Optimization in Product Design with CAE

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ABSTRACT:

Before a design or structure is manufactured in real life, the virtual model needs to undergo a series of tests and analyses. One of these tests and analyses is to predict if the design or structure's mass can be optimized without compromising the safety and structural requirements that are to be met by the design. This thesis explores the design and optimization of a bicycle frame in the SolidWorks environment. The appropriate material for the bike frame is selected by using the Ashby plots. The stresses on all truss members of the bike frame were also calculated manually by using the method of sections and the method of joints. During the simulation process, five different load cases were studied. These five load cases included static startup, steady-state pedalling, vertical loading, horizontal loading, and rear-wheel braking. The Von Mises stress, displacements and strains that resulted from all five load cases were compared and the case that had the highest equivalent Von Mises stress was used to carry out the design study. This optimization was done by using the Design study tool in the SolidWorks simulation environment. The optimization was done by defining variables, constraints, and goals. While running the study, a total of 222 scenarios were generated of which out of all 222 scenarios, 137 of them were successful. At the end of the optimization of the design, there was a significant decrease in mass of the design from $3.880\ kg$ to $2.273\ kg$. This optimization does not only lead to the decrease in mass of material needed to manufacture the product but also reduces the manufacturing time, manufacturing cost and also makes the manufacturing process more sustainable. Conclusively, this optimized design had a factor of safety of 1.83 and a maximum stress $252\ MPa$ which is both acceptable and reliable so far as safety is concerned.

Keywords:	Bicycle frame, stress, design, simulation, optimization.
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LIST OF SYMBOLS

- σ Normal stress (Pa).
- τ Shear stress (Pa).
- ε Strain (unitless).
- L_0 Initial length (m).
- ΔL change in length (m).
- E Young's modulus (Pa).
- F Force (N).
- m Mass (kg).
- FOS Factor of safety (unitless).
- φ Psi (degrees).
- P Material performance index.
- C_v Relative cost per unit volume.
- σ_x normal stress parallel to the x −axis (Pa).
- σ_y normal stress parallel to the y − axis (Pa).
- σ_z normal stress parallel to the z − axis (Pa).
- τ_{xy} shear in y direction on the plane normal to the x −axis (Pa).
- τ_{xz} shear in z direction on the plane normal to the x −axis (Pa).
- τ_{yz} shear in z direction on the plane normal to the z −axis (Pa).

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1. INTRODUCTION

This bachelor's degree thesis is based on the design and optimization of a bicycle frame in Computer Aided Engineering. In this thesis, the CAD software that is used for the design and optimization of the structure is SolidWorks 2023 developed by Dassault's Systems. The bike chassis is a standard component of a bike and most companies that manufacture these bikes manufacture them in a variety of designs. The bicycle is also made of wheels, tyres, pedals, and gears; However, this thesis is focused on the bike frame and all other components are out of the scope of this work. The performance of a bike is equally affected by its frame design, this frame is made up of several lengths and angles within the structure and the sizes of these lengths and angles might affect the bike rider's comfort and behaviour during usage. This thesis contains the stress analysis and optimization of the design by using SolidWorks 2023.

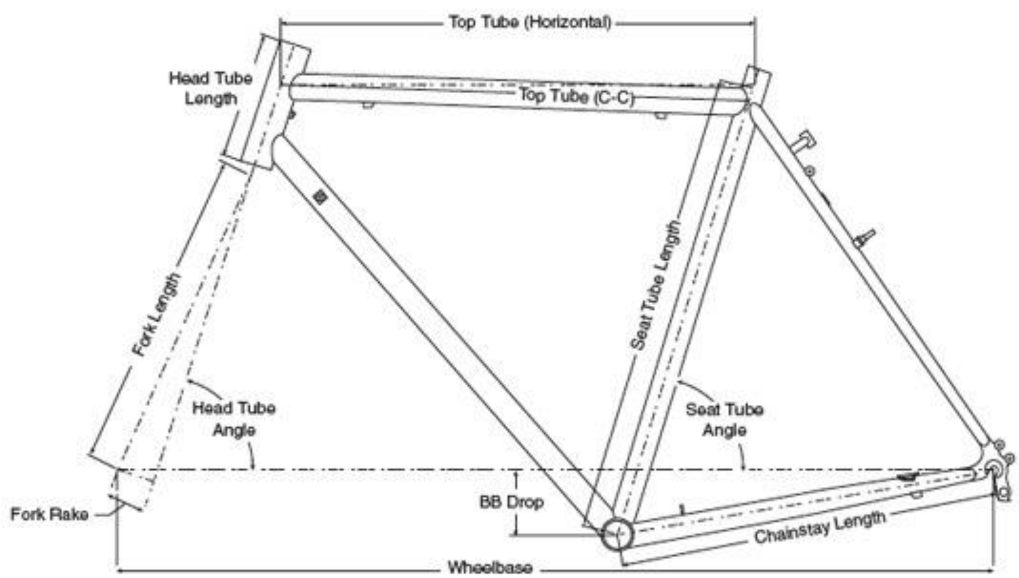


Figure 1: Bike frame geometry with its lengths/angles of components *(Denham, 2013)*.

1.1. Problem definition

A wide range of engineering tasks involves the manufacturing of products, components, and devices before these products and components are manufactured, and before the manufacturing process begins the products need to be designed by using the CAD software. For the design to reach its final stage before the real-life product is manufactured, the design needs to be optimised to minimize the quantity of material needed for sustainable design, reduce the manufacturing cost and reduce the time taken for the final product to reach the market.

1.2. Objectives

The aim of this bachelor's degree thesis is to design a bicycle chassis in SolidWorks, carry out a stress analysis on the design and then optimize the design by using SolidWorks. This thesis work was divided into the following parts.

- Select a suitable bicycle frame and design it by using SolidWorks.

- Calculation of the stresses in the frame members by hand with the application of all governing equations.
- Optimization of the design by using the design study tool in SolidWorks. Sensors and constraints are added in the design study window that will generate a given number of scenarios when the optimization is run. This is done by setting up the constraints, variables, and goals.

1.3. Compliance with degree

Mechanical and Sustainable Engineering is one of the degree programmes offered by Arcada University of Applied Sciences. This programme deals with mechanics and thermodynamics, properties of engineering materials, sustainable design, and manufacturing of prototypes. Mechanical engineering principles are also applied in sectors such as manufacturing, the aerospace industry, construction and the development of robots, car engine components and other tools. Moreover, mechanical engineers use a wide range of scientific skills such as statics and dynamics, materials science, thermodynamics, fluid mechanics, manufacturing and economics, and practical skills such as problem-solving and creativity to perform their duties. This thesis topic is specifically related to materials which involves selecting a suitable material for a bicycle frame, testing its strength under different conditions and loads and optimizing the design.

1.4. Disposition.

This thesis work is divided into six sections which are as follows.

1. ***Introduction.*** This section introduces the problem, provides an overview of the topic, and defines the problem statement to guide the reader to obtain what he/she expects to learn and obtain from the rest of the thesis work.
2. ***Literature review.*** This section provides information on the relevant theories and documented methods that support the study.
3. ***Research approach and methods.*** Introduces the approach and methods used to carry out the research, and the various computational and analytical methods used in the study.
4. ***Results.*** In this section, the results are obtained after the methodology has been carried out and it's used to obtain the goals of the thesis.
5. ***Discussion.*** In this section, the results are discussed regarding theory and the quality of the thesis work.
6. ***Conclusion.*** In the conclusion, the main results of the thesis are presented.

