in a material is determined by Von Mises theory and predicts failure when this stress exceeds the yield strength. Whereas Tresca theory determines yielding by analyzing the maximum shear stress and predicts failure if it exceeds the yield strength on any plane. Both are valid approaches for predicting failure, however the Tresca maximum shear stress theory is more conservative.

Materials

Material selection is a crucial element in the design and manufacturing of any product. Selecting the appropriate material not only impacts the performance and functionality but also the manufacturability, life cycle, and cost of the product. It ensures the structural integrity of the system or component as inadequate material selection can lead to catastrophic failure. This project compares structural steel to another popular material used in bike frame manufacturing. Steel frames are often used for this application as they provide the rider with cost effective frames known for their strength and durability. The properties of steel, however, lead to a heavy frame. Titanium is a widely used material for the fabrication of bike frames as it has a high strength to weight ratio, making it strong without the added weight. Titanium has many other benefits such as its resistance to corrosion and fatigue failure.

This project will analyze the bike frame constructed of structural steel and a titanium alloy (Ti6Al4V) for the two load distributions. Although titanium can be more expensive, its material properties provide the consumer with many benefits. The tensile and ultimate yield strength of titanium, displayed in figure 5, are more than double that of structural steel, increasing the load bearing capacity of the material and decreasing the risk of plastic deformation. Structural steel is stiffer than the chosen titanium alloy, evident by its higher modulus of elasticity and lower Poisson’s ratio. This should be reflected in the simulation through a lower elastic deformation in the structural steel frame.



Material Properties					
Material	**Tensile Yeild Strength (MPa)**	**Tensile Ultimate Strength (MPa)**	**Elongation at Break (%)**	**Young's Modulus (Gpa)**	**Poisson's Ratio**
Structural Steel	250	460	20	200	0.3
Titanium Alloy (Ti6Al4V)	880	950	14	113.8	0.342

Figure 5 Material Properties

Results and Discussion

The static structural simulation results for scenarios 1a and 1b, shown in Figures 6 and 7, indicate that the maximum deformation for both materials occur at the bottom of the fork. The deformation for the titanium frame is approximately double that of the steel frame at 4.259mm and 2.2085mm respectively. These results are consistent with the expectations of the two material properties, as steel is stiffer than titanium with a modulus of elasticity that is 86.2GPa higher than that of the titanium alloy.

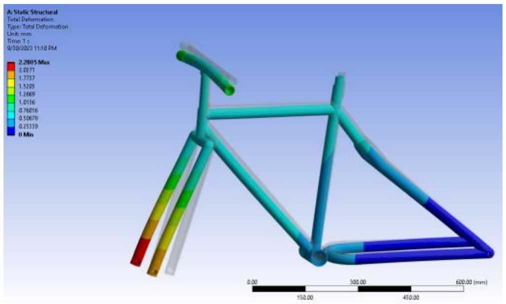


Figure 6 Scenario 1a Steel frame deformation under (70/30) load distribution

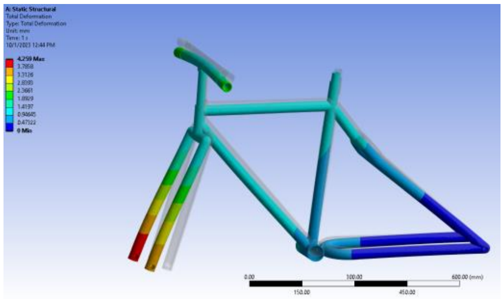


Figure 7 Scenario 1b Titanium frame deformation under (70/30) load distribution

It is imperative that the nature of deformation is considered when analyzing simulation results to prevent uninformed design decisions. This is further explained by the equivalent stress plots for scenarios 1a and 1b shown in the figures below. The maximum stress is located near the bottom of the fork for both cases, as is consistent with the expectations from the previous deformation plots. The stress analysis demonstrates that despite experiencing greater deformation in the titanium frame, it remains in the elastic region. The maximum stress of 312.53 MPa is still 567.47 MPa below the yield strength of the material, indicating the Ti6Al4V frame can withstand the applied load without any permanent deformation. In contrast, the steel frame displays less deformation. However, the equivalent stress plot predicts the maximum stress to be 314.44 MPa, which is 64.44 MPa over the yield strength, revealing that this frame will undergo permanent plastic deformation. This shows the importance of understanding the nature of deformation. Although it may appear as if the steel frame is a better choice as it exhibits less overall deformation, when considering that this material is no longer in the linear elastic range and the frame will sustain permanent damage , the titanium frame is the better alternative.

