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Optimization of Bicycle Frame Design with Variation of Materials

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Abstract

This study shows how to model the best results of several bicycle frame designs with a variety of materials. The use of various materials to change the design of a bicycle frame is the main topic of this research. Materials such as aluminum, titanium and carbon steel have specific features that can affect the strength, weight and response of a bicycle frame. This research involves designing a bicycle frame design using SolidWorks 2022, which is then used for simulation and strength analysis with Ansys. In this experiment, various materials were used, including aluminum alloy, titanium and carbon steel to measure the stress and deformation of each design and material tested. The purpose of this research is to study how the use of different types of materials when changing the design of a bicycle frame impacts the performance and strength of the bicycle. Tests were conducted through ansys simulation, with dynamic loads under conditions of daily bicycle use. The best data obtained in design 1 on titanium material, the top-tube section experienced a stress of 18.156 MPa and a deformation of 0.012078 mm. For aluminum material, the head-tube section experienced the lowest stress of 1.211 MPa and deformation of 0.0034886 mm. These results provide important insights for developing more efficient bicycle frame designs that can be tailored to user requirements and also impact the development of new materials in the bicycle industry aimed at improving the performance and durability of bicycle frames.
Keywords: *Design, material, frame, bicycle, Solidworks*

Abstrak

Penelitian ini menunjukkan bagaimana memodelkan hasil terbaik dari beberapa desain rangka sepeda dengan berbagai jenis material. Penggunaan berbagai material untuk memodifikasi desain rangka sepeda menjadi fokus utama dalam penelitian ini. Material seperti aluminium, titanium, dan baja karbon memiliki karakteristik khusus yang dapat memengaruhi kekuatan, bobot, serta respons rangka sepeda. Penelitian ini melibatkan perancangan rangka sepeda menggunakan SolidWorks 2022, yang kemudian digunakan untuk simulasi dan analisis kekuatan dengan Ansys. Dalam eksperimen ini, berbagai material digunakan, termasuk paduan aluminium, titanium, dan baja karbon untuk mengukur tegangan (stress) dan deformasi dari setiap desain dan material yang diuji. Tujuan penelitian ini adalah untuk mengkaji bagaimana penggunaan berbagai jenis material dalam perubahan desain rangka sepeda memengaruhi kinerja dan kekuatannya. Pengujian dilakukan melalui simulasi Ansys dengan beban dinamis pada kondisi penggunaan sepeda sehari-hari. Data terbaik diperoleh pada desain 1 dengan material titanium, di mana bagian top-tube mengalami tegangan sebesar 18,156 MPa dan deformasi sebesar 0,012078 mm. Pada material aluminium, bagian head-tube mengalami tegangan terendah sebesar 1,211 MPa dengan deformasi sebesar 0,0034886 mm. Hasil penelitian ini memberikan wawasan penting untuk pengembangan desain rangka sepeda yang lebih efisien, dapat disesuaikan dengan kebutuhan pengguna, serta berkontribusi pada

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pengembangan material baru di industri sepeda yang ditujukan untuk meningkatkan performa dan daya tahan rangka sepeda.
Kata kunci: Desain, bahan, rangka, sepeda, Solidworks.

1. Introduction

Bicycles were first introduced in Europe in the 19th century and now number over one billion worldwide—twice the number of cars [1]. They are a practical and environmentally friendly mode of transportation; however, their cruising range and speed remain limited [2]. Bicycles are lightweight structures required to support significantly heavier loads, namely the rider. Several factors must be considered in the design and manufacturing of bicycle frames, including the rider's weight, aerodynamic forces, and friction [3]. In any vehicle, one of the key criteria for passenger safety is the degree of deformation experienced by the main frame. This deformation is influenced by the amount of energy absorbed by the frame during operation or impact [4].

Despite advancements in material science, many conventional bicycles still utilize steel frames. Steel presents several drawbacks, such as high weight and susceptibility to corrosion [5]. Numerous studies have investigated the potential of replacing steel with lighter alternatives such as aluminum, magnesium, carbon fiber, and composite materials [6]. While steel, titanium, and aluminum are commonly used in the bicycle industry, carbon fiber has emerged as the most popular material for frame construction and is increasingly used in other bicycle components as well [3]. Since the 1980s, composite materials have received significant attention in bicycle design.