2. LITERATURE REVIEW.

2.1. Engineering design and 3D modelling.

Computer-aided design has become an indispensable tool which is required by most manufacturing and production companies ranging from automotive, aeronautics, and aerospace industries such as Boeing and Airbus, and other mega factories and giga factories. A lot of engineering companies in the world nowadays have adopted several software programs such as Onshape, SolidWorks, Autodesk Inventor, Siemens NX, Fusion 360, PTC Creo and CATIA to be used for Computer Aided Design. Among these CAD software programs; SolidWorks is among the first CAD programs that were developed and it has been compatible with the Microsoft Windows operating system since it was released in 1995. SolidWorks is the 3D modelling software which is currently used by most companies worldwide to design machines and mechanical structures. It would be very hard for one to imagine that in the early 1990s, while CAD software programs existed these software programs were extremely costly and usually required computers with very high processing speeds such as workstations for installation.

An investment of at least 50,000$ was needed per workstation without the training of the operator (Howard & Musto, 2023). This implies that all companies that provide CAD services need to possess both the software and the hardware, however, some of these companies couldn't afford both the hardware and the software for 3D modelling because they were relatively expensive. However, with a rise in the competition in the 3D modelling software market, newer CAD programs have been developed over the years that have made the prices of almost all CAD programs top in the market. Apart from using CAD software to create 3D models of objects and engineering structures, CAD software is also used to carry out stress analyses, and structural analysis, calculate the strength and evaluate the factor of safety of a design.

The term *design* is generally used to describe the aesthetic view of an object or product. Many types of industries and production plans make their designs in different ways, the textile industry designs new styles and fashions of dresses. The design of a product is generally referred to as how the product looks like (the outward appearance). In a more detailed form, design refers to designating out. Design can be considered as all processes which are involved in the process of coming up with the idea, creating it, visualizing it calculating it and defining the specifications of a product. It all commences from the idea. (Childs, 2004).

Ugural (2021, p. 4) says that "*Mechanical Engineering design deals with the conception, design, development and applications of machines and mechanical apparatus of all types, it involves all disciplines of mechanical engineering.*"

2.1.1. Uses of CAD programs.

- **Concept designing:** This involves the development and design of a product from a new idea, maybe a product that has not existed before. After designing the product, the CAD software can be used to create the Engineering drawing of the product that has been created out of a new idea. This enables the product designer to have an in-depth revision of the product since it's still in the virtual form, it's possible to make any adjustments to the dimensions of the model.

- **Reverse engineering:** Reverse engineering is the re-manufacturing of another person's product by carefully examining a sample of the original product, its structure and composition. These CAD programs have enabled engineers to be able to reverse engineer a wide range of products from the original product by creating the 2D model, 3D model and manufacturing drawings of the product.
- **Product engineering:** CAD software is used for designing products and meeting all their mechanical and technical requirements by the mechanical designer and coordinating the whole manufacturing process.

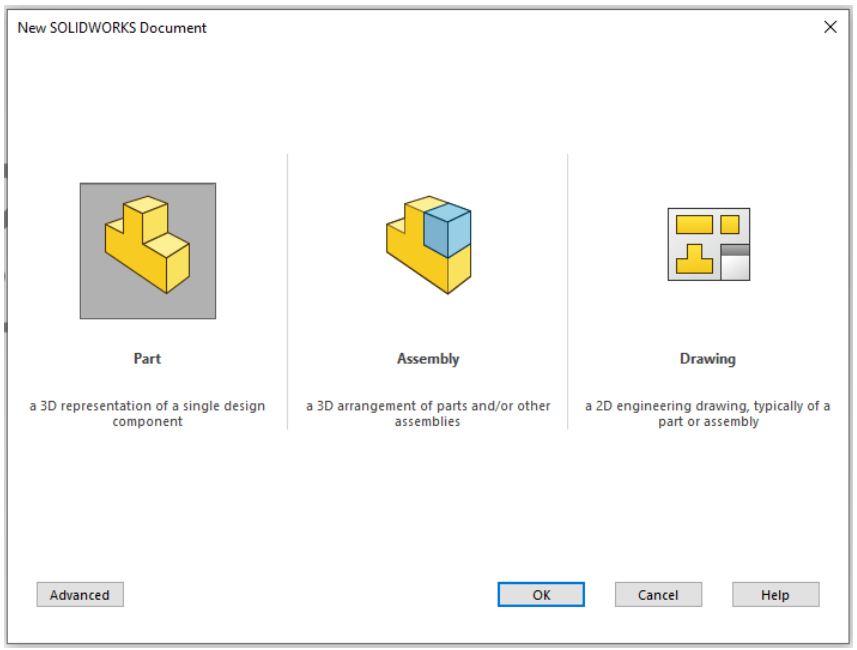


Figure 2: The New SolidWorks Document dialog showing templates for parts, assemblies, and engineering drawings.

- **Conversion from 2D to 3D:** The process of converting the Engineering drawing of a product to the 3D model is at times highly technical to perform such a task. The CAD software can be used to convert the engineering drawings which is the 2D representation of the product to its 3D model.
- **Industrial design:** CAD software is also used to design products so that they can be produced in large numbers. The CAD software is used here to create the 2D drawing and 3D model of several products and assemblies to be used in the manufacturing process. (ISO-9001:2015, 2023)

2.2. SolidWorks as a simulation software.

SolidWorks simulation is the application of Finite Element Analysis (FEA) within the SolidWorks environment. One of the advantages of SolidWorks as a simulation software and other CAD software is that it is user-friendly. SolidWorks simulation plays the role of a fast solver in numeric computations. SolidWorks simulation breaks down the analysis work by generating a detailed solution to complex problems that involve statics, fluid flow, dynamics, buckling, fluid flow, thermal, frequency and pressure vessels (Mustapha, 2022). The SolidWorks simulation tools are incorporated into the SolidWorks environment and can help SolidWorks users and design engineers to do the following.

- To reduce the time taken for the final product to reach the market. Since SolidWorks simulation does not use physical parts, the simulation process will reduce the total time taken for the design and manufacturing process because it enables the first phases to be done within the simulation software that acts as the virtual environment (Mustapha, 2022).
- Reduction of manufacturing cost by not using physical materials in real life, this makes the testing and manufacturing process comparatively inexpensive because it enables the engineers to save a lot of material that must be wasted in real life if design changes are to be made on the prototype (Indovance, 2021).
- Conduct numerical computations on complex parts and assemblies.
- Optimizing designs by the application of sensors and constraints to improve the performance and efficiency of the design.
- SolidWorks simulation provides a cheap simpler and swift method for design engineers to make an early decision in the product development cycle on how to produce the final optimized product (Wasserman, 2014).
- Selection of the best material needed for the design especially when it is to be used for a specific application.

2.3. Types of SolidWorks simulation tools.

2.3.1. Parametric optimization.

Designers use parametric optimization to optimize a design to save time and reduce the manufacturing cost by varying the dimensions, and materials and setting goals, sensors, and constraints.

2.3.2. Buckling analysis.

This is used to analyse buckling in a structure which is subjected to a compressive load so that failure in the design can be avoided because of buckling.

2.3.3. Static analysis

This SolidWorks simulation tool tests designs by using linear materials which are under steady-state load conditions for analysis and iterations which are dependent on the safety factor, stress, strain, and displacement.

2.3.4. Dynamic analysis

This type of analysis is used to study the peak response, acceleration, stress, and displacement of assemblies when the modal time history, vibrational analysis and harmonic analysis are evaluated.

2.3.5. Thermal analysis

Thermal analysis deals with heat transfer both in steady state and transient mode by the various modes of heat transfer such as conduction, convection, and radiation. These results can also be used in other simulation analyses to study how the thermal conditions will affect the mechanical behaviour of a design.

2.3.6. Fatigue analysis

This SolidWorks simulation tool is used to test the fatigue life of a design by applying several load scenarios and by changing the load cycles to determine the lifespan of the material from the maximum stress below its yield point.

