Bike Frame Finite Element Analysis Under Variable Amplitude Loading

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Abstract

Bike frames are often subjected to complex loading histories during operation necessitating finite element analyses to predict the structural responses to impacts and vibrations. Finite element analysis (FEA) software such as ANSYS and nCode are often utilized to simulate, analyze, and optimize the design of a component or system. The objective of this project is to redesign the original bike frame for the load history with the shortest life to resist fatigue failure. Static structural analysis in ANSYS was used to prepare the model for multiple 1.5g load distributions of a 100kg person. nCode's design life fatigue software was then used to analyze the effects of fluctuating load histories on the life of the bike frame. The result of the original bike frame subjected to variable amplitude loading shows the highest probability of failure during the life cycle of the frame with 50% of the weight on the seat and pedals, and 50% of weight on the handlebars through the stress-life method. To redesign the frame for a minimum life of 4000 hours, the frame must be able to undergo 9000 repeats of the loading history. The geometric optimization of the bike frame resulted in a final design with a 90 percent probability of lasting 750,000 repeats (300,000 hours).

Introduction

As bike frames often experience intense forces, vibrations, and other physical effects, the intent of this project is to analyze the fatigue life under variable amplitude loading for multiple load distributions. ANSYS static structural analysis is used with nCode's stress-life and strain-life predictions to determine the effect of this type of load history on the fatigue life of a steel-framed bike. The preliminary static simulation shows higher stresses and lower safety factors for the static 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 bike frame based on the fatigue life predictions for various load distributions. The most critical case will be used for redesign to mitigate damage and enhance its durability and longevity so that the bike will last 4000 hours with a 90% probability of survival.

Methodology

Engineers often design components to last for a specified life to ensure they operate within safe limits throughout the intended service duration. A comprehensive understanding of the number of cycles a component will undergo allows engineers to appropriately design systems for durability. Life design approaches help prevent failures while optimizing resources and avoiding overdesigning, which can lead to elevated manufacturing and maintenance costs. The use of finite element analysis is integral as it provides engineers with the ability to evaluate the component, identify potential failure points, and implement risk mitigating changes that could prevent catastrophic failures. Finite element analysis software helps find solutions in a reduced amount of time, allowing for informed design decisions that focus on safety, reliability, and cost-efficiency.

Fatigue is a critical design consideration when predicting the life cycle of any component under cyclic loading conditions and fluctuating stresses. Fatigue failure is often a result of the accumulation of small damages that occur over many cycles. This project utilized ANSYS to complete a static structural analysis of a bike frame subjected to two loading distributions of a 100 kg person. The simulation results show the predicted deformation, stresses, and safety factors for the bike frame. nCode is used in conjunction with

ANSYS to determine the expected fatigue life of the frame when subjected to the cyclic variable amplitude loading.

Various methods are used for fatigue life predictions depending on the load conditions and the number of cycles. The stress-life (S-N) method is best suited for high cycle constant amplitude loading where the applied stresses are mostly in the elastic range of the material. [1] The stress life method is a total life approach, encompassing both crack initiation and propagation. However, the strain-life (E-N) method is often used for applications with a low number of cycles where plastic deformation is prevalent. It is an initiation life approach, that focuses on the initiation of cracks in a component. [1] Both methods were utilized during the analysis of the fluctuating load on the bike frame to compare the predicted fatigue life for each approach.

To simulate the effects of fatigue on the structure of the bike frame, many factors must be considered such as the material, geometry, multiaxial and mean stresses. nCode's design life software was utilized for the analysis, requiring two inputs, a finite element (FE) input, that includes the static load distribution of the geometry, and a time series input, including the fluctuating load history as a function of time (s) and load scaling. The next step in analyzing the effects of fatigue on the bike frame was to implement life predictions. For both the S-N and E-N methods, material mapping must be completed to allow the software to read the material properties necessary for the predictions. Steel-UML-UTS500 and Steel-UML-UTS300 were used for the stress-life and strain-life methods, respectively. These predictions must also account for mean stress effects as they can have a significant impact on the fatigue life of a component. This is particularly relevant for high cycle fatigue where materials may exhibit different fatigue limits when compared to alternating stresses. In order to include the effects of mean stresses in the FEA results, the goodman equation was enabled in the stress-life engine and the morrow equation was used in the strain-life engine. To analyze the final simulation results, the finite element display and data table display were added to the clipboard. These displays allow for ease of viewing and interpreting the results. The final simulation map is displayed in figures 1 and 2 below.

