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Comparison of strength and stability of bicycle frames made from 6061-T6 Aluminum (SS) and Commercially Pure CP-Ti UNS R50700 Grade 4 (SS) materials

***Iip Muhlisin*[a,1], *Niera Feblidiyanti*[a]**

[a]*Department of Industrial Engineering, Universitas Pamulang, Jl. Surya Kencana No.1 South Tangerang City, Banten*

[1]Corresponding author: dosen01937@unpam.ac.id

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ABSTRACT

This study examines the comparison of strength and stability between two commonly used materials in bicycle frame manufacturing, Aluminum 6061-T6 (SS) and Commercially Pure CP-Ti UNS R50700 Grade 4 (SS), through simulations using SolidWorks software. By analyzing the mechanical response of bicycle frames made from these materials under static loading conditions, the research focuses on mechanical characteristics, stress distribution, strain, safety factors, and structural stability. The results reveal significant differences in material response and structural performance between Aluminum 6061-T6 (SS) and Commercially Pure CP-Ti UNS R50700 Grade 4 (SS). These findings provide crucial insights into material selection for bicycle frame design, aiming to achieve an optimal balance between strength, elasticity, and stability. The practical significance of these findings lies in their potential applications in the bicycle industry, where understanding the strengths and limitations of different materials can lead to better-informed decisions in frame design. By optimizing material selection based on specific performance requirements, manufacturers can develop bicycle frames that cater to a wide range of uses, from high-performance sports models to durable, everyday commuting bikes. These insights serve as a foundation for further research and the development of superior bicycle frame designs, ultimately enhancing efficiency and performance in real-world applications.

ABSTRAK

Studi ini membahas perbandingan kekuatan dan stabilitas antara dua material yang umum digunakan dalam pembuatan rangka sepeda, yaitu Aluminium 6061-T6 (SS) dan Commercially Pure CP-Ti UNS R50700 Grade 4 (SS), melalui simulasi menggunakan perangkat lunak SolidWorks. Dengan menganalisis respons mekanis rangka sepeda yang terbuat dari material ini di bawah kondisi pembebanan statis, penelitian ini berfokus pada karakteristik mekanis, distribusi tegangan, regangan, faktor keamanan, dan stabilitas struktural. Hasilnya mengungkapkan perbedaan signifikan dalam respons material dan kinerja struktural antara Aluminium 6061-T6 (SS) dan Commercially Pure CP-Ti UNS R50700 Grade 4 (SS). Temuan ini memberikan wawasan penting tentang pemilihan material untuk desain rangka sepeda, dengan tujuan mencapai keseimbangan optimal antara kekuatan, elastisitas, dan stabilitas. Signifikansi praktis dari temuan ini terletak pada potensi penerapannya dalam industri sepeda, di mana pemahaman tentang kekuatan dan keterbatasan berbagai material dapat membantu dalam pengambilan keputusan yang lebih baik dalam desain rangka. Dengan mengoptimalkan pemilihan material berdasarkan persyaratan kinerja spesifik, produsen dapat mengembangkan rangka sepeda yang memenuhi berbagai kebutuhan penggunaan, mulai dari model olahraga berkinerja tinggi hingga sepeda komuter sehari-hari yang tahan lama. Wawasan ini menjadi dasar bagi penelitian lebih lanjut dan pengembangan desain rangka sepeda yang lebih unggul, yang pada akhirnya meningkatkan efisiensi dan kinerja dalam aplikasi dunia nyata.

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1. Introduction

The background of this research is related to the crucial role of bicycle frames in determining the overall reliability and performance of bicycles. In the development of bicycle technology, the proper selection of materials for the frame is a key aspect that influences the strength and stability of the bicycle [1][2]. This research focuses on comparing the materials Aluminum 6061-T6 (SS) and Commercially Pure CP-Ti UNS R50700 Grade 4 (SS) in the context of strength and stability of bicycle frames through SolidWorks simulation. Both materials are known to have different mechanical characteristics, and this study aims to provide a deep understanding of the performance of these materials in situations that represent real-world bicycle conditions. It is expected that the results of this research can contribute significantly to the optimal material selection to enhance the safety and performance of bicycles.

This research aims to compare the strength and stability of bicycle frames made from Aluminum 6061-T6 (SS) and Commercially Pure CP-Ti UNS R50700 Grade 4 (SS) using SolidWorks simulation. The main focus is to understand the mechanical characteristics of both materials and identify differences in their performance under various load scenarios, providing profound insights into the optimal material selection for bicycle frames [3].

The strength of bicycle frames made from Aluminum 6061-T6 (SS) and Commercially Pure CP-Ti UNS R50700 Grade 4 (SS) has been compared under SolidWorks simulation conditions. There are stability differences between these two materials when subjected to static forces. The mechanical characteristics of Aluminum 6061-T6 (SS) and Commercially Pure CP-Ti UNS R50700 Grade 4 (SS) affect the overall performance of bicycle frames in various simulation conditions.