2.3.7. Frequency analysis

Another name for frequency analysis is modal analysis because it determines the modal and natural frequencies of vibrating objects such as beams, and it is also used to analyse assemblies. The analysis is conducted on designs that are destined to be used in vibrational environments.

2.3.8. Drop test analysis.

Drop test analysis is a tool which is used for simulating a drop test impact of a component or an assembly. This analysis oversees the impact surface, the height, the velocity, and the drop angle. This will enable the designer to see how the design will behave upon impact.

2.4. Advantages and disadvantages of simulation software.

Advantages

- **Access to material databases:** The software comes with databases that contain most of the materials which are studied with their mechanical and thermal properties.
- **User friendly interface:** SolidWorks has a user-friendly interface which makes it easier for a user to learn how to use the software and easily get acquainted with it.
- **Cost and time saving:** SolidWorks simulation makes it possible to identify and eliminate flaws when the design is still in the virtual environment. This saves the money, time and material which is wasted when expensive prototypes are evaluated in real life.

Disadvantages.

- **Hardware requirements:** The Simulation software demands a lot of hardware requirements on the computer system on which it has been installed. Most of this software requires exceptionally large RAM, very high processor speed, large hard disk space for installation and high graphics memory.

- **Cost:** Simulation software has an extremely expensive license that not everyone who is willing to use the software can afford. Such licenses cost up to thousands of euros.
- **Limited problem-solving capabilities:** The simulation software is limited and might not manage extremely complex and more specialized simulation problems due to its limited capabilities when it comes to such advanced problems. At times the software even crashes and causes the computer to freeze. This has also been personally experienced in the case that the assembly that was been simulated had a screw. Some of SolidWorks simulation tools include SolidWorks Simulation Xpress, SolidWorks Plastics, SolidWorks Motion, SolidWorks Flow Simulation and SolidWorks Sustainability.
- **Results are not 100% accurate:** Simulation software at times has discrepancies in their results when products are tested by engineers. But with time the software can be updated in future to obtain better results. This is because simulation deals with the virtual model of the system which is under test and the accuracy of the results can be affected by factors such as the geometry of the design, and the accuracy of the data used for generating the model (Javatpoint, No date).

2.5. Factor of safety (FOS).

The factor of safety of a design is defined as the ratio of the ultimate stress to the design stress. The factor of safety represents the additional strength of the part or component and assures that an unexpected failure should not occur in a structural design (BYJU'S, 2023).

$$\textbf{Factor of safety (FOS)} = \frac{\textit{Maximum stress}}{\textit{Working or design stress}}$$

$$\textbf{Factor of Safety (for brittle materials)} = \frac{\textit{Ultimate stress}}{\textit{Working or design stress}}$$

$$\textbf{The factor of Safety (for ductile materials)} = \frac{\textit{Yield stress}}{\textit{Working or design stress}} \qquad \textbf{2.1}$$

When selecting this factor of safety, the working stress depends on the following factors:

- **Nature of the loading:**
  The nature of the application of the load matters here the load can either be applied progressively or suddenly, the load can be a constant or fluctuating load, and the design holds the load for a short or longer time.
- **Nature of the material:**
  The presence of residual stresses, voids, and cracks within the material might affect its mechanical performance. It also must be checked whether the material is isotropic or anisotropic.
- **Past cases:**
  Past cases of structural failure that which the structure or component was made up of the same material should be analysed and studied.
- **Environmental factors:**

The nature of the environment in which the material will be used has to be taken into consideration, the factor of safety will also depend on whether the environment is wet, and the effects of rust, corrosion, and wear. (Punmia, Kumar, & Kumar, 2001).

2.6. Stress.

When a body is subjected to an external force and internal resistive force is developed within this body as a response to the external load that has been applied, this internal resistive force is offered to deformation.

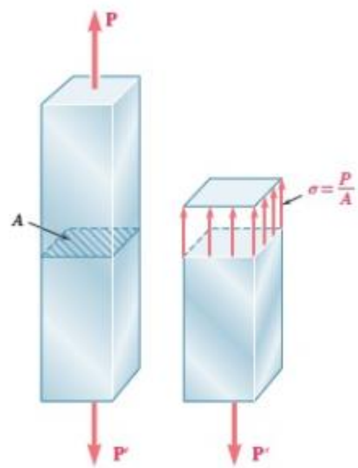


Figure 3: A member under stress which has been caused by an axial load. *(Peer, Jonston, DeWolf, & Mazurek, 2021)*

$$Stress\ (\sigma) = \frac{P}{A}$$

Were, $\sigma = Stress = internal\ resistance$

When the force P acts perpendicular to the cross-sectional area, it is called Normal stress. Normal stress is defined as the ratio of the perpendicular force to the cross-sectional area. Its SI units is Pascals (Pa). The various kinds of stresses include:

- Normal stress (which includes tensile and compressive stress)
- Shear stress or tangential stress.
- Bending stress.
- Torsional stress.
- Fatigue stress
- Volumetric stress

In mechanics, when a material is subjected to an external force, an internal resistance is developed as a response to the external load, this internal resistance can cause the design to deform and may be even reach its yield point and breaking point. The structure can either deform elastically or plastically. When a material undergoes elastic deformation, it retains its original shape and size when the external force is removed. However, when it undergoes plastic deformation, it does not regain its original shape and size when the external load has been removed (Xometry, 2023). This moment that the material passes from the elastic regime to the plastic regime is called the yield point, the material reaches the yield point because the applied stress has overcome the internal resistance offered by the material to the deformation. When this material reaches the yield point, it becomes unable to resist the stress which is being applied to it. (Marinho, 2023). Stress is very important in Mechanics because it can help determine whether a structure will fail if it's made up of a particular material. Apart from external loads, stress in materials can also be caused by other factors such as temperature, humidity, and corrosion (Xometry, 2023). The various types of stresses also help understand the failure modes that can occur in a material, if a structure is loaded with a very heavy load, it will break (Cyprien, 2017). When a structure fails, the failure might have been caused by several failure modes such as mechanical fatigue, fracture, buckling, deflection failure, creep failure, corrosion failure and thermomechanical fatigue (Infinitia Industrial Consulting, 2022).

2.7. Strain

When a force is applied to an object, this force generates stress which causes the object to deform. When this object is pulled, it gets longer and when it is compressed it gets shorter. The deformation of the object measures how it has stretched. This deformation is the difference of the final length to the original length of the object. The strain is the ratio of the elongation to the original length of the object (Boston University, No date).

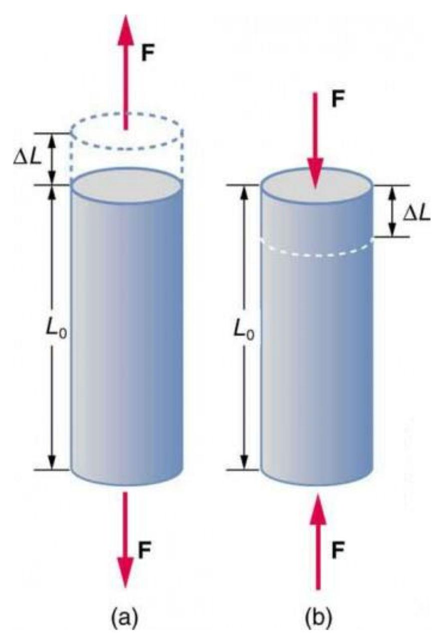


Figure 4: a) Tension in a rod b) Compression in a rod *(Lumen learning , No date)*.

$$\boldsymbol{\varepsilon = \frac{\Delta L}{L_0}} \quad \textbf{(2.1)}$$

ε is strain. It is unitless.

Where ΔL is the change in length$(\boldsymbol{m})$.

L_0 is the original length$(\boldsymbol{m})$.

Strain is unitless.