Carbon fiber is particularly favored in the bicycle industry as a reinforcement material in composite frames due to its low weight and high specific stiffness [1]. These materials offer advantages such as low density and corrosion resistance. Moreover, their mechanical properties—including strength and stiffness—are considered comparable to or even superior to those of steel [7]. Variations in frame design must be thoroughly tested to ensure both functionality and safety. One key objective of such testing is to evaluate the structural strength of the frame. By comparing results across various frame designs, optimal configurations can be identified [2]. In addition to the geometry of the frame, the choice of material significantly affects structural integrity. Frame materials can thus be selected based on specific performance requirements [8].

Tomasz Tomaszewski's 2020 study, Fatigue Life Analysis of Steel Bicycle Frames According to ISO 4210, examined fatigue failure in mountain bike frames constructed from 25CrMo4 alloy steel after three years of use. The study aimed to estimate fatigue life through failure analysis and an evaluation of fatigue strength in accordance with ISO 4210 safety standards. The analysis incorporated a combination of experimental testing using mini-specimens extracted from the failure site, numerical simulations via the finite element method, and probabilistic modeling techniques, including P-S-N curves, high-pressure volume concepts, and weakest link theory. The results revealed that the fatigue life at a 10% failure probability was below the threshold recommended by ISO 4210, largely influenced by operational conditions such as the angle of load application on the pedal [9].

In another study, Regenwetter, Weaver, and Ahmedini (2022), in their journal article FRAMED: An AutoML Approach for Structural Performance Prediction of Bicycle Frames, explored a data-driven methodology for the structural design and optimization of bicycle frames using automated machine learning (AutoML). The case study focused on predicting the structural performance and geometric feasibility of parametric bicycle frame designs. To this end, the authors introduced the FRAMED dataset, which includes 4,500 bicycle frame designs along with ten structural performance metrics derived from finite element simulations. AutoML was used to train an optimal surrogate model capable of accurately predicting both performance and feasibility. The findings demonstrated that the ensemble model selected by AutoML outperformed traditional machine learning models—such as neural networks and XGBoost—achieving a 24% improvement in F1 score and a 12.5% reduction in mean absolute error [10].

In the journal article by Li Shengqin and Feng Xinyuan (2019), titled "Study of Structural Optimization Design on a Certain Vehicle Body-in-White Based on Static Performance and Modal Analysis", the authors address the issue of structural design optimization for a vehicle body-in-white (vehicle body frame) based on static and modal performance analysis. They developed a finite element model of the body-in-white and conducted analyses of flexural stiffness, torsional stiffness, and vibration mode characteristics. The results indicated that the initial static and dynamic performance indices did not meet the required standards. To address this, a sensitivity analysis was conducted to identify the components that most significantly affected structural performance. Based on the findings, the authors optimized the thickness of certain panels and modified the geometry in several areas. Following optimization, both flexural and torsional stiffness improved to meet the target reference values, while the overall weight of the body-in-white was reduced by 9.2%, thus fulfilling the lightweight design objective [11].

This study aims to optimize the design of a bicycle frame by considering various material types. Specifically, five different frame designs will be analyzed using three materials: aluminum, carbon steel, and titanium. The analysis will be conducted through simulations using ANSYS software to evaluate the stress and deformation experienced by each design and material combination.

The independent variables in this study consist of the five frame designs and the three types of materials. The dependent variables are the stress and deformation observed in the bicycle frame. Control variables include loading conditions (such as applied force and moment), boundary conditions, and the simulation method (ANSYS).

By simulating each combination of frame design and material, the study aims to determine which configuration yields the most optimal results in terms of minimizing stress and deformation. The findings are expected to contribute valuable insights for the design and production of more efficient and safer bicycle frames.