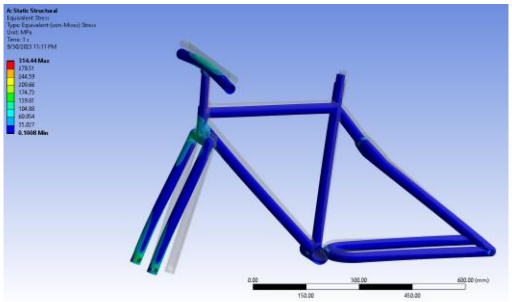


Figure 8 Scenario 1a Steel frame Von-Mises stress under (70/30) load distribution

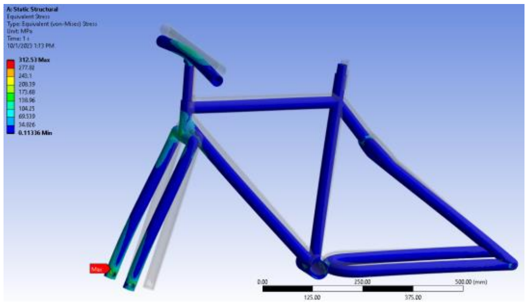


Figure 9 Scenario 1b Titanium frame Von-Mises stress under (70/30) load distribution

The results and conclusions from the equivalent stress plots are further verified by analyzing the factor of safety (FS) predictions from the static structural analysis. Figures 10 and 11 show the factor of safety across the bike frame. To make an informed decision on the probability of material failure, the minimum safety factor must be analyzed. Any value less than one will lead to plastic deformation and in turn degradation of the structural integrity of the product. The minimum FS, 0.79506 for steel and 2.8157 in the titanium frame, are located at the points with the highest residual stresses, further supporting the accuracy of the simulation.

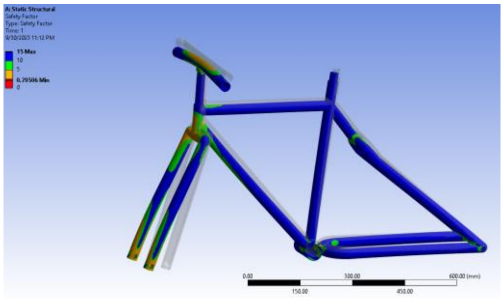


Figure 10 Scenario 1a Steel frame Von-Mises stress safety factor under (70/30) load distribution

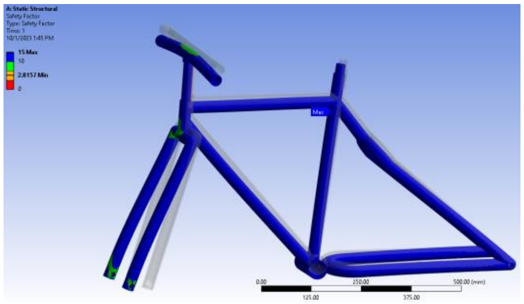


Figure 11 Scenario 1b Titanium frame Von-Mises stress safety factor under (70/30) load distribution

The static structural simulation results for scenarios 2a and 2b follow the same trends in terms of deformation, stresses, and safety factor when comparing the material properties as described above. The maximum deformation for both materials is still located at the bottom of the fork, at 4.9243mm in the titanium frame and 2.642mm in the steel frame, displayed in the figures 12 and 13 below. This demonstrates a 15% increase in deformation from the previously examined load distribution.