2.8. Young's modulus$(\boldsymbol{E})$.

Young's modulus is a very important material property because it's very important when it comes to materials engineering. Mechanical engineers, materials engineers and structural engineers use it to study the stress-strain relationship of a material. Elasticity is the ability of a material to deform when a force is applied to it and then return to its original shape and size when the applied force has been removed. Depending on the materials, some of them have no elastic range. Some of these specific materials such as elastomers deform abruptly while brittle materials such as ceramics break with almost no deformation.

Young's modulus is a numerical constant named after the English Physicist Thomas Young. Young's modulus is the ratio of stress (force per unit area) to the strain (extension per unit length) of a material. Young's modulus is represented by the symbol $(\boldsymbol{E})$. Young's modulus is represented by the dimensional formula $[ML^{-1}T^{-2}]$. Young's modulus has units. On a stress stain curve like the one shown in **Figure 5**, Young's modulus is the slope of the linear elastic region.

- Pascals $(\boldsymbol{Pa})$
- Pound per square inch $(\boldsymbol{psi})$

Young's modulus formula

Young's modulus $(E) = \frac{\sigma}{\varepsilon}$

Splitting the formula into other quantities gives; $E = \frac{\sigma}{\varepsilon} = \frac{F/A}{\Delta L/L_0} = \frac{FL_0}{A\Delta L}$, where.

- E is Young's modulus (Pa).
- σ is the uniaxial stress (Pa).
- ε is the strain (it is unitless).
- F is the tensional force (N).
- A is the cross-sectional area of the sample (m^2).
- ΔL is the change in length.
- L_0 is the original length. (Karthik, 2023)

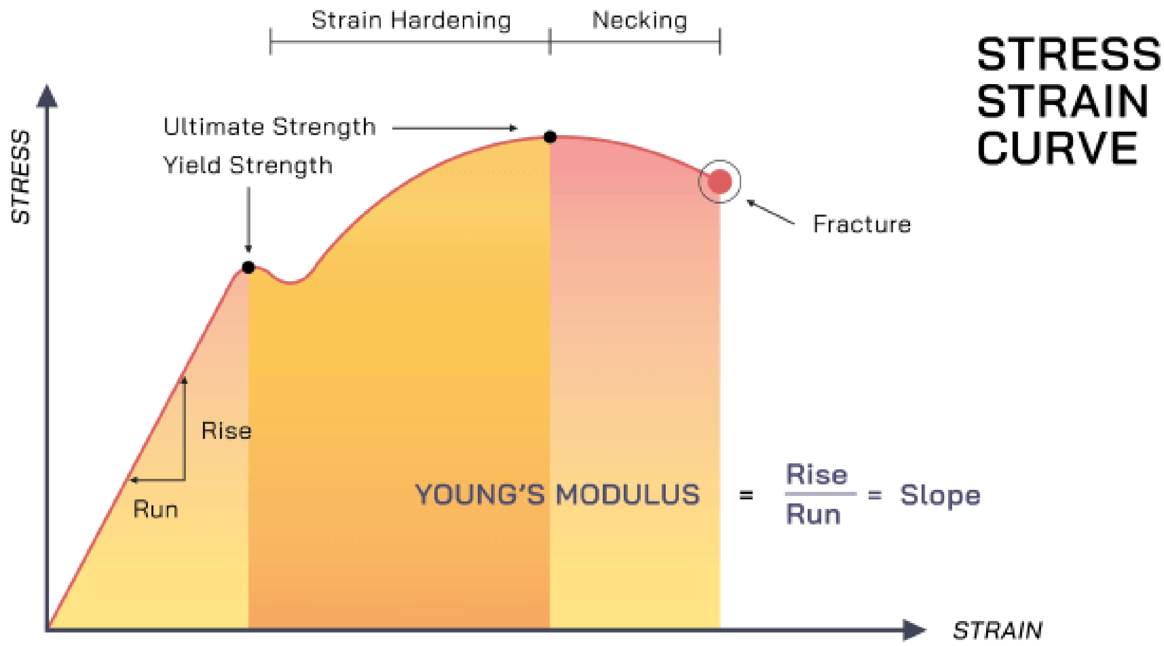


Figure 5: A typical stress-strain curve for ductile materials. *(McGuinness, 2019)*

2.8.1. Importance of Young's modulus.

Nowadays Young's modulus is used in several applications in most of the engineering fields linked to material selection and structural design. It's a vital material property that can help determine when a material can fail. Most of these applications are discussed below.

- In Engineering applications, Young's modulus is used to calculate the thickness required by a material to withstand a certain load before the object is designed, here it's used to predict the material's elastic behaviour.
- Young's modulus gives information about a material's stiffness, and it can be determined the maximum extension of a material or deflection of a beam without reaching its yield point, here it's used for the characterization of the material's property.
- The Young's modulus of a material is used in structural design to predict how a material will behave under certain load conditions. Especially when the design is made of beams, tensile and compressive structures that must respond to loads under certain conditions.
- Young's modulus is used in quality control to verify if the product has reached its manufacturing standards. This can also be done by using both destructive testing and non-destructive testing techniques.
- Engineers consider Young's modulus as an important property when selecting materials to design a structure or component. This will help them determine whether the component can withstand certain stresses that will be experienced. A material with a higher Young's modulus indicates that the material has a higher stiffness, which implies it deforms less under higher loads. Materials with a higher stiffness don't easily stretch when loads are applied. When a material has a lower

Young’s modulus, this implies that it undergoes a large elastic deformation when subjected to a small load, these materials deform so easily. Elastomers such as rubbers are found in this class of materials (Xometry, Young's Modulus: Definintion, values and examples, 2023).

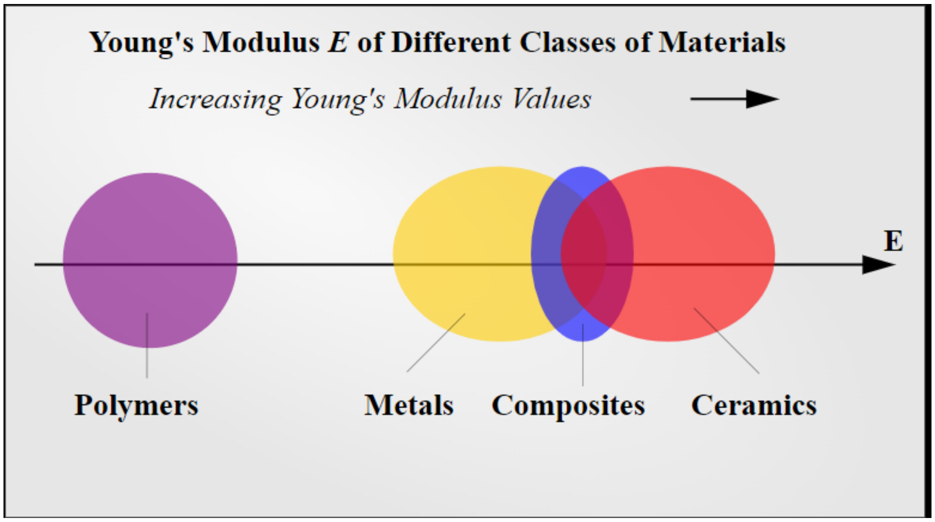


Figure 6: Young's moduli of different classes of materials *(Brandon, 2023)*

2.8.2. Role of Young’s modulus in materials selection and design.

In Engineering applications, when engineers want to design a component or a structure, Young’s modulus plays a significant role in the materials selection process. Young’s modulus provides meaningful information about a material’s stiffness and behaviour, and with this important material property, it can provide information for engineers to choose the materials that meet up with the specific mechanical requirements for applications. This will help secure the safety standard of the of the product, component and structure and make it more reliable. This is how Young’s modulus plays a role in materials selection.