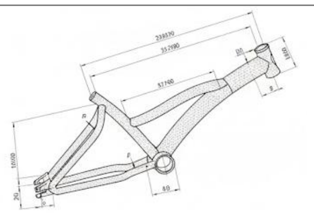
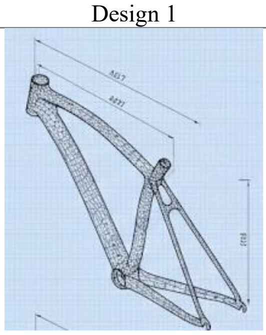
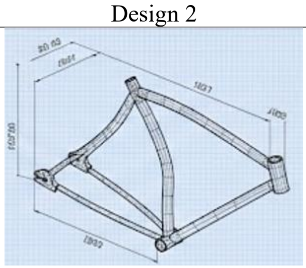
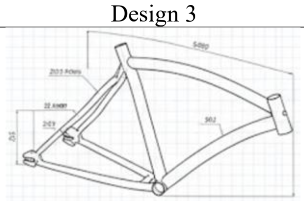
2. Methods

In this section, we will discuss some of the methodologies behind data collection regarding design parameterization, modeling, loading and material selection.

2.1 Parameterization and Modeling

The design of the bicycle frame in this study involves several parameters and design variables that will be optimized. The primary parameters to be varied include the types of frame materials, specifically aluminum, titanium, and carbon steel. These three materials possess different mechanical properties in terms of strength and stiffness, which will significantly influence the overall performance of the bicycle frame. Parameterization is conducted to enable a comparative analysis of strength, weight, cost, and environmental sustainability across frames constructed from different materials [12]. In addition to material selection, the optimization process will also consider the diameter and wall thickness of the main frame tubing. The pipe diameters used in the simulations are presented in Table 1, with consistent dimensions applied across all five frame designs. Another parameter subject to optimization is the bicycle stem angle, which will also be evaluated for its impact on frame performance.

Tabel 1. Dimensions

Design	Vertical (cm)	Horizontal (cm)
 Design 1	12	12
 Design 2	8	10
 Design 3	9	8
 Design 4	10	9

The modeling of the bicycle frame was conducted using SolidWorks software. In this software, the main components of the bicycle frame, such as the tubing, handlebars, saddle, and handlebar stem were modeled as individual parts, with dimensions adjusted according to the specified design variations. The main frame tubes were created using the "Pipe" feature in SolidWorks, with diameter variations as listed in Table 1. Other components were modeled using standard parts available in the SolidWorks library.

Once all parts were completed, they were assembled to form the complete bicycle frame. The assembly process included the application of appropriate mate constraints to ensure accurate alignment and connectivity between components.

Following the assembly, surface meshing was performed using solid elements to prepare the model for simulation in ANSYS. Mesh refinement was applied in welded joints and other critical regions of the frame to improve accuracy. In the ANSYS Structural simulation stage, various loading conditions were applied, including steering load, rider weight, and acceleration forces. The simulation was executed to obtain the stress distribution and deformation behavior of the frame. It also served to validate the structural strength and reliability of the frame under applied loads and forces. This validation is crucial to ensure that the frame design performs effectively under expected conditions and meets the necessary safety requirements [13].

The simulation results were validated using experimental data or reference benchmarks. Finally, topology optimization was carried out to determine the optimal frame design based on variations in material types and geometric dimensions.

2.2 Loading

Loading refers to the application of forces or loads on a structure to evaluate its strength and reliability, such as in the case of a bicycle frame subjected to loads that simulate normal riding conditions [14]. Additionally, loading plays a crucial role in structural testing, as it helps to determine the strength, deformation, and overall response of a structure under applied forces [15]. In this simulation, the bicycle frame is subjected to static loading conditions in accordance with ISO 4210 standards for bicycle safety requirements.

The applied static load represents a rider's mass of 80 kg, converted into a vertical force and applied to the handlebar at the front section of the frame, simulating the steering load condition specified in ISO 4210. To accurately replicate real operating conditions, appropriate boundary conditions are defined. The rear dropouts of the bicycle frame are fully constrained in all translational degrees of freedom, representing the fixed contact between the rear wheel and the ground as prescribed in the standard. Meanwhile, the front fork region is constrained in the vertical and lateral directions while allowing rotational freedom about the steering axis, simulating the front wheel support condition during static equilibrium.

These boundary conditions follow the recommendations of ISO 4210 and ensure that the loading configuration closely approximates the actual support and load transfer mechanisms experienced by the bicycle frame during typical riding conditions, thereby providing reliable and standardized simulation results.