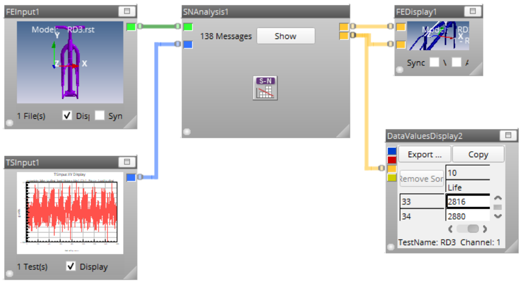


Figure 1 nCode S-N Analysis Clipboard

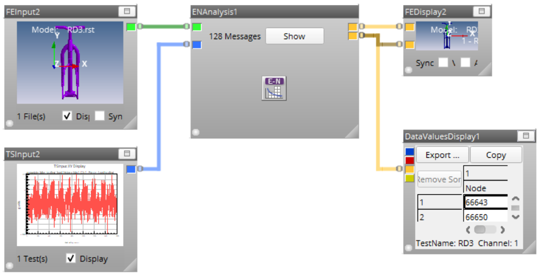


Figure 2 nCode E-N Analysis Clipboard

Materials

Material selection is an important aspect for the design and fabrication of any component as it influences multiple stages of a component's life cycle. Materials exhibit many different mechanical properties such as strength, ductility, and stiffness which determines their suitability for specific environments and applications. Bike frames are often made of various steels as they are cost effective, have high strength, and are durable due to their relatively high yield strengths. This project will analyze the bike frame constructed of Steel-UML-UTS300 for the stress-life predictions and Steel-UML-UTS500 for the strain-life predictions of all loading cases and frame designs. The material properties for each were determined from testing fully reversed loading as is evident by the R ratio of -1, displayed in table 1. Both materials have the same stiffness determined by the modulus of elasticity. The tensile yield and ultimate strength of Steel-UML-UTS500 are higher than that of Steel-UML-UTS300, increasing the load bearing capacity and decreasing the risk for plastic deformation. This should be shown through the fatigue life predictions. The steel with the higher ultimate and yield strength should exhibit longer lives when using the strain life method for predictions as it focuses on plastic deformation.

Steel-UML-UTS300			
Yeild Strength (Mpa)	Ultimate Strength (MPa)	Elastic Modulus	R- Ratio of Test
230.769	300	2.10E+05	-1
Steel-UML-UTS500			
Yeild Strength (Mpa)	Ultimate Strength (MPa)	Elastic Modulus	R- Ratio of Test
384.615	500	2.10E+05	-1

Table 1 Material Properties

Results and Discussion

The simulation was performed for two different loading scenarios of a 100kg person, one with 50% of the weight distributed on the seat and pedals, and 50% of weight on the handlebars (loading scenario a) and one with 70% of the weight distributed on the seat and pedals, and 30% of weight on the handlebars (loading scenario b), displayed in figures 3 and 4.

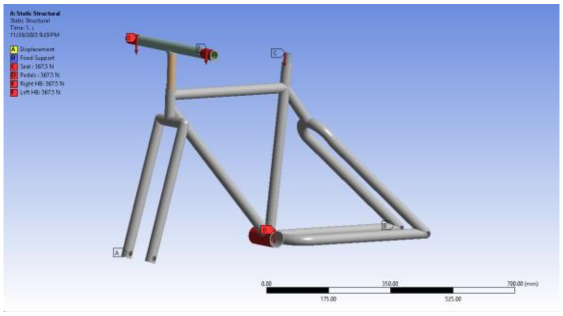


Figure 3 Scenario 1a load distribution and boundary conditions

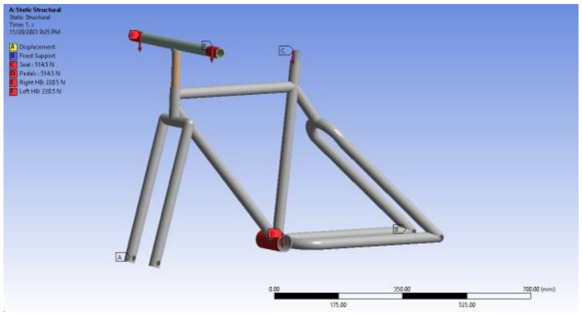


Figure 4 Scenario 1b load distribution and boundary conditions

The static structural simulation results, performed in nCode revealed that, for both scenarios, the maximum stress occurs at the bottom of the fork where the bike experiences the most deformation. Figures 5 and 6 show that scenarios 1a and 1b experience a maximum stress of 118.9MPa and 104.2MPa respectively. This is consistent with the expected outcomes, considering that loading scenario 1a, where more weight is distributed to the handlebars, has more deformation at the bottom of the forks resulting in higher stresses. The elevated stresses identified in the bike frame, particularly in loading scenario 1a, should result in a lower fatigue life when compared to that of scenario 1b.