This research is significant in contributing to the development of bicycle technology by providing a deep understanding of the performance of Aluminum 6061-T6 (SS) and Commercially Pure CP-Ti UNS R50700 Grade 4 (SS) materials in the context of strength and stability. The research results are expected to offer practical guidance for optimal material selection in bicycle frame design, not only for structural efficiency but also for enhancing rider safety and comfort. Additionally, this research may serve as a foundation for the development of more innovative and effective bicycle designs in the future.

Aluminum 6061-T6 (SS) is a versatile alloy with many desirable properties. Here are some of its key properties based on... Material Weight: This material is lightweight, approximately one-third the weight of steel, making it well-suited for structural applications where static loads are a concern. Deformation Capability: Aluminum 6061-T6 has good deformation properties, meaning it can be bent or stretched without experiencing permanent damage. It exhibits good corrosion resistance. Aluminum 6061-T6 is easily workable and can be formed into various product shapes such as sheets, strips, plates, bars, forgings, tubes, pipes, wires, extruded sections, and structural shapes for bicycles. It possesses good welding properties. Therefore, Aluminum 6061-T6 (SS) is a suitable choice for various applications, including aircraft components, automotive parts, and other industrial components requiring high strength with lightweight characteristics [4].

Commercially Pure Titanium (CP-Ti) UNS R50700 Grade 4 (SS) is a type of pure titanium known for its high mechanical strength, lightweight, and corrosion resistance. This material is a good choice for applications requiring structural strength without significantly adding weight to the structure. Additionally, CP-Ti Grade 4 also has resistance to high temperatures and good workability. Its biocompatibility makes it used in medical applications such as implants without causing negative reactions in the human body. These properties, along with ease of processing, make CP-Ti Grade 4 a sought-after material in various engineering and health-related fields [5].

Several previous studies have been conducted to analyze the strength of bicycle frames with a focus on a deep understanding of material responses to various loads and usage conditions. Some studies have explored modeling and numerical simulation using software such as SolidWorks, Ansys [6] [7] Autodesk Inventor [8], and Matlab Simulink [9] to simulate various load scenarios that bicycle frames may encounter. These studies tend to pay attention to critical aspects such as stress distribution, strain, and deformation in various parts of the bicycle frame. Some research has focused more on understanding failure mechanisms, including material fatigue analysis at critical points. Furthermore, previous research has also included comparisons of various materials used in bicycle frames, with an emphasis on aluminum and steel [10]. These studies provide insights into material performance in various bicycle usage conditions, enabling designers to make informed decisions in material selection and optimal geometric design [11]. While previous research has laid a solid foundation, this study aims to contribute further by focusing on a direct comparison between two popular materials, Aluminum 6061-T6 (SS) and Commercially Pure CP-Ti UNS R50700 Grade 4 (SS), in the context of SolidWorks simulation to obtain a comprehensive overview of the strength and stability of bicycle frames.

2. Research Methodology

This diagram outlines the sequential steps involved in conducting the analysis of bicycle frames, encompassing various stages to ensure a comprehensive evaluation of the strength and stability of frames made from Aluminum 6061-T6 (SS) and Commercially Pure CP-Ti UNS R50700 Grade 4 (SS). The first step involves creating a detailed three-dimensional model of the bicycle frame using SolidWorks software, with accurate representations based on their respective material properties. The specific mechanical properties of each material, including modulus of elasticity, yield strength, and density, are input into the simulation software to ensure accurate representation. Various load scenarios are applied to the bicycle frames to simulate real-world conditions, including static loads to assess the response of the frames under different stress conditions. The simulation setup involves defining boundary conditions, constraints, and loading conditions to replicate the actual mechanical behavior of the bicycle frames, ensuring the analysis captures the critical aspects of frame performance. SolidWorks software is utilized to perform finite element analysis (FEA) simulations on both frames, enabling a detailed examination of stress distribution, strain, and deformation in the materials under different loading conditions. The results from the simulations are collected, including stress maps, deformation profiles, and other relevant data points [12], providing a quantitative basis for comparing the strength and stability of the frames. A comprehensive comparison is conducted between the Aluminum 6061-T6 (SS) and Commercially Pure CP-Ti UNS R50700 Grade 4 (SS) frames, analyzing key performance indicators such as maximum stress, deformation characteristics, and overall stability to draw meaningful conclusions. The obtained results are validated against known mechanical properties of the materials to ensure the accuracy and reliability of the simulation outcomes, and the final step involves interpreting the results and drawing conclusions regarding the relative strengths and stabilities of the two materials in the context of bicycle frame applications. This methodology ensures a systematic and rigorous approach to evaluating the performance of Aluminum 6061-T6 (SS) and Commercially Pure CP-Ti UNS R50700 Grade 4 (SS) bicycle frames through SolidWorks simulations.