2.3 Material Selection

The materials used in the optimization of the bicycle frame design are Aluminum 6061, Titanium alloy Ti-6Al-4V, and Carbon Steel AISI 1020. Aluminum 6061 has a tensile strength of 310 MPa, yield strength of 275 MPa, elastic modulus of 69 GPa, and shear modulus of 26 GPa. Titanium alloy Ti-6Al-4V offers significantly higher mechanical properties, with a tensile strength of 1050 MPa, yield strength of 827 MPa, elastic modulus of 105 GPa, and shear modulus of 41 GPa. In contrast, Carbon Steel AISI 1020 exhibits a tensile strength of 731 MPa, yield strength of 460 MPa, elastic modulus of 205 GPa, and shear modulus of 80 GPa [12].

These three materials were selected due to their relatively high strength and low to moderate density, making them suitable for bicycle frame applications. The mechanical property data will be used as material input parameters in the ANSYS software during stress and deformation simulations.

2.4 Material Properties

Aluminum, titanium, and carbon steel are widely used metallic materials in various industrial applications. Aluminum has a relatively low density of 2.7 g/cm³ and a melting point of 660.3°C. Its tensile strength ranges from 90 to 600 MPa, depending on the alloy composition and heat treatment applied. The elastic modulus of aluminum is approximately 70 GPa, and it has good thermal conductivity at 235 W/(m·K). In addition, aluminum exhibits excellent corrosion resistance due to the formation of a protective oxide layer [16].

Titanium has a higher density than aluminum, at 4.51 g/cm³, and a significantly higher melting point of 1670°C. Its tensile strength ranges from 345 to 1380 MPa, depending on the alloy and heat treatment. The elastic modulus of titanium ranges between 105 and 116 GPa. Titanium is well known for its exceptional corrosion resistance, attributed to a stable oxide layer, and for its high strength-to-weight ratio [17].

In contrast, carbon steel has the highest density among the three materials, at approximately 7.8 g/cm³, with a melting point ranging from 1370 to 1530°C, depending on its carbon content. Its tensile strength varies widely from 300 to 2500 MPa, influenced by heat treatment and composition. The elastic modulus of carbon steel is between 190 and 210 GPa. Although its corrosion resistance is moderate and environment-dependent, carbon steel offers excellent mechanical properties at a relatively low cost [17].

Therefore, in this study, the ANSYS simulations of the bicycle frame use the material properties of aluminum, titanium, and carbon steel, as summarized in Table 2.

Tabel 2. Material Properties

Properties	Aluminum	Titanium	Carbon Steel
Density (g/cm³)	2,7	4,51	7,85
Melting Point (°C)	660	1668	1425-1540
Modulus of Elasticity (GPa)	69	105	200
Ultimate Tensile Strength (MPa)	90-185	350-1100	420-780

Properties	Aluminum	Titanium	Carbon Steel
Thermal Conductivity (W/m.K)	237	-	-
Corrosion Resistance	Good	Very Good	Depends on the mix
Other Properties	Lightweight, corrosion resistant, malleable, recyclable.	Light, strong, corrosion resistant, high temperature resistant.	Strong, hard, easy to shape, relatively inexpensive.

Table description:

- The values in this table are typical ranges for each material.
- A "-" indicates that data is not available or not relevant for that material.

2.5 Mesh Resolution

When conducting simulations using ANSYS on the bicycle frame, one of the critical factors to consider is mesh resolution. The appropriate selection of mesh resolution significantly affects the accuracy of the simulation results, computational time, and the required computational resources. For global meshing applied across the entire frame model, the recommended mesh size is approximately 1/10 to 1/20 of the smallest geometric feature on the frame [18]. Meanwhile, for local meshing in specific regions—such as areas with high stress concentrations or large deformations—the recommended mesh size ranges from 1/50 to 1/100 of the smallest geometric detail in those areas [19].

In addition to global and local meshing, adaptive meshing techniques can enhance simulation accuracy without requiring a uniformly fine mesh across the entire model. Adaptive meshing adjusts the mesh size automatically based on stress or deformation gradients during the simulation. For frame simulations, adaptive mesh sizes ranging from 1/20 to 1/50 of the smallest local geometric feature are recommended in regions experiencing high stress concentrations or significant deformation [20].