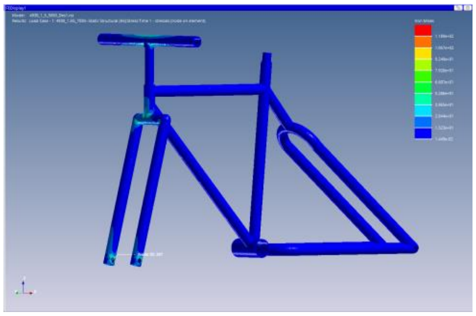


Figure 5 Scenario 1a Stress Distribution

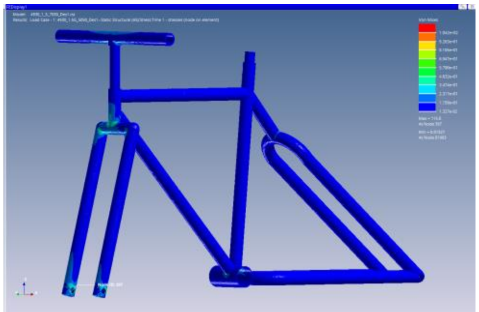


Figure 6 Scenario 1b Stress Distribution

The fatigue life analysis involved two prediction techniques: the stress-life method and strain-life method. The initial simulation utilized the stress-life method which does not account for true stress-strain behavior of both the plastic and elastic deformation but instead assumes linear elasticity. However, in applications involving high cycle fatigue, where steels often exhibit minimal plastic strains, the S-N method is still relatively accurate. While this method is often used to predict the fatigue life of components subjected to high cycle fatigue, such as bike frames, it is important to note that its traditional application is for constant amplitude loading. [1] The results of the finite element analysis performed in nCode followed the expected trends, showing a shorter life expectancy for scenario 1a with a 90% probability of lasting 657.2 repeats (292 hours) whereas scenario 1b was predicted to last for 3215 repeats (1428.9 hours), illustrated in figures 7 and 8. The data from the static structural analysis confirms the relationship between stress and fatigue life, demonstrating that components with higher stresses experience more damage and a shorter life span.

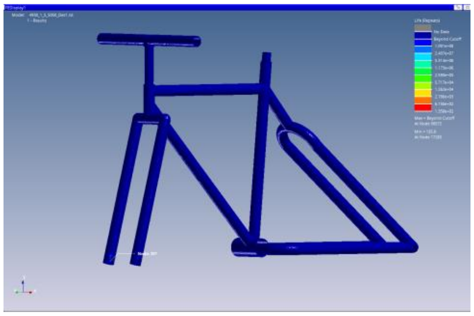


Figure 7 Scenario 1a Stress-Life Prediction

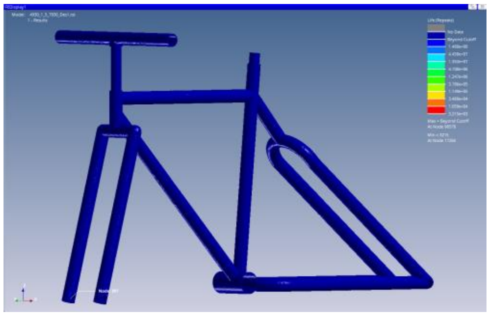


Figure 8 Scenario 1b Stress-Life Prediction

The second simulation utilized the strain-life method, a technique typically applied to systems that are subjected to elevated loading levels and a low cycle count. This method focuses on the accumulation of plastic strains which is primarily important for low cycle fatigue where the strain range approaches the plastic region and components endure higher stresses. The validity of the results and conclusions from the previous simulation are further confirmed by the strain-life predictions, showing shorter lives for the loading distribution with higher stresses (scenario 1a) with a 90% probability of lasting 5658 repeats (2514.7 hours), where scenario 1b predicts a life of 1.146E10 repeats (5093.3 hours), shown in figures 9 and 10.