- **Stiffness and deformation:** Young’s modulus measures a material’s stiffness, and a higher value of the stiffness indicates that the material deforms less when a relatively low load is applied to it. Depending on the field of application, such as medical, aerospace, or packaging products, it helps determine the material to be chosen so that the deflection can be minimized (McGuinness, 2019).
- **Safety and performance:** Young’s modulus helps engineers to determine if safety will be compromised if a particular material is used in a particular application. This can be used to predict whether the design will meet up safety standards and performance criteria.

In the material selection process, Ashby plots are used to select materials needed for a specific application in the field of Engineering. In **Figure 7**, the Young’s modulus and densities of the most common Engineering materials have been plotted, most of the materials which are found in the same family of materials have been differentiated by using coloured envelopes. The Young’s moduli range from 10^{-4} to $1000\ GPa$, while the densities of the various classes of materials range from 20 to $20,000\ kg/m^3$. From this figure, the class of materials with the highest stiffness are technical ceramics while the class of material with the lowest stiffness are foams. In terms of the densities of these materials, the densest materials are metals while the least dense materials are foams.

In the material selection process, there are also some designs that the main aim is to reduce and minimize the cost of manufacturing, this makes engineers choose a material that has a lower cost per unit volume. **Figure *8*** shows a material property chart of Young's moduli of the classes of materials and their cost per unit volume, tungsten alloys are among the most expensive while concrete is among the cheapest.

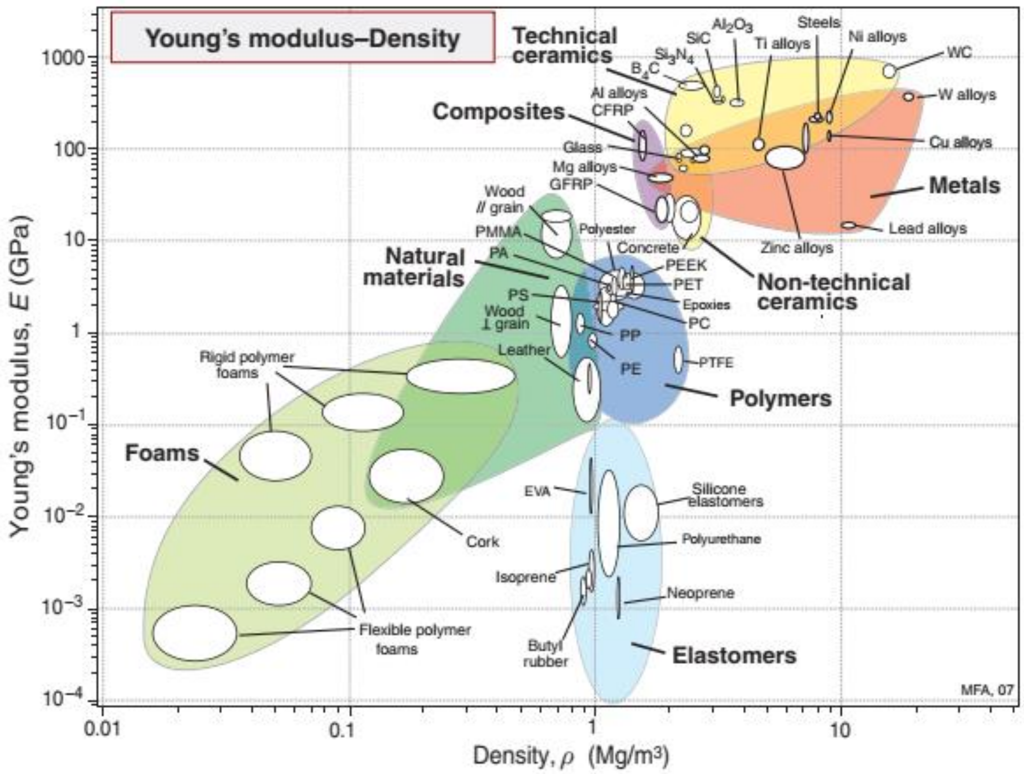


Figure 7: Young's modulus-density chart used in material selection*. (Ashby, Sherdiff, & Cebon, 2007, p. 57)*

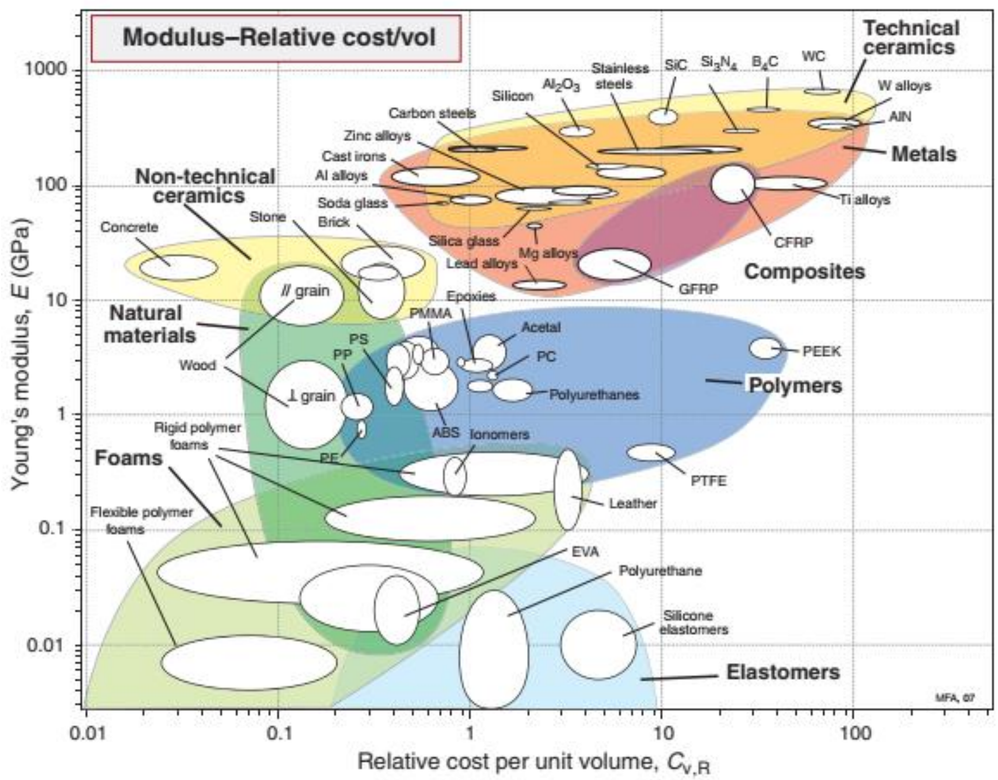


Figure 8: Young's modulus-relative cost per unit volume chart used in material selection. *(Ashby, Sherdiff, & Cebon, 2007, p. 58)*

2.9. Strength of a material (σ).

The strength of a material is the most important property of a material when it comes to Mechanical Engineering design. According to Punmia, Kumar, & Kumar (2001), "*The strength of a material enables it to resist fracture under load"*. The ultimate strength of a material is the ratio of the load required to cause a fracture to the cross-sectional area of the specimen, it is measured in Pascals (Pa). For materials which are used in the tensile environment, the Ulitmate tensile strength of a material is the maximum stress which is reached during a tensile test. In Engineering design, the strength of a material is one of the most important material properties to be considered when designing engineering structures that support and transmit loads as the ones in bridges and aeroplanes. The load that is needed for the structure to reach its breaking point has to be less than the design load that the structure can support. This implies the factor of safety of the structure has to be greater than 1 and the most recommended safety factor of an engineering design is 2.

2.10. Von Mises stresses.

Von Mises stress is a measure to predict if a material will reach its yield point or undergo permanent deformation. Von Mises stress is used in mechanical engineering design to predict if a structure can withstand the desired loads without reaching its breaking point. The structure will fail if the maximum Von Mises stress that is induced on the design is greater than the strength of the material. So, it is used to predict whether a ductile material will fail when subjected to complex loading conditions throughout its lifetime.