In this study, structural simulations using ANSYS were conducted to analyze the behavior of a bicycle frame constructed from three different materials: aluminum, titanium, and carbon steel. A mesh resolution of 10 was used, meaning the maximum element size in the mesh was 10 mm. This relatively coarse mesh resolution was chosen to improve computational efficiency; however, this choice comes with the trade-off of reduced simulation accuracy.

The simulation results indicate that with a mesh resolution of 10, the accuracy may be insufficient, especially in regions with complex geometries or significant shape changes. Although the total computation time was significantly reduced due to the lower number of elements, the simulation may fail to capture finer details or localized phenomena, such as stress concentrations at sharp corners or junctions between frame components made of different materials.

For the relatively simple frame geometry and the relatively uniform stress and deformation distributions across the three materials, a mesh resolution of 10 may be sufficient in terms of computational efficiency and general accuracy. Nevertheless, it is important to note that simulation accuracy is also influenced by other factors, including element type selection, boundary conditions, loading scenarios, material properties of aluminum, titanium, and carbon steel, as well as interactions between different materials.

Therefore, a mesh convergence study is strongly recommended to determine the optimal mesh resolution that ensures accurate simulation results without excessive computational cost.

3 Results and Discussion

3.1 Design 1

In Design 1, the highest stress and deformation values are observed in the top tube section of the bicycle frame made from titanium. The simulation results show that the frame experiences a stress of 18.156 MPa and a deformation of 0.012078 mm.

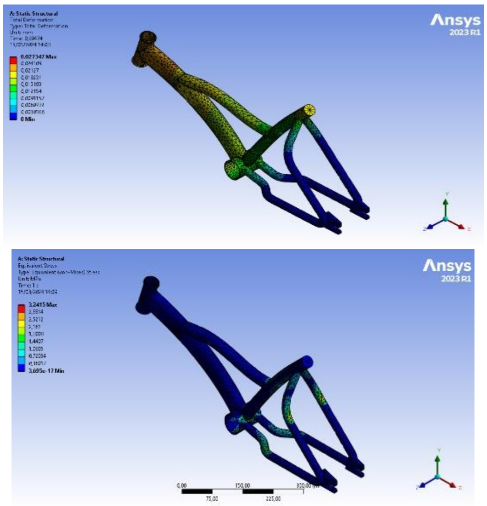


Fig 1. Stress and deformation for aluminium material

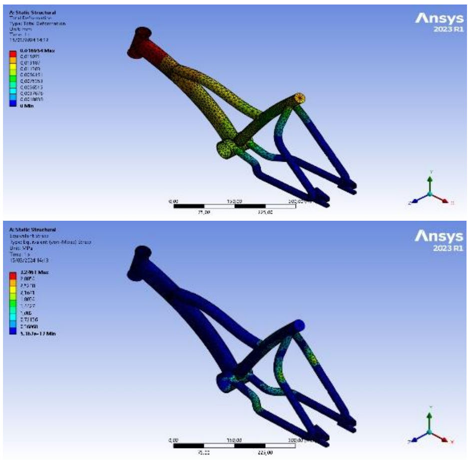


Fig 2. stress and deformation for titanium material

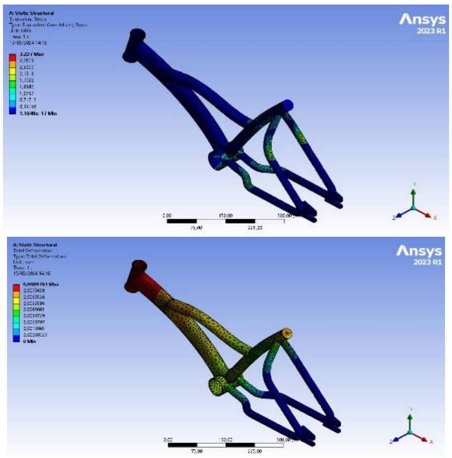


Fig 3. Stress and deformation for Carbon steel

The yield strength of the titanium material used ranges between 480 MPa and 1100 MPa, depending on the specific alloy and heat treatment applied. Meanwhile, the allowable deformation for a bicycle frame typically ranges from 0.1% to 0.5% of the component length.