2.1 SolidWorks Simulation Parameters Used

SolidWorks simulation requires specific parameters to model and analyze bicycle frames effectively [13]:The key parameters used in this simulation include.

- ***Material Properties:***

  Configuring material parameters, namely elastic modulus, tensile strength, and yield strength, is crucial for accurately simulating material responses. Figure 1 and Figure 2 provides information on the Material Properties from SolidWorks data for both bicycle frame materials.

Material Properties

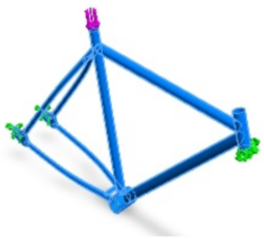
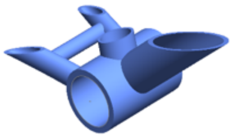
Model Reference	Properties	Components
	Name: 6061-T6 (SS) Model type: Linear Elastic Isotropic Default failure criterion: Max von Mises Stress Yield strength: 2.75e+08 N/m^2 Tensile strength: 3.1e+08 N/m^2 Elastic modulus: 6.9e+10 N/m^2 Poisson's ratio: 0.33 Mass density: 2,700 kg/m^3 Shear modulus: 2.6e+10 N/m^2 Thermal expansion coefficient: 2.4e-05 /Kelvin	SolidBody 1(Cut-Extrude2) (2 mm thin Frame Bike) 
Curve Data:N/A		

Figure 1. Material Property of Aluminum 6061-T6 (SS):

Material Properties

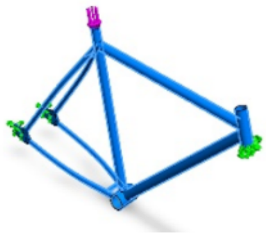
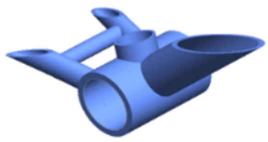
Model Reference	Properties	Components
	Name: Commercially Pure CP-Ti UNS R50700 Grade 4 (SS) Model type: Linear Elastic Isotropic Default failure criterion: Max von Mises Stress Yield strength: 5e+08 N/m^2 Tensile strength: 5.5e+08 N/m^2 Elastic modulus: 1.05e+11 N/m^2 Poisson's ratio: 0.37 Mass density: 4,510 kg/m^3 Shear modulus: 4.5e+10 N/m^2 Thermal expansion coefficient: 9e-06 /Kelvin	SolidBody 1(Cut-Extrude2) (2 mm Thin Frame Bike) 
Curve Data:N/A		

Figure 2. Material Property of Commercially Pure CP-Ti UNS R50700 Grade 4 (SS):

- ***Loads and Boundary Conditions:***

  Determining the loads applied to the bicycle frame and boundary conditions that reflect everyday usage situations or specific test scenarios. Setting a minimum limit of not less than 200 kg is related to the assumed load the bicycle frame receives from the rider and rider's belongings.

- ***Geometry and Dimensions:***

  Inputting accurate geometric dimensions and configurations to ensure the 3D model reflects the actual bicycle structure. The material design takes the form of tubes with a thickness of 2 mm.

- ***Analysis Method:***

  Choosing an appropriate analysis method, namely static analysis [14].

- ***Factor of Safety:***

  Setting the factor of safety is a parameter that determines how much strength is desired in the bicycle frame. This helps ensure that the bicycle frame has a safe tolerance for loads exceeding those anticipated; therefore, in this study, a minimum safety factor of 2.5 is set [15].

By optimizing these parameters, SolidWorks simulations can provide a deep understanding of the strength and stability performance of bicycle frames made from both materials, Aluminum 6061-T6 (SS) and Commercially Pure CP-Ti UNS R50700 Grade 4 (SS), in various usage scenarios.

2.2 Design of 3D Bicycle Frame Model:

The design of the 3D bicycle frame model involves creating an accurate geometric representation of the bicycle frame structure. Attention is given to the main tube geometry, wheel supports, and primary junctions, with a material thickness of 2 mm. This design aims to reduce the weight of the frame while adhering to structural engineering principles to ensure reliability and strength in realistic bicycle usage scenarios. The bicycle frame design is illustrated in Figure 3.