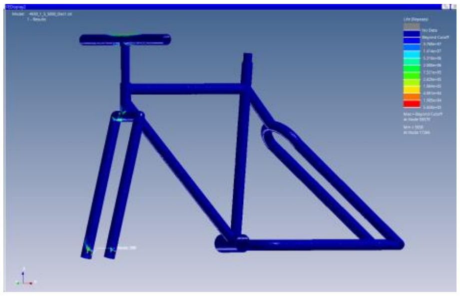


Figure 9 Scenario 1a Strain-Life Prediction

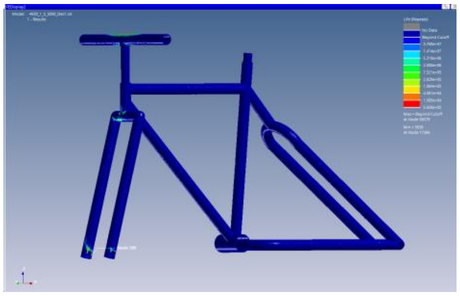


Figure 10 Scenario 1b Strain-Life Prediction

The previously described simulations, involving two weight distributions under variable amplitude loading reveals that when 50% of the weight is on the seat and pedals, and 50% is on the handlebars the bike frame experiences higher stresses and lower life expectancies. The probability of failure is an important aspect to consider when performing a fatigue analysis as it significantly affects the overall life of a component. The linear increase in life with a decrease in probability of failure is displayed in figure 11. This observation emphasizes the importance of not only identifying the location of high intensity stress points but the need to design the component for the most critical case which exhibits the minimum life prediction. Any value less than 9000 repeats poses a high risk of failure before the intended life of the component has been reached. Prioritizing the worst-case scenario is imperative to designing against mechanical failure and ensuring product durability under the most extreme operating conditions. This approach is a fundamental practice for engineers to increase the life of a product while also decreasing the risk of failure.

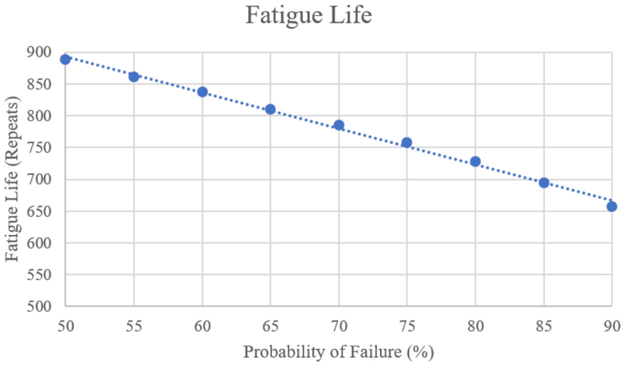
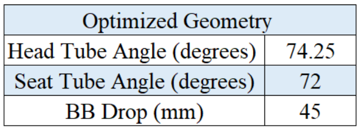


Figure 11 Fatigue Life vs Probability of Failure

Redesign of the Bike Frame

While designing a component for infinite life may seem like the best solution, it is important to consider the consequences of an over-designed system. Over engineering can lead to unnecessary expenses, wasted resources, and increased weight. A well optimized design prioritizes meeting the requirements and constraints without incorporating unnecessary features. The original bike frame was optimized by considering various geometric parameters to increase the structural integrity and predicted fatigue life.

Mechanical designs of any component or system require an iterative process that involves many cycles of modifying and analyzing the design to develop the final product. The first issue with the original frame was the off-center head tube that produced increased stresses on the left side of the bike. The initial redesign focused on centering the head tube to provide more structural stability and decrease the stress on the left fork of the bike frame. Additionally, improvements were made to optimize the angles between tubes. To identify the critical angles, a Parametric Finite Element Analysis of Bicycle Frame Geometries was conducted by Procedia Engineering in 2014. This research aimed to optimize the angles of a bike frame under various load distributions by performing a finite element analysis. [2] Both the vertical compliance and lateral stiffness were accounted for in the simulation resulting in the optimal geometry displayed in table 2 below. The study's determined head and seat tube angle as well as the bottom bracket drop (BB drop) were included in the next iteration of the bike frame design, figure 12.