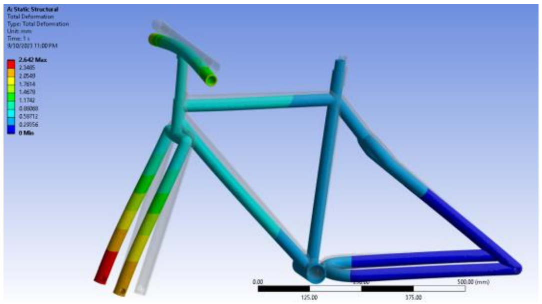


Figure 12 Scenario 2a Steel frame deformation under (50/50) load distribution

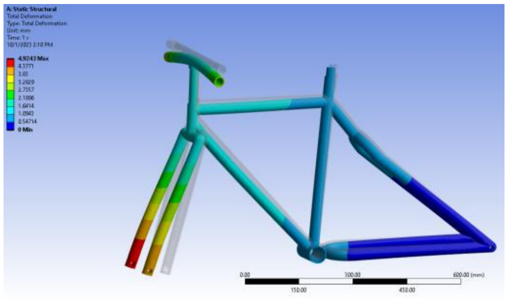


Figure 13 Scenario 2b Titanium frame deformation under (50/50) load distribution

The equivalent stress plots for the loading distribution in scenarios 2a and 2b are shown below in figures 14 and 15. The maximum stress remains located near the bottom of the fork for both cases, as is consistent with the expectations from the previous deformation plots. This load distribution predicts a maximum stress of 355.88 MPa in the steel frame and 353.28 MPa throughout the titanium alloy frame. This demonstrates a 13% increase in the maximum stress from the previously examined cases. Based upon the increase in stress, the load distribution with 50% of the weight on the seat and pedals, and 50% of the weight on the handlebars is the critical case as it exhibits higher stresses than the previous scenarios.

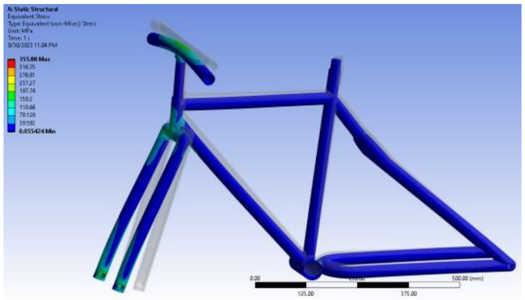


Figure 14 Scenario 2a Steel frame Von-Mises stress under (50/50) load distribution

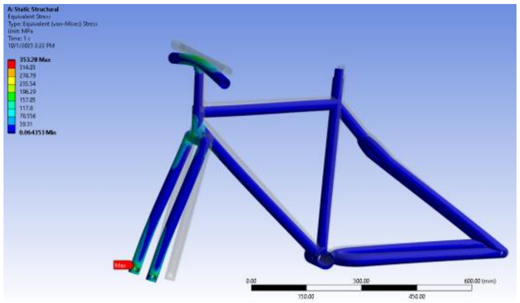


Figure 15 Scenario 2b Titanium frame Von-Mises stress under (50/50) load distribution

The validity of the results and conclusions from the equivalent stress plots under the second load distribution is reinforced by the predictions of the factor of safety (FS) from the static structural analysis. Figures 16 and 17 illustrate the factor of safety across the entire bike frame. The minimum safety factor, 0.70248 for steel and 2.491 in the titanium frame, remain located at the points with the highest residual stresses, further verifying the previous results. This demonstrates an 11% decrease in the safety factor from the previous load distribution.

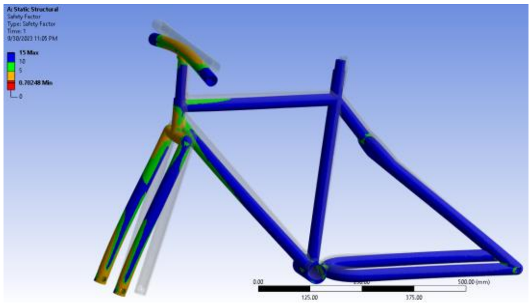


Figure 16 Scenario 2a Steel frame Von-Mises stress safety factor under (50/50) load distribution