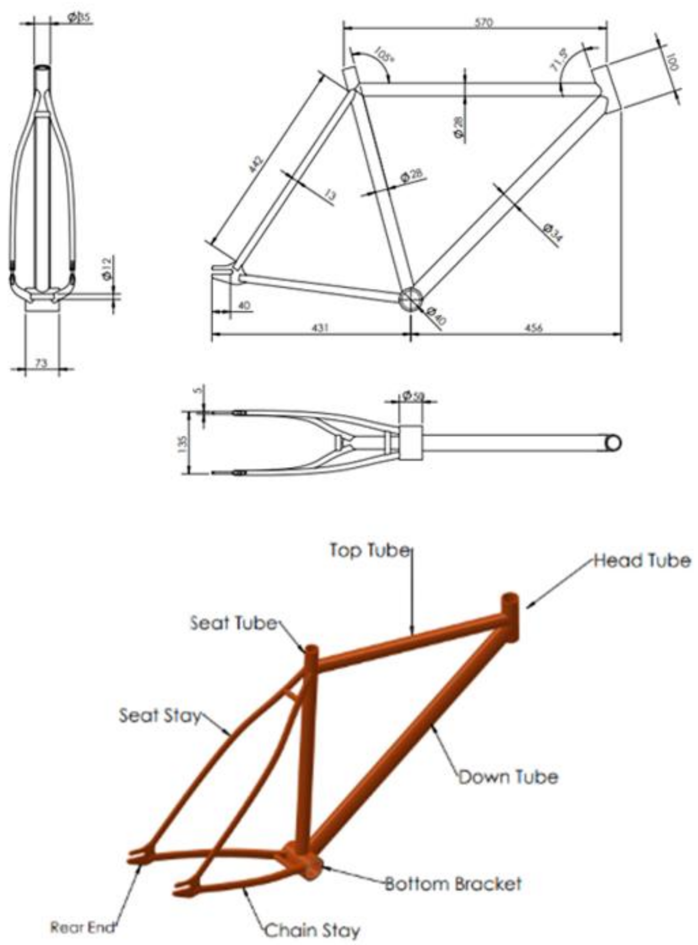


Figure 3. 2D and 3D Modeling of Bicycle Frame

Volumetric properties in SolidWorks are calculated after we create a 3D model. The software analyzes the geometry of our model and uses it to determine various properties like volume, mass, volume,density, and weight These properties are incredibly useful for Performing structural analysis: Volumetric properties are essential inputs for various structural analysis tools in SolidWorks, allowing you to assess the strength and stability of your design. weight and volume information is depicted in Figures 4 and 5, automatically calculated by SolidWorks based on the created 3D model.

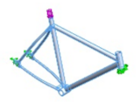
Document Name and Reference	Treated As	Volumetric Properties
Cut-Extrude2 	Solid Body	Mass:1.37165 kg Volume:0.000508015 m^3 Density:2,700.03 kg/m^3 Weight:13.4422 N

Figure 4. Volumetric Properties of Aluminum 6061-T6 (SS) Frame

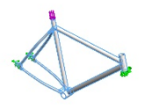
Document Name and Reference	Treated As	Volumetric Properties
Cut-Extrude2 	Solid Body	Mass:2.29117 kg Volume:0.000508015 m^3 Density:4,510.05 kg/m^3 Weight:22.4535 N

Figure 5. Volumetric Properties of Commercially Pure CP-Ti UNS R50700 Grade 4 (SS) Frame

2.3 Determine the fixtures or pivot points

The next step is to determine the fixtures or pivot points. The type of constraint in this simulation uses Fixed Geometry. The pivot points are placed at 2 (two) points on the bicycle frame that has been modeled in 3D. Then, determine the load point, which is at the position of the bicycle rider on the bicycle sea. Furthermore, the load or force to be received by the bicycle frame is determined, with a minimum load of 200 kgf. The applied load in the simulation is in the form of Force (N) and is placed at the upper Seat tube point. The simulation process will be conducted gradually with load variations to achieve comprehensive results. Figure 6 shows specific points that will receive external forces, representing the forces exerted by the rider.