The Von misses stress is particularly useful when a design is subjected to a complex load that does not have a single stress component. When the load is complex, instead of using a single stress component, three stresses that act in the three principal directions are used to represent the Von Mises stress which is a scalar quantity and it's the equivalent stress which is obtained when all three principal stresses are combined at any given point.

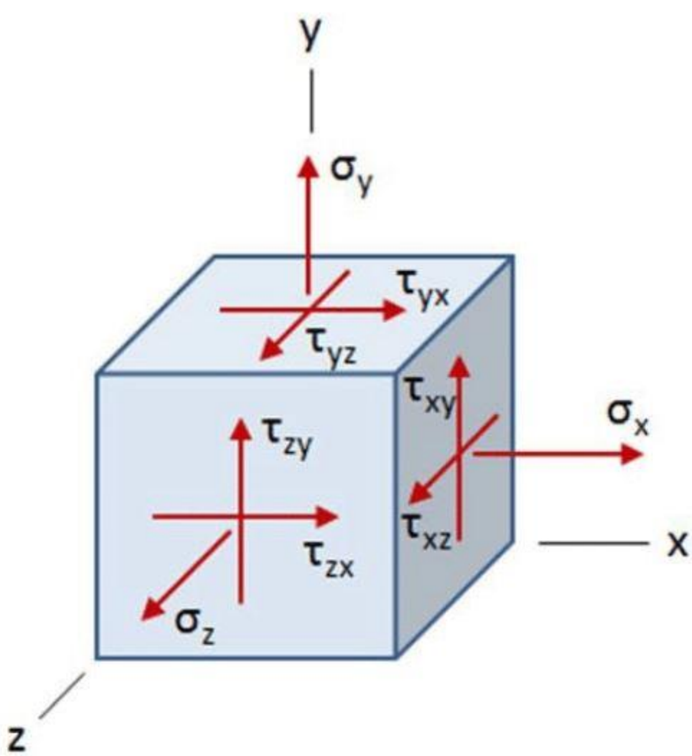


Figure 9: The stress tensor with stress components *(Patel, Riveros, Thompson, & Tordesillas, 2019)*.

$$\boldsymbol{\sigma_{VM}} = \sqrt{0.5\left[\left(\boldsymbol{\sigma_x} - \boldsymbol{\sigma_y}\right)^2 + \left(\boldsymbol{\sigma_y} - \boldsymbol{\sigma_z}\right)^2 + (\boldsymbol{\sigma_z} - \boldsymbol{\sigma_x})^2\right] + 3(\boldsymbol{\tau_{xy}^2} + \boldsymbol{\tau_{yx}^2} + \boldsymbol{\tau_{zx}^2})} \qquad \textbf{2.2}$$

Where.

- σ_x is the normal stress parallel to the x –axis.
- σ_y is the normal stress parallel to the y – axis.
- σ_z is the normal stress parallel to the z – axis.
- τ_{xy} is shear in y direction on the plane normal to the x –axis.
- τ_{xz} is shear in z direction on the plane normal to the x –axis.
- τ_{yz} is shear in z direction on the plane normal to the y –axis.

2.11. Mohr's circle.

The Mohr's circle is a graphical method that embodies mathematical precision and elegance to visualize the transformations for normal and shear stresses at a particular angle in an object that has been loaded (VanWagnen, 2022).

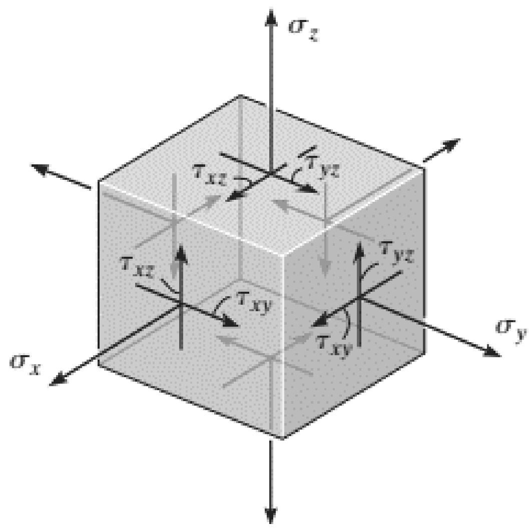


Figure 10: General 3D stress state of an element. *(Hibbeler R. , 2018, p. 463)*

The normal and shear stresses on this stress element in this stress element shown in Figure 10 3D can be brought together by using the 3×3 matrix in below which is called the stress tensor.

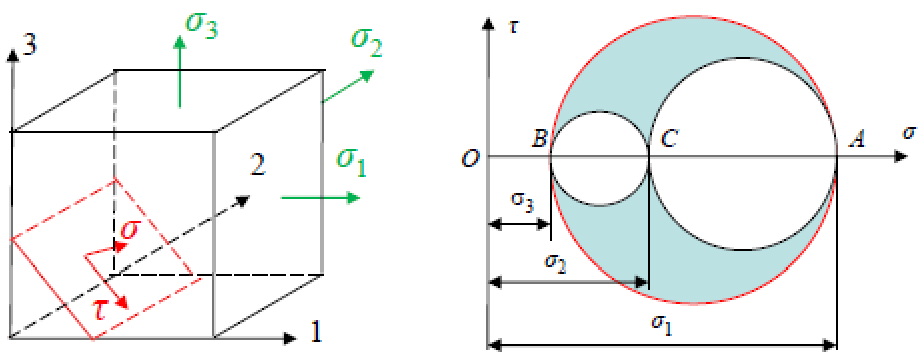
$$\begin{pmatrix} \boldsymbol{\sigma}_{xx} & \boldsymbol{\tau}_{xy} & \boldsymbol{\tau}_{xz} \\ \boldsymbol{\tau}_{yx} & \boldsymbol{\sigma}_{yy} & \boldsymbol{\tau}_{yz} \\ \boldsymbol{\tau}_{zx} & \boldsymbol{\tau}_{zy} & \boldsymbol{\sigma}_{zz} \end{pmatrix}$$

Where;

- σ_{xx} is the normal stress acting along the x- direction.
- σ_{yy} is the normal stress acting along the y- direction.
- $\tau_{xy} = \tau_{yx}$ is the shear stress acting along the xy- plane.
- $\tau_{xz} = \tau_{zx}$ is the shear stress acting along the xz- plane.
- $\tau_{yz} = \tau_{zy}$ is the shear stress acting along the yz- plane.

The normal stresses are on the diagonal while the shear stresses are on the off-diagonal $\boldsymbol{\tau_{xy} = \tau_{yx}}$, $\boldsymbol{\tau_{xz} = \tau_{zx}}$, $\boldsymbol{\tau_{yz} = \tau_{zy}}$

On Mohr's circle, the normal stress is located on the x axis while the shear stress is located on the y axis and it's positive down and negative up. It gives an easier graphical way to determine the normal and shear stress components when an element is rotated at different orientations rather than using the stress transformation equations which will be more time-consuming. The Mohr's circle shown in Figure *11* and **Figure *12*** can also be used to determine the principal stresses σ_1, σ_2 and σ_3



(Balasubramani, 2016)

Figure 11: 3D stress state and indication of principal stress and directions and its corresponding Mohr's circle.