The obtained stress value of 18.156 MPa is significantly lower than the yield strength range of titanium (480–1100 MPa), indicating that the frame is structurally safe and will not undergo permanent plastic deformation under a 100 kg load. The deformation value of 0.012078 mm also falls well within the allowable deformation limit. For example, assuming a frame length of 1 meter, the acceptable deformation range would be 1 mm to 5 mm, making the observed deformation of 0.012 mm highly acceptable.

In addition to material strength and deformation limits, the safety factor must also be considered in the design process to ensure the overall safety and reliability of the bicycle frame. Based on the simulation results and the given material properties, the titanium frame design can be considered safe under a 100 kg load, both in terms of stress and deformation performance.

Lowest Stress

The simulation results indicate that the bicycle frame, particularly in the head tube area, experiences a stress of 1.211 MPa and a deformation of 0.0034886 mm. The yield strength of the aluminum material used ranges between 20 MPa and 600 MPa, depending on the specific alloy and heat treatment applied. Meanwhile, the allowable deformation for a bicycle frame typically falls within the range of 0.1% to 0.5% of the component's length.

The obtained stress value of 1.211 MPa lies well within the yield strength range of aluminum (20–600 MPa). This suggests that the stress experienced by the bicycle frame remains within a safe range and will not result in permanent plastic deformation under a 100 kg load. Additionally, the deformation value of 0.0034886 mm is significantly lower than the permissible deformation limit. For instance, assuming the frame length is 1 meter, the allowable deformation would range from 1 mm to 5 mm. Therefore, the observed deformation is negligible and can be considered acceptable.

3.2 Design 2

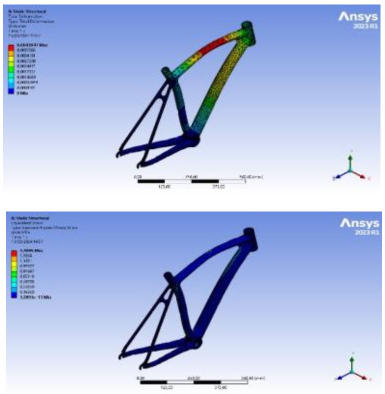


Fig 4. Stress and deformation for aluminium material

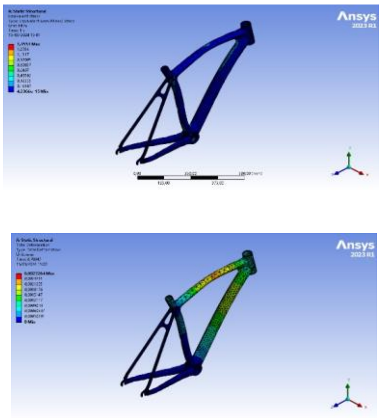


Fig 5. Stress and deformation for titanium material

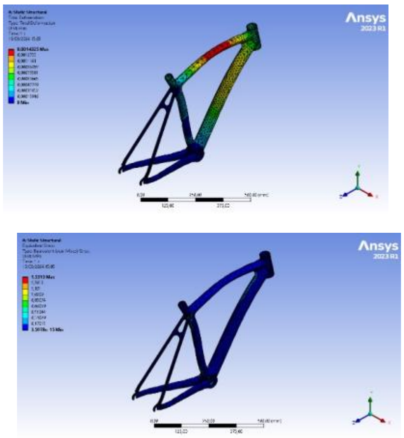


Fig 6. Stress and deformation for carbon steel

The bicycle frame made of titanium exhibited a stress value of 6.9155 MPa in the top tube section and a deformation of 0.012078 mm under a 100 kg load. While the stress is relatively low, the deformation value has reached 0.012078 mm, which falls within the allowable deformation range of 0.1% to 0.5% of the component's length. The yield strength of titanium ranges from 480 to 1100 MPa. However, based on the available information, it is not possible to determine whether the frame approaches or exceeds its yield strength. Therefore, although the deformation remains within acceptable limits, further evaluation of the specific titanium grade used is necessary to ensure the structural safety and optimal performance of the frame.