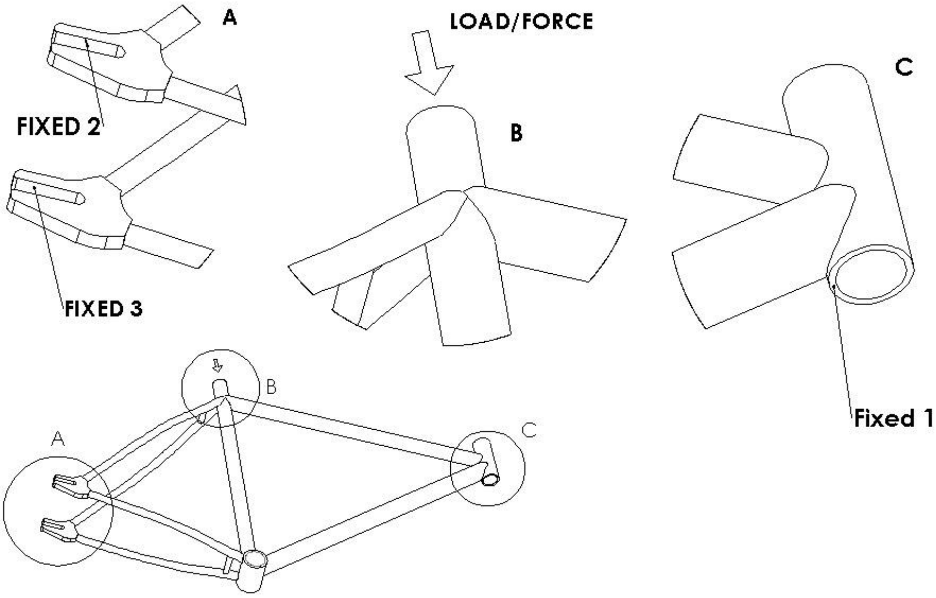


Figure 6. Pivot Points and Load/Force Positions

2.4 Virtual Simulation and Static Testing Process

The virtual simulation and static testing process in this research involve several critical steps to ensure accurate representation and in-depth analysis of the bicycle frames made from Aluminum 6061-T6 (SS) and Commercially Pure CP-Ti UNS R50700 Grade 4 (SS). Firstly, precise 3D models of both bicycle frames are created, considering the appropriate geometry, dimensions, and material characteristics. Subsequently, SolidWorks simulations are run by inputting simulation parameters, including loads, boundary conditions, and material properties. This process is followed by virtual static testing, where the bicycle frames are virtually subjected to loads to evaluate their structural responses. This simulation allows the observation of stress distribution, strain, and deformation in both materials, providing a deep understanding of structural performance under specific conditions.

2.5 Data Analysis and Comparison Method

After completing the simulation process, the simulation results data from Aluminum 6061-T6 (SS) and Commercially Pure CP-Ti UNS R50700 Grade 4 (SS) are analyzed in detail. Stress and strain distributions are evaluated for each material under various loading conditions and critical points. Comparison methods are employed to compare their structural responses, including safety factors, critical points, and potential failure characteristics. Data analysis also includes discussions on how differences in material properties and geometric design affect structural performance. This comparison method allows the identification of the strengths and weaknesses of each material, providing a solid foundation for optimal material selection in bicycle frame design.

3. Results and Discussion

3.1 Figures and Tables values

This section presents the figures and values of simulation test results, summarized in tables, including the results for Stress/Von Mises, Strain, Displacement, and Safety Factor. For the Aluminum 6061-T6 (SS) material, simulations were conducted to determine the maximum load capacity, which was found to be 213 kgf, maintaining the desired safety factor of 2.5. For the Commercially Pure CP-Ti UNS R50700 Grade 4 (SS) material, the simulations identified a maximum load capacity of 395 kgf, also with a safety factor of 2.5.

These findings have significant practical implications for bicycle design and manufacturing. The higher load capacity of the CP-Ti UNS R50700 Grade 4 (SS) indicates its suitability for applications requiring enhanced durability and strength, such as mountain biking or heavy-duty commuting. Its ability to withstand higher stress without compromising safety makes it ideal for frames subjected to rigorous conditions. On the other hand, the Aluminum 6061-T6 (SS), with its lower maximum load capacity, still offers advantages in scenarios where weight and maneuverability are crucial, such as in racing or urban cycling. Its lighter weight contributes to easier handling and faster acceleration, making it a preferred choice for performance-oriented designs.

By understanding these material characteristics, manufacturers can better tailor their bicycle designs to meet specific performance requirements. This targeted approach allows for the development of specialized bicycles that cater to diverse consumer needs, from robust and durable models for rough terrains to lightweight and agile options for speed and efficiency. The insights gained from these simulations can guide the optimization of material selection, contributing to the advancement of bicycle technology and enhancing the overall user experience.