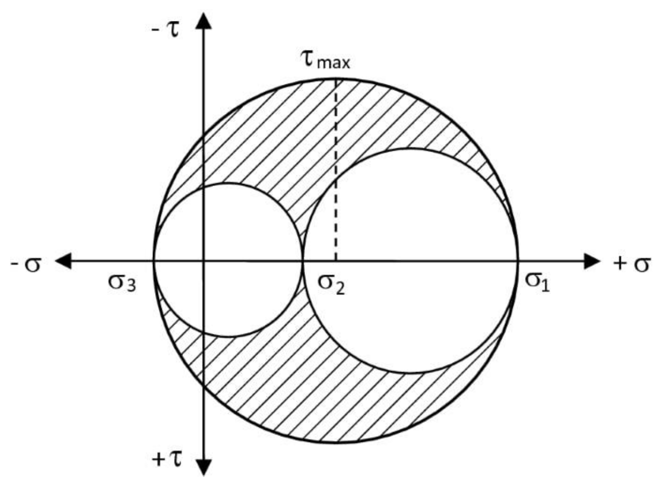


Figure 12: Mohr's circle showing the location of the principal stresses. *(Velázquez, 2020)*

The maximum shear stress occurs when $\boldsymbol{\tau_{\max} = \frac{\sigma_1 - \sigma_3}{2}}$ and $\boldsymbol{\sigma_3 > \sigma_2 > \sigma_1}$

The absolute maximum shear stress is the same as the in-plane shear stress which is found from rotating an element in Figure *10* 45° about the z- axis. The Mohr's circle can also be used to determine the absolute maximum in-plane shear stress on which the strength of a ductile material depends.

2.12. Mechanics of bicycle frame

Let us assume that the average weight of an adult is 75kg. When the rider has such a mass climb on the board, it's not going to buckle or snap because the bicycle frames are made up of materials that have high strengths and stiffness such as aluminium alloys, steels, and carbon fibre composites irrespective of the fact that the steel tubes are hollow. The truss structure of the bicycle frame also improves its stability and rigidity. The bicycle frame does not simply support the rider, but it's made up of two triangles that have been joined together to form a truss (Woodford, 2022). "*A truss is a structure which is composed of slender members joined together at endpoints*" (Hibbeler R. C., 2017, p. 273) . The role of the truss is to distribute the load to the metal structure and wheels. This truss structure helps to give more rigidity to the bicycle frame especially when riding through difficult terrains such as mountains to avoid over-flexing. The bicycle frame has crucial functions on the bicycle as follows.

- **Stress distribution:** This is one of the most crucial functions of the bicycle frames, this will significantly reduce the stress concentrations around a specific area, especially around the joints and this also helps in the prevention of material fatigue.
- **Structural integrity:** The bike frame acts as a connection point to most of its critical components like the front and rear wheels, the steering, the pedal, and the suspension system. This connection acts as a form of reinforcement to the bike.
- **Load bearing:** The bike frame bears most of the loads and force induced on the bike, these forces might come from the rider's weight, pedalling forces, and external impact forces. The truss section of the bike also distributes the loads to all its members.
- **Impact resistance:** Bikes might crash into a wall, or a tree or collide with any other object. Upon impact, the frame absorbs and spreads the forces that are exerted on the bike during impact, and this reduces the impact caused by the crash or impact, carbon fibre is the best bike frame material in terms of energy absorption during collision and impact.

2.12.1. Frame design.

The frames of modern bicycles are designed in a diamond shape with two triangles (the main triangle and the rear triangle) as shown Figure 13 which gives structural integrity and makes the structure to be rigid (West Virginia University , 2023).

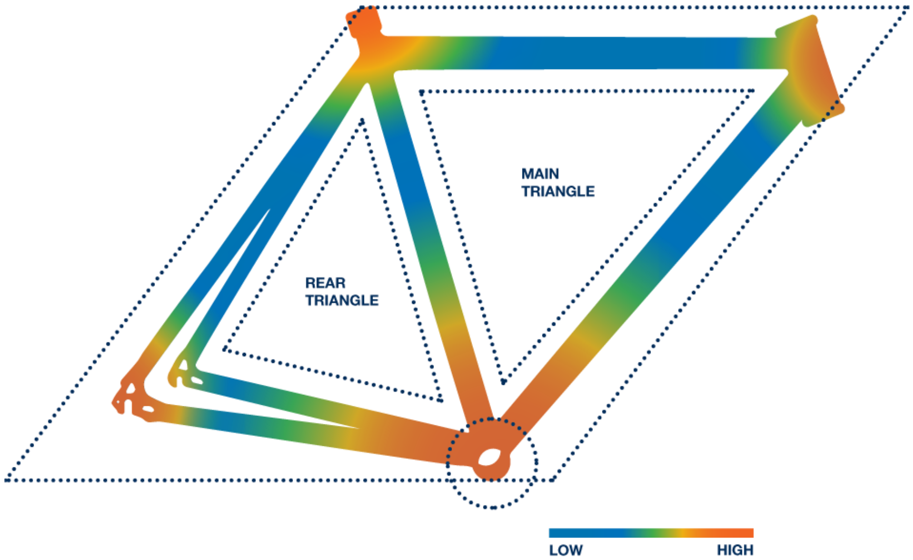
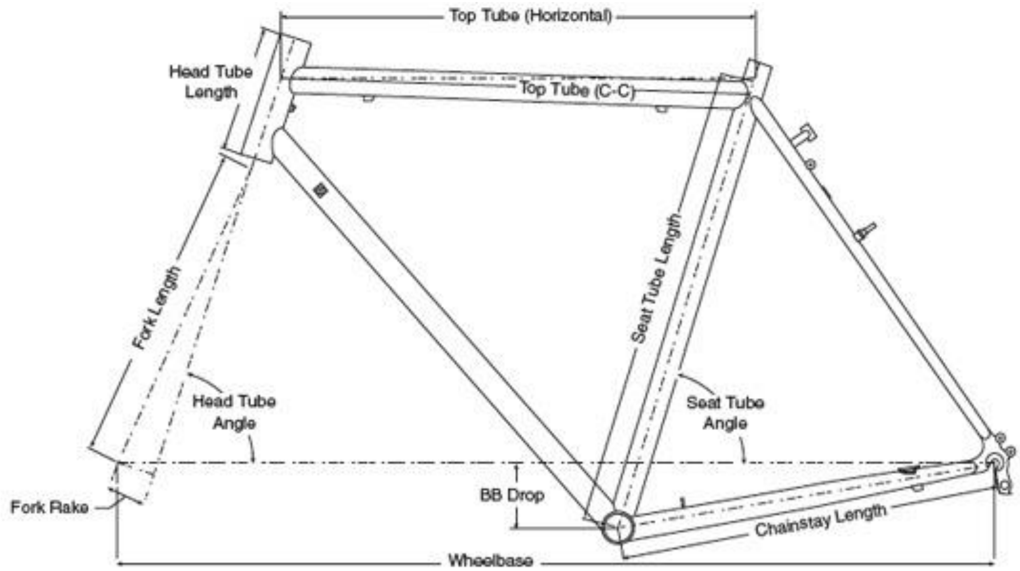


Figure 13: The two principal triangles of a bicycle frame*. (West Virginia University , 2023)*

These two triangles of the standard bike frame are made up of several parts which will be discussed in detail in this section. The main triangle is made up of the head tube, down tube, top tube, and head tube while the rear triangle is made up of the seat tube, chain stays and seat stays as shown (Normann, 2023).

Figure 14: A diamond frame of the most common bicycle frame design (Ellis, 2022)



(Denham, 2013)

Figure 15: Standard bicycle frame geometry showing its components.