The bicycle frame made of carbon steel showed a stress value of 1.3813 MPa and a deformation of 0.013705 mm in the top tube under a 100 kg load. Although the resulting stress is relatively low, the deformation exceeds the allowable range of 0.1% to 0.5% of the component's length. This indicates that, while the stress level is still below the yield strength of carbon steel (typically between 500 and 800 MPa), the amount of deformation may pose a risk to the structural integrity of the frame. As such, further evaluation of the frame design or material selection may be necessary to ensure the frame's safety and performance under real-world conditions.

3.3 Design 3

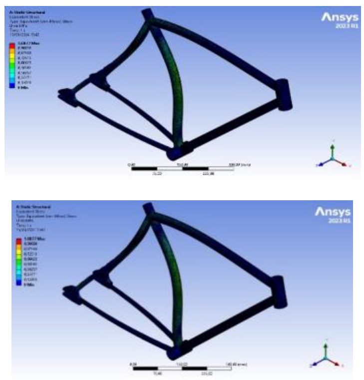
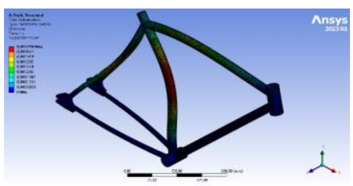


Fig 7. Stress and deformation for aluminimium material



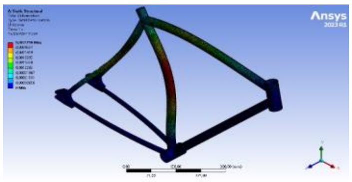


Fig 8. Stress and deformation for titanium material

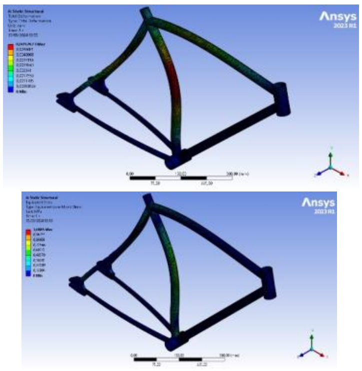


Fig 9. Stress and deformation for carbon steel

The bicycle frame made of carbon steel exhibited a stress value of 7.4787 MPa and a deformation of 0.12196 mm under a 100 kg load. The obtained stress value falls within the yield strength range of carbon steel, which is approximately 500 to 800 MPa, indicating that the material is capable of withstanding the applied load without structural failure. However, the measured deformation exceeds the allowable deformation limit of 0.1% to 0.5% of the component's length. This suggests that, although the frame remains below the material’s yield strength, the significant deformation may reduce the performance or long-term reliability of the bicycle frame. Therefore, further evaluation of the frame design or material selection is recommended to ensure the safety and optimal performance of the bicycle.

The bicycle frame made of titanium exhibited a stress value of 3.7728 MPa in the top tube and a deformation of 0.02799 mm under a 100 kg load. Although the stress value is relatively low, the deformation of 0.02799 mm exceeds the allowable deformation limit of 0.1% to 0.5% of the component's length. Nevertheless, the stress remains well below the yield strength of titanium, which ranges from 480 to 1100 MPa. This indicates that, while the material remains within safe limits in terms of strength, the excessive deformation may negatively affect the frame’s performance and reliability over time. Consequently, further refinement of the frame design may be necessary to ensure both structural integrity and long-term functionality.

3.4 Design 4

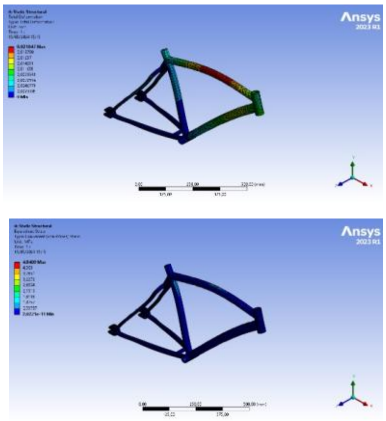


Fig 10. Stress and deformation for aluminium material

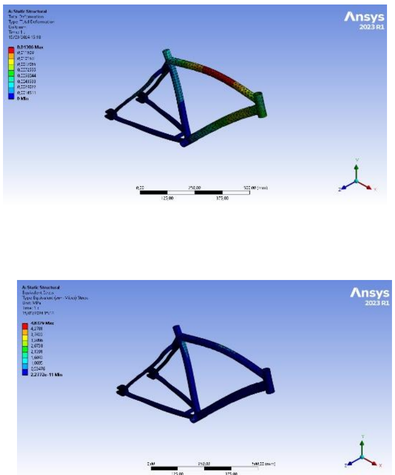
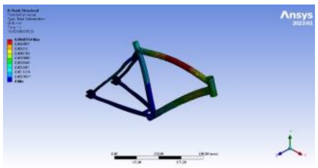