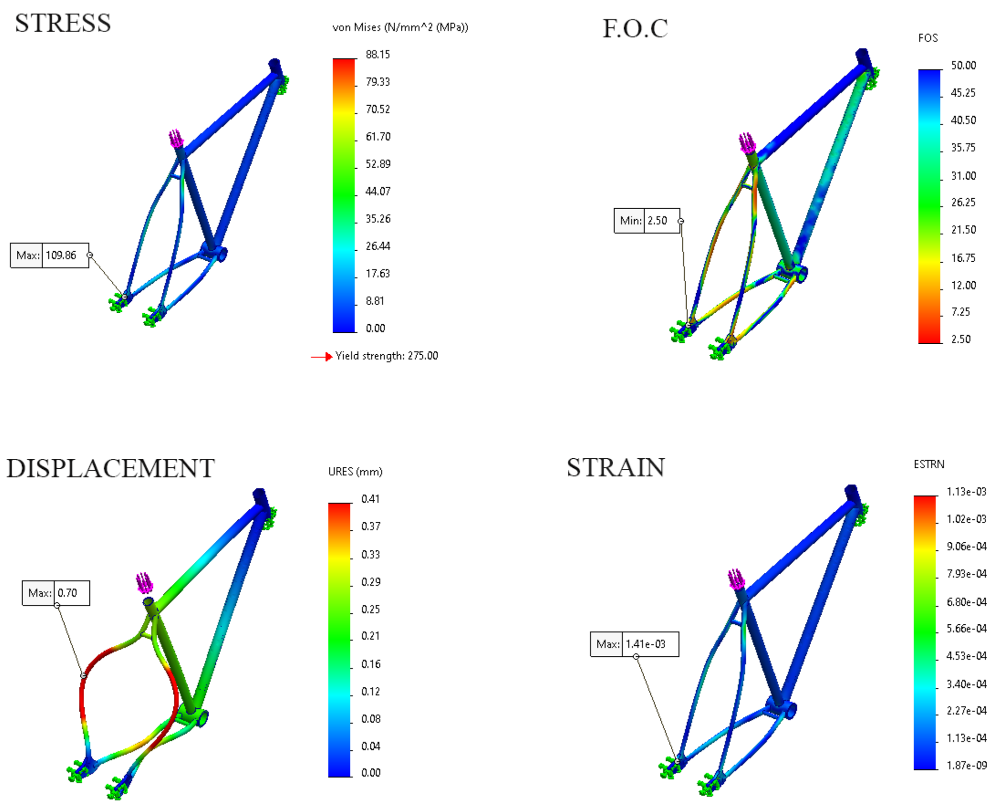


Figure 7. Simulation of Aluminum 6061-T6 (SS) with a load of 213 kgf

Table 1. Aluminum 6061-T6 (SS) with a load of 213 kgf

No	Material	Stress Von Mises (N/mm^2)	Strain	Displacement (mm)	Factor of safety
1	Aluminium 6061-T6 (SS)	109.86	0.00141	0.7	2.5

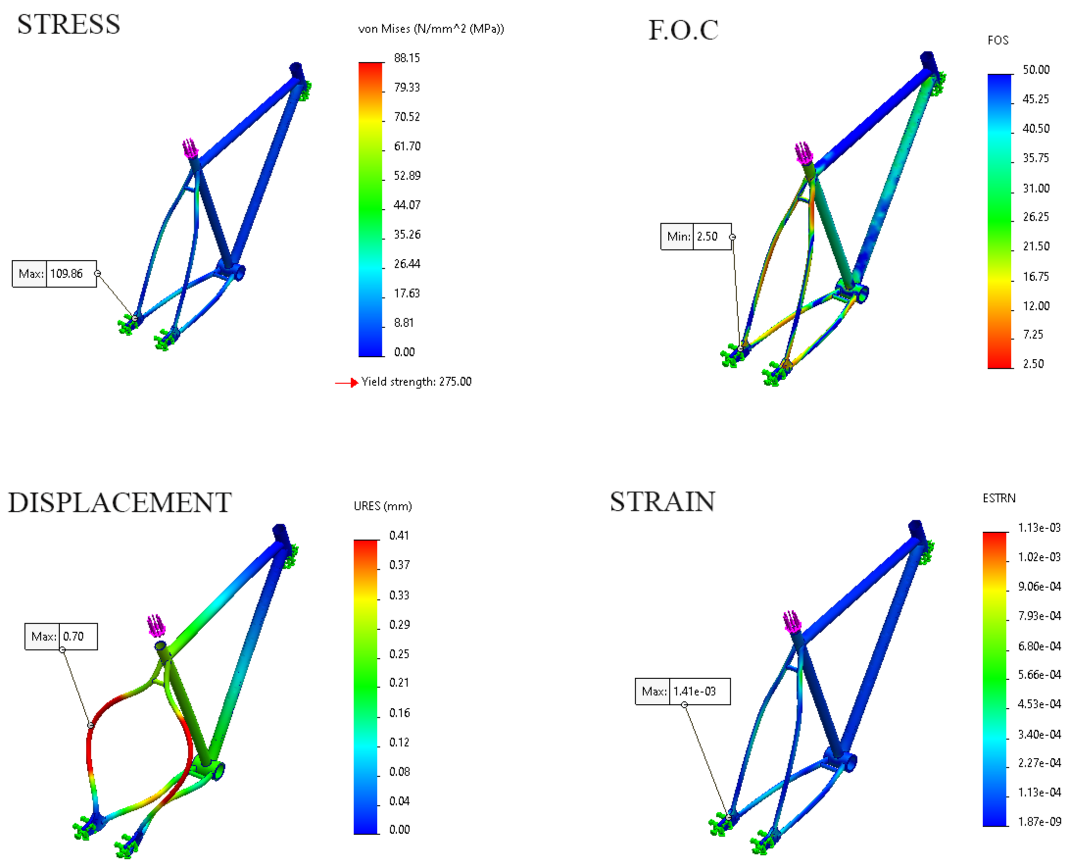


Figure 8. Simulation of Commercially Pure CP-Ti UNS R50700 Grade 4 (SS) with a Load of 213 kgf.