Optimized Geometry	
Head Tube Angle (degrees)	74.25
Seat Tube Angle (degrees)	72
BB Drop (mm)	45

Table 2 Procedia Engineering's Optimized Geometry [2]

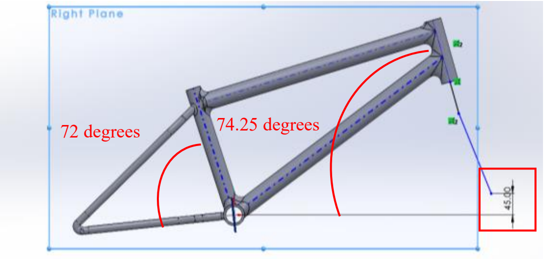


Figure 12 Bike Frame Design Iteration 1

The second design iteration focused on optimizing both the thickness and geometry of the front wheel forks as well as mitigating the adverse effects of the high stress concentrations observed from abrupt changes in geometry, specifically near the handlebars and connecting interfaces between the tubes. The redesigned fork was based on the conclusions of the Fatigue Analysis of a Bicycle Fork conducted by the Worcester Polytechnic Institute. [3] This study demonstrated that crack formation was likely to occur near the connection of the head tube and fork blades due to stress concentrations and heat effected zones that result from welding. The stress concentrations were reduced by implementing gradual transitions (chamfers, filets) and tapered front forks as illustrated in figure 13.

Figure 13 Bike Frame Design Iteration 2

A comprehensive finite element analysis including the static structural simulation in ANSYS and the fatigue life predictions in nCode was then performed on the redesign based upon the critical load distribution of scenario 1a. The final fatigue predictions using the stress-life and strain-life methods are displayed in figures 14 and 15. These plots depict the minimum number of repats the bike can sustain with a 90% probability of failure to be 7.52E5 for the S-N method and 5.268E4 for the E-N method. These simulations demonstrate the significant increase in fatigue life of the bicycle frame when compared to that of the original design.

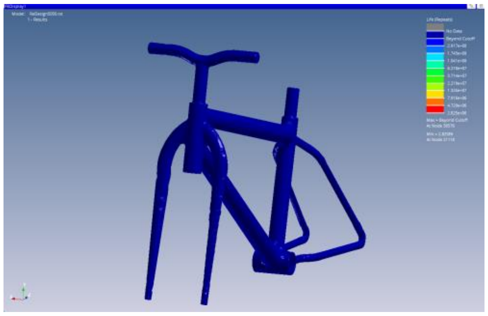


Figure 14 Redesigned Frame Stress-Life Prediction

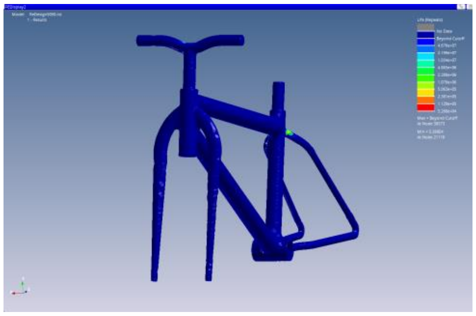


Figure 15 Redesigned Frame Strain-Life Prediction

Conclusion

While a bike frame may seem like a simple structure, they are frequently subjected to complex loading scenarios that necessitate the careful consideration of many factors throughout the design process. Finite element analysis proves to be an invaluable resource for engineers to analyze the structural response of variable amplitude loading in such systems. Analyzing a bike frame under various loading distributions through a static structural analysis in Ansys and nCode's design life fatigue software illustrates the stresses and fatigue life predictions across the frame. The preliminary simulation shows significant stresses resulting in the reduced life of the structure. This calls for a need to redesign the frame to mitigate stress and increase the overall lifespan.

The objective of this project was to redesign the original bike frame for the loading scenario that resulted in the shortest life for a final design that has a 90% probability of survival for at least 4000 hours (9000 repeats). The modifications to the design included the manipulation of the critical angles, implementing gradual transitions, and tapering the front forks. The methods used to perform the finite element analysis of the frame accounted for both multiaxial stresses and mean stresses through the Goodman and Morrow equations. The final design resulted in a significant increase in lifespan that will allow the user to operate the bike under the given loading history for up to 750,000 repeats (300,000 hours). This simulation demonstrates the importance of fatigue life predictions used to design components against mechanical failures.

References

[1]
J. A. Bannantine, J. J. Comer, and J. L. Handrock, *Fundamentals of Metal Fatigue Analysis*. Pearson College Division, 1990.

[2]

D. Covill et al., “Parametric finite element analysis of bicycle frame geometries,” Procedia Engineering, vol. 72, pp. 441–446, 2014. doi:10.1016/j.proeng.2014.06.077

[3]

Jannetti, Nathaniel A., and L. B. Lynch. "Fatigue Analysis of a Bicycle Fork." (2010).