Fig 11. Stress and deformation for titanium material



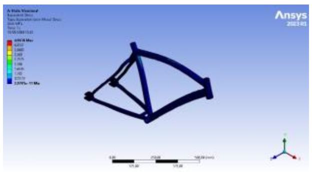


Fig 12. Stress and deformation for Carbon steel

The bicycle frame made of carbon steel exhibited a stress value of 24.679 MPa and a deformation of 0.11515 mm under a 100 kg load. Although the stress value appears numerically low, it must be noted that it significantly exceeds the allowable deformation limits rather than the yield strength. The yield strength of carbon steel ranges from approximately 500 to 800 MPa; thus, the material remains structurally within safe stress limits. However, the deformation value of 0.11515 mm far exceeds the allowable deformation threshold, typically defined as 0.1% to 0.5% of the component's length. This level of deformation suggests a substantial loss of structural rigidity and indicates that the frame may experience undesired shape changes, compromising both performance and safety. Consequently, further evaluation of the design or alternative material selection is necessary to ensure the structural integrity and optimal functionality of the bicycle frame.

The bicycle frame constructed from aluminum exhibited a maximum von Mises stress of 4.5781 MPa and a total deformation of 0.822746 mm under a static load equivalent to a rider mass of 100 kg. The obtained stress value is relatively low when compared to the yield strength of commonly used aluminum alloys for bicycle frames, which typically ranges from 200 to 600 MPa depending on the alloy series and heat treatment condition. According to the theory of elastic–plastic deformation, a structure operating well below its yield strength remains in the elastic region, indicating that no permanent deformation is expected under the applied load.

However, despite the low stress level, the observed deformation significantly exceeds the acceptable serviceability limit, which is commonly defined as 0.1%–0.5% of the component's characteristic length for lightweight structural components. From the perspective of structural stiffness theory, deformation is governed not only by material strength but also by the elastic modulus, cross-sectional geometry, and load distribution. Aluminum alloys possess a relatively low elastic modulus (approximately 69–72 GPa) compared to steel or composite materials, which results in higher deflection under similar loading conditions.

Excessive deformation, even within the elastic range, may lead to a reduction in dimensional stability, adversely affecting riding comfort, handling precision, and fatigue performance of the bicycle frame. According to fatigue and durability theories, repeated cyclic loading under large elastic deflections can accelerate crack initiation and propagation, ultimately reducing the service life of the structure. Therefore, although the aluminum frame demonstrates sufficient strength against yielding, the excessive deformation indicates insufficient structural stiffness.

These results suggest that further optimization of the frame design is necessary, such as increasing tube diameter, modifying cross-sectional geometry, or incorporating local reinforcements to improve bending stiffness. Alternatively, the use of materials with higher elastic modulus or hybrid material configurations may be considered to enhance structural rigidity while maintaining acceptable weight and safety requirements.

4 Conclusions

The simulation results indicate that the titanium-based frame in Design 1 exhibited the highest stress value of 18.156 MPa and a deformation of 0.012078 mm in the top tube region. However, these values remain below the yield strength of the titanium material and within the allowable deformation limits. On the other hand, the lowest stress was observed in the aluminum frame (Design 1) at the head tube, with a stress value of 1.211 MPa and a deformation of 0.0034886 mm. These values also fall within safe limits in terms of both stress and deformation. Overall, the findings of this study provide valuable insights into designing bicycle frames that are both efficient and structurally safe by optimizing material selection and frame geometry. Nevertheless, further evaluation is recommended to ensure the long-term safety and performance of the proposed bicycle frame designs.

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