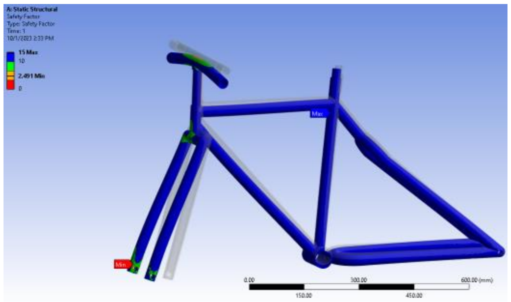


Figure 17 Scenario 2b Titanium frame Von-Mises stress safety factor under (50/50) load distribution

The previously described simulations involving two materials, structural steel and a titanium alloy, under various applied loads reveal that when 50% of the weight is distributed on the seat and pedal and 50% is distributed on handlebars the bike frame experiences more deformation, higher maximum stresses, and lower safety factors. This observation emphasizes the importance of not only identifying the cause of these high stress points but the need to design the component for the most critical case. This focus on the worst-case scenario is imperative to design against mechanical failure by ensuring product safety under the most extreme operations. This is a fundamental practice for engineers to increase product life and safety while also decreasing the risk of failure.

Redesign of the Bike Frame

While selecting a new material such as titanium would lead to a higher a factor of safety, it is important to understand that new material selection is not always a viable option under certain design constraints. In cases where new material selection is not possible, alternative optimization methods must be considered. With respect to the bike frame, an alternative method for redesigning the component or system can include geometric optimization, which can be done by changing the geometry of the part to increase structural integrity by minimizing the forces through each component. This provides an opportunity to meet the design requirements while utilizing the available materials. To geometrically redesign the frame, various aspects of the product must be considered such as load distribution, dimensions, and stress concentration areas.

Mechanical design is an iterative process which requires many cycles to reach the final design. The off-center head tube in the original design produced increased stresses and deformations on one side of the bike during the previously discussed simulations. The first iteration focuses on centering the head tube over the fork to provide the rider with more stability and distribute the load to the front wheel uniformly. Further the bike geometry was enhanced by optimizing the angles between tubes. In order to determine the optimal angles, A Parametric Finite Element Analysis of Bicycle Frame Geometries was conducted by Procedia Engineering in 2014. This study analyzed a bike frame under various load distributions to optimize the critical angles throughout the frame. [4] This study further determined the optimal seat angle, clockwise from the x-axis, to be 74 degrees and identified the ideal head tube angle, clockwise from the x-axis, as 71 degrees. Based upon this study the two angles were implemented in the redesign of the bike frame, shown in the figure below.

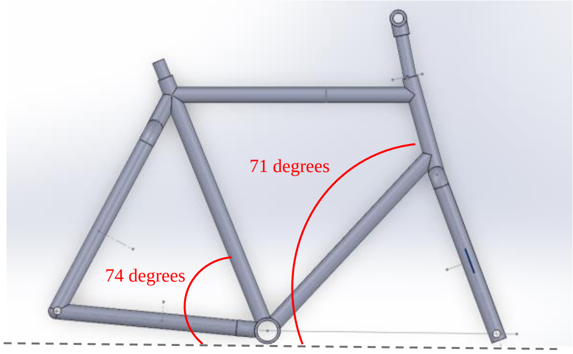


Figure 18 Bike Frame Design Iteration 1

The second iteration focuses on mitigating the adverse effects of high stresses areas. Stress concentration can be defined as a localized increase in stress due to significant and abrupt changes in geometry. [3] These spikes in stress can be detrimental to any good design. Many practices are used to reduce these stress concentrations, such as implementing gradual transitions (chamfers, filets) and the use of relief notches. Both techniques are implemented during this iteration to increase the factor of safety of the design. The use of relief notches was implemented near the base of the fork to alleviate some stress concentration as shown in figure 19. This aids in minimizing high stress areas throughout the design that otherwise have a high probability of failure.