Table 2. Commercially Pure CP-Ti UNS R50700 Grade 4 (SS) Load of 213 kgf.

No	Material	Stress Von Mises (N/mm^2)	Strain	Displacement (mm)	Factor of safety
1	Commercially Pure CP-Ti UNS R50700 Grade 4 (SS).	108.05	0.00094	0.46	4.63

From the simulation test results with a load of 213 kgf, it turns out that the factor of safety is greater than 2.5, specifically 4.63. This means that the frame made of Commercially Pure CP-Ti UNS R50700 Grade 4 (SS) material is stronger than the Aluminum 6061-T6 (SS) material. Consequently, the simulation proceeds to the next stage by adding a higher load to achieve a factor of safety of 2.5. This will ultimately reveal the maximum load that the frame made of Commercially Pure CP-Ti UNS R50700 Grade 4 (SS) material can withstand.

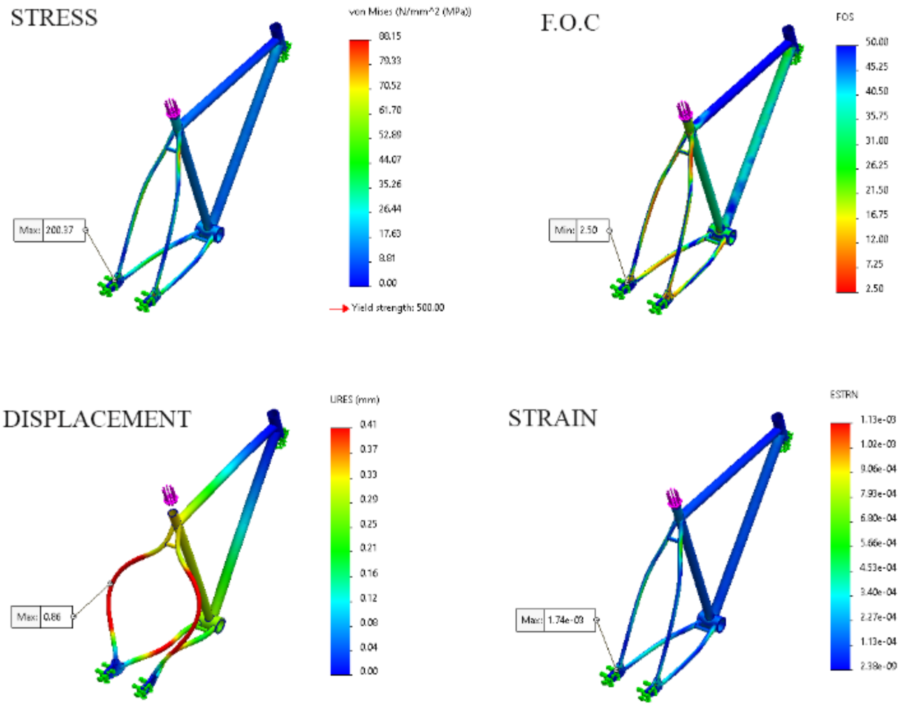


Figure 9. Commercially Pure CP-Ti UNS R50700 Grade 4 (SS) with a Load of 395 kgf

Table 3. The SolidWorks simulation results for Von Mises test (stress), Strain, Displacement, and Safety Factor with a load of 395 kgf on Commercially Pure CP-Ti UNS R50700 Grade 4 (SS) material. The test results show a safety factor of 2.5 and a maximum load of 395, indicating that this material excels in strength compared to Aluminum 6061-T6 (SS) tested at the same safety factor of 2.5.

Table 3. Commercially Pure CP-Ti UNS R50700 Grade 4 (SS) with a Load of 395 kgf

No	Material	Stress Von Mises (N/mm2)	Strain	Displacement (mm)	Factor of safety
1	Commercially Pure CP-Ti UNS R50700 Grade 4 (SS)	200.37	0.00174	0.86	2.5

The summarized results of the conducted simulations can be outlined in Table 4, aiming to provide a comprehensive comparison for each simulation test. This facilitates a holistic understanding of the simulation outcomes for both materials.

Table 4. Simulation Summary.