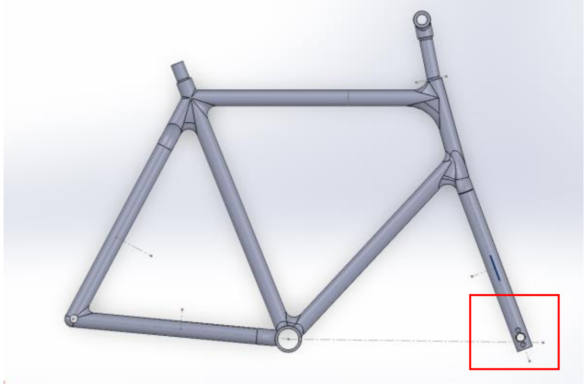


Figure 19 Bike Frame Design Iteration 2

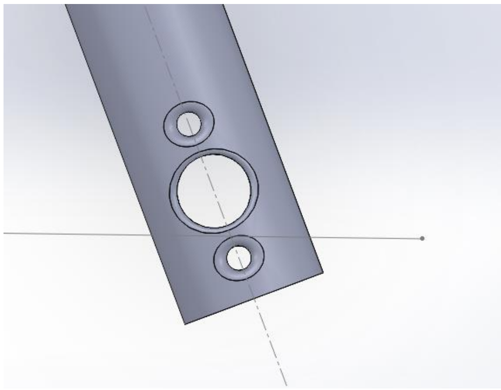


Figure 20 Close-up of Bike Frame Design Iteration 2

A static structural analysis was then performed on the redesign based upon the critical load distribution for both materials, Scenarios 3a and 3b. The deformation plots, shown in figures 21 and 22, depict the maximum deformation at the bottom of the fork, at 1.405mm in the titanium frame and 0.7526mm in the steel frame. Demonstrating a significant decrease in the deformation when compared to that of the original design.

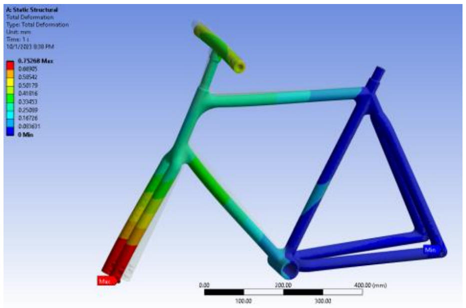


Figure 21 Scenario 3a Steel frame deformation under (50/50) load distribution

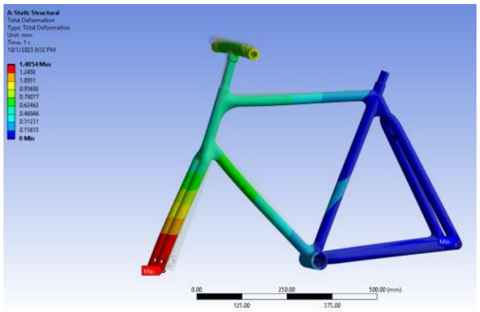


Figure 22 Scenario 3b Titanium frame deformation under (50/50) load distribution

The equivalent stress plots for the loading distribution in scenarios 3a and 3b are shown below in figures 23 and 24. The maximum stress locations remain consistent with the expectations from the previous simulations and deformation plots. This load distribution predicts a maximum stress of 112.95 MPa in the steel frame and 112.4 MPa throughout the titanium alloy frame. This demonstrates a 68% decrease in the maximum stress from the original bike frame.

Figure 23 Scenario 3a Steel frame Von-Mises Stresses under (50/50) load distribution

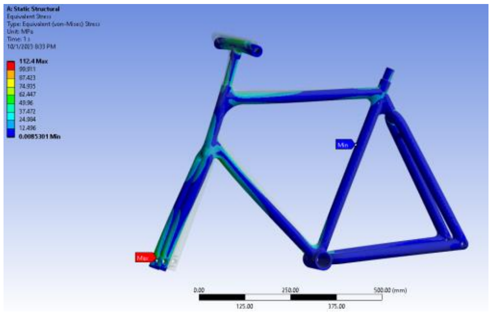


Figure 24 Scenario 3b Titanium frame Von-Mises Stresses under (50/50) load distribution

The factor of safety (FS) plots from the static structural analysis, shown in figures 25 and 26 show the factor of safety across the redesigned bike frame. The minimum safety factor, 2.2134 for steel and 7.8924 in the titanium frame display a significant increase of 68% for the new bike frame design.

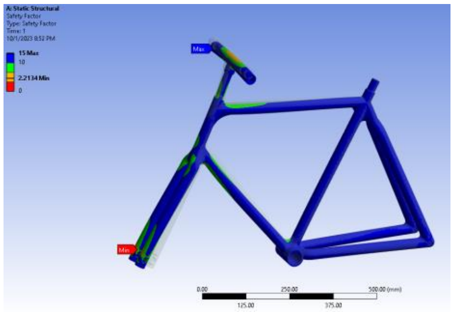


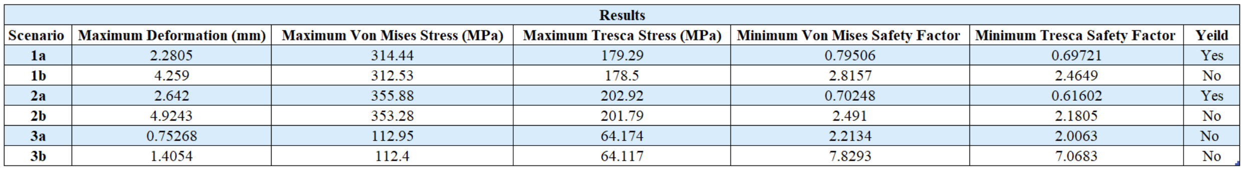
Figure 25 Scenario 3a Steel frame safety factor under (50/50) load distribution

Figure 26 Scenario 3b Titanium frame safety factor under (50/50) load distribution

Conclusion

Although a bike frame is a relatively simple structure, the process of redesigning one to prevent failure requires careful consideration of many factors. The application of finite element analysis in this process is crucial in determining the points with the highest stress and thus the highest probability of failure. A bike frame subjected to multiple load distributions of a 100kg person was analyzed under 8g loading through static structural analysis in ANSYS to illustrate deformation plots, stresses, and safety factor distributions throughout the frame. The preliminary simulation with structural steel shows significant plastic deformation near the base of the fork and thus depicts failure. This calls for a need to redesign the bike frame to reduce the probability of failure and provide enhanced safety for the consumer.

The objective of this project was to redesign the original bike frame for the load distribution with the most deformation to increase the factor of safety and prevent material failure. The geometric revision of the frame included manipulation of critical angles within the frame, the implementation of gradual transitions where the structure faced abrupt changes in geometry, and the placement of several relief notches in areas where there was a high stress concentration. Material selection also played a pivotal role in the functionality and safety of the bike frame. Appropriate material choice can significantly increase the load bearing capacity of any component. Titanium was analyzed for the revised bike frame due to its high strength to weight ratio and durability. Geometric revisions and material choice were both considered in the optimization of the bike frame. Finite element analysis was utilized to calculate the safety of the redesigned bike frame and determined it to have an increase in safety of approximately 68% for the frame made from the same structural steel whereas implementing the design with titanium showed a 91% increase in the safety when compared to that of the original design. A comprehensive summary of the analyzed deformation, stresses, and factors of safety for each case is shown in figure 27 below. This simulation shows the importance of yield theories and criteria used to design components against mechanical failure.



Results						
Scenario	**Maximum Deformation (mm)**	**Maximum Von Mises Stress (MPa)**	**Maximum Tresca Stress (MPa)**	**Minimum Von Mises Safety Factor**	**Minimum Tresca Safety Factor**	**Yeild**
1a	2.2805	314.44	179.29	0.79506	0.69721	Yes
1b	4.259	312.53	178.5	2.8157	2.4649	No
2a	2.642	355.88	202.92	0.70248	0.61602	Yes
2b	4.9243	353.28	201.79	2.491	2.1805	No
3a	0.75268	112.95	64.174	2.2134	2.0063	No
3b	1.4054	112.4	64.117	7.8293	7.0683	No

Figure 27 Table of Results

References

[1]

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[2]

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[3]

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[4]

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