No	Material	Frame Mass (kg)	Load (kgf)	Stress Von Mises (N/mm2)	Strain	Displacement (mm)	Factor of safety
1	Aluminium 6061-T6 (SS)	1.37	213	109.86	0.00141	0.7	2.5
2	Commercially Pure CP-Ti UNS R50700 Grade 4 (SS)	2.29	213	108.05	0.00094	0.46	4.63
3	Commercially Pure CP-Ti UNS R50700 Grade 4 (SS)	2.29	395	200.37	0.00174	0.86	2.5

3.2 Simulation Results:

The results of the simulation are as follows:

- ***Stress Simulation:***

  The SolidWorks simulation results comparison between Aluminium 6061-T6 (SS) and Commercially Pure CP-Ti UNS R50700 Grade 4 (SS) under a load of 213 kgf indicate that the bicycle frame made of Aluminium 6061-T6 (SS), weighing 1.37 kg, has a strength of 109.86 MPa. Meanwhile, Commercially Pure CP-Ti UNS R50700 Grade 4 (SS), weighing 2.29 kg, has a strength of 108.05 MPa. Aluminium 6061-T6 (SS) stands out for its lightweight and high strength, while Commercially Pure CP-Ti UNS R50700 Grade 4 (SS) provides high stability and durability despite being heavier.

- ***Strain Simulation:***

  At the same load of 213 kgf, Aluminium6061-T6 (SS) produces a strain value of 0.00141, indicating the extent to which the material can be compressed or stretched before experiencing permanent deformation. In other words, it measures how well the material can "follow" the load before damage occurs. Commercially Pure CP-Ti UNS R50700 Grade 4 (SS), under the same load, produces a strain value of 0.00094. This lower value compared to Aluminium6061-T6 suggests that the material is harder and less prone to deformation than Aluminium6061-T6. The simulation results indicate that Aluminium6061-T6 is suitable for applications requiring flexibility and the ability to withstand loads without permanent deformation, while Commercially Pure CP-Ti UNS R50700 Grade 4 is suitable for applications requiring hardness and stability over flexibility.

- ***Displacement Simulation:***

  In the Solidworks simulation, Aluminium 6061-T6 (SS) weighing 1.37 kg produces a displacement of 0.7mm under a load of 213 kgf, indicating that this material has good flexibility. Meanwhile, Commercially Pure CP-Ti UNS R50700 Grade 4 (SS) weighing 2.29 kg produces a lower displacement of 0.46 mm, indicating that this material is more stable and less prone to deformation compared to Aluminium6061-T6.

- ***Factor of Safety (FOS) Simulation:***

  In the Solidworks simulation, Aluminium6061-T6 (SS) weighing 1.37 kg produces a Factor of Safety (FOS) of 2.5 under a load of 213 kgf, indicating a sufficient safety margin for the material. Meanwhile, Commercially Pure CP-Ti UNS R50700 Grade 4 (SS) weighing 2.29 kg produces a higher FOS of 4.63, indicating a larger safety margin compared to Aluminium6061-T6. In the Solidworks simulation, Commercially Pure CP-Ti UNS R50700 Grade 4 (SS) weighing 2.29 kg produces a Factor of Safety (FOS) of 2.5 under a load of 395 kgf. This FOS value indicates a sufficient safety margin for the material to withstand a load of 395 kgf without failure. It demonstrates that this material has sufficient strength and stability for use as a bicycle frame. However, the best material choice will depend on the specific needs of the user and the operational conditions of the bicycle. If stability and safety margin are prioritized, then Commercially Pure CP-Ti UNS R50700 Grade 4 may be the right choice.

4. Conclusion

The comparative study of strength and stability between bicycle frames made of Aluminium 6061-T6 (SS) and Commercially Pure CP-Ti UNS R50700 Grade 4 (SS) in SolidWorks simulations yielded intriguing findings. Aluminium 6061-T6 (SS), with its lighter weight, demonstrates quicker responsiveness and the potential for more agile maneuvering but exhibits a lower safety factor at critical points, specifically the rear end. Meanwhile, Commercially Pure CP-Ti UNS R50700 Grade 4 (SS), with a higher weight, exhibits superior strength and stability, providing a significantly higher safety factor at critical points.

Aluminium 6061-T6 (SS) offers a responsive and agile effect with a weight of 1.37 kg and a safety factor of 2.5 at the pivot point for a maximum load of 215 kgf, making it suitable for usage requiring maneuverability and high speed. On the other hand, Commercially Pure CP-Ti UNS R50700 Grade 4 (SS) is stronger and more stable with a weight of 2.29 kg and a safety factor of 2.5 at the rear end for a maximum load of 395 kgf, making it more suitable for rough terrain conditions and heavy-load usage.

The results of this study have significant implications for the bicycle industry. Awareness of strength and stability based on materials can assist manufacturers in designing products that align with user needs and preferences. Developing bicycles with specific materials can be directed according to the intended use, whether for sports, daily transportation, or adventures in more challenging terrains. A profound understanding of material characteristics and bicycle performance opens up opportunities for better design innovations that cater to various consumer needs.

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