- The down tube is the component of the bicycle chassis that slopes upward from the bottom bracket to the head tube. This downtube maintains structural integrity in the frame and gives a greater contribution to the bike's strength and stability.
- The top tube is the horizontal tube which is parallel to the ground, and it's slightly angled (that is, it normally slopes downward from the head tube to the seat tube). It's sometimes called the crossbar (Ellis, 2022). Some sloped top tubes might compromise the integrity of the bike frame design and will require additional tubes as an alternative or a different material that has the same strength (Omo, 2021).
- The seat tube connects the bottom bracket to the seat post of the bike. It's located at the back of the bicycle frame's main triangle. The saddle height can be changed by adjusting how far the seat post is inserted into the seat tube. In some bicycles, this is done by the application of a quick-release lever. Some seat tubes also contain a minimum insertion mark to which the seat post must be inserted. (Omo, 2021)
- The head tube is the shortest tube which is found in the main triangle of the bicycle chassis. It links the handlebars to the wheel fork; it also supports the headset bearings that secure the position of the fork. These bearings allow the rider to steer the fork by using the handlebars. (Normann, 2023)
- The seat stays are two inner tubes that connect the saddle to the rear wheel hub, this helps secure the position of the wheel. A standard bike chassis is composed of two seat stays and each of the seat stays is connected to one side of the spindle of the rear wheel.
- The chain stays are the two inner metal tubes that run parallel to the ground from all two sides of the pedals to all two sides of the rear wheel. They are called chain stays because they run alongside the bike's chain. These chain stays connect the bottom bracket shell to the lower ends of the seat stays. When the seat chain stays are shorter, it implies the bicycle will move faster and

easier when climbing uphill while the front wheel doesn't lose contact with the ground (Omo, 2021).

- The bottom bracket shell is a short tube that connects the chain stays, the seat tube, and the down stays. This bottom bracket shell houses the crankset that links all two pedals on both sides of the bicycle, the shell houses the bearings that facilitate the rotation of these pedals by the rider. It gives additional rigidity to the whole bicycle frame because it links most of its components.

2.13. Materials used in bicycle frames.

Bike frame materials and technology have revolutionized over the years. As years pass, the materials have been changing from heavy to lighter, stiffer, and more flexible materials. All these bike frame materials have their advantages and drawbacks depending on the terrain and environment in which they are used. The choice of the bike frame is at times challenging but depends on several factors such as the cost per kg, the weight, tensile strength, stiffness and flexibility, aesthetic view, repairability, corrosion resistance, durability, and ride characteristics. Here are all four most common materials which are used in bicycle frames.

Figure 16: Most used bicycle frame materials. *(Ahmed, 2014)*

2.13.1. Aluminium alloys

Aluminium alloy is the most used material in bike frames in the modern bicycle industry. In most of the applications, pure aluminium is not used because it's relatively weak, so, a small percentage of other metals and minerals such as magnesium (Mg), silicon (Si), chromium (Cr) and copper (Cu) to improve the material properties (World Material, No date). The most used aluminium alloy in bicycle frames is Al 6061 which was developed by Alcoa in 1935. The apparent composition of Al 6061 is 97.9% AL, 0.6% Si, 1.0%Mg, 0.2% Cr, and 0.28% Cu (Cavallo, No date). During the manufacturing process, the aluminium alloy is always heat treated to maximise the strength of aluminium, this heat treatment helps get rid of the residual stress left in the material after welding, which might affect its tensile strength and ductility but not the material's stiffness (Novović, 2023). This aluminium alloy almost has the same strength and stiffness as steel, but steel has three times its density, which implies aluminium alloy has a relatively greater specific strength as compared to steel, this explains why aluminium metal tubing is made thicker to obtain the required stiffness to the bike frame. The wall thickness of aluminium bike tubing is around two times that of steel if the same stiffness is to be maintained which makes its diameter to be about 20-30% longer (Pfender, 2020).

Advantages of using aluminium alloys as a bike frame material.

- It is a lightweight material.
- The manufacturing cost is low and mass production is easier.
- Has an excellent stiffness.
- Can easily undergo hydroforming. (British Cycling, No date)

Disadvantages of using aluminium as a bike frame material

- Aluminium bike frames are more difficult to repair than other alloys.
- As these frames are cheap, they produce a very harsh ride due to their stiffness and rigidity.
- It can easily lose its strength over time due to material fatigue. (Hersey, Bike frame materials: Anything you need to know , 2022)

2.13.2. Carbon fibre.

Carbon fibre is an excellent material for modern bike frames, it was found at the summit of the bicycle chassis market. This material is just like a "magic material". It has excellent mechanical properties to the extent that it's not used for any kind of application. This is a material which is anisotropic (meaning its mechanical properties are not the same in all directions, and this also depends on the directions of the fibres). It's mostly used for the manufacturing of chassis of modern sports bikes and cars or any other bike which is being raced at the professional level. This material has a high stiffness-to-weight ratio, this is the main advantage of this material because at a given stiffness carbon fibre is relatively lighter than all other metals which are used in producing bicycle frames. This lower density also means that bike frames which are made up of this material absorb the road vibrations rather than transmitting them, this makes the rider feel more comfortable (Sumner & Hurford, 2022). However, with all these excellent properties carbon fibre has over other metals, the reason why it's at times not used to design bike frames is because it tends to be brittle. Imagine that if we take a bunch of parallel continuous fibres and join them together with glue, this will form what's known as a ply, these plies form a laminate, and these laminates tend to be tough which at times make them brittle whereas metals can be bent and their originals shapes can be regained and this makes them last longer (Kei, No date).

Advantages of using carbon fibre as a bike frame material

- Carbon fibre has a relatively high stiffness-to-weight ratio, this makes it have a higher stiffness than other bike frame materials but of a smaller mass.
- It has a low thermal expansion.
- The orientations of the fibres can be changed to favour the stiffness so that the riding comfort can be improved (Pfender, 2020).

- It can be manufactured in complex shapes making it possible for the bike makers to manufacture aerodynamically stable designs which offer the least air resistance. This also makes it possible to produce frames of a variety of shapes (Trifox, 2023).

Disadvantages of using carbon fibre as a bike frame material.

- Carbon fibre-reinforced composites are very expensive, and the production cost is very high.
- Carbon fibre-reinforced composites have an excellent stiffness; however, this material is brittle which makes its sudden failure have devasting consequences because when the material reaches its yield point when cycling is in action, it might fail without showing any warning to the rider.
- Carbon fibre-reinforced composites are anisotropic, meaning that the mechanical properties of this material are direction-dependent. This might complicate the design and analysis process because the load direction must be carefully chosen.
- It's hard to repair.

2.13.3. Steel

Steel was chosen as the universal material for making bike frames before the 1970's and the 1980's when aluminium took over steel and carbon fibre-reinforced composites started been used to manufacture some bike frames from the 1990's (The Bike Exchange team, 2017). Steel is a cheap material, durable, it's resistant to fatigue and can easily be repaired. However, the main reason for steel's decline in the manufacturing of bicycle frames is that it has high density which makes it relatively heavier and that it's more vulnerable to rust especially when neglected. Steal is principally used to manufacture bicycles for kids and city bicycles (Pillay, 2020).

Advantages of using steel as a bike frame material.

- Steel is cheap and its manufacturing cost is low.
- Can be easily repaired since a welder can weld the joints if there's a fracture at the joints.
- Steel frames last longer than other bike frame materials, even when it's scratched and dented, this might not compromise its structural integrity. Most of these steel frames can survive sudden impact without failing. (Friedman, 2023)
- Steel frames can withstand heavy weights and heavy riders. At times, even when the rider is heavier than the maximum specified weight that has been recommended by the manufacturer, this rider can still use the bike without compromising the structural integrity of the bicycle.

Disadvantages of using steel as a bike frame material.

- It's relatively heavier as compared to other bike frame materials. This makes the rider ride at a slower average speed which has been caused by the weight of the frame. This is worse when it comes to a competitive ride.
- Has a high vulnerability to rust especially when abandoned without using a rust inhibitor that can slow down the process.
- If it's made too light, this will make the frame to be excessively flexible (British Cycling, No date).

- Steel frames are made from steel tubing that have been welded together, this makes it less technologically advanced whereas aluminium and carbon fibre frames can also be manufactured by using advanced manufacturing techniques (Friedman, 2023).

2.13.4. Titanium alloy

Titanium has two times the density of Aluminium but about half the density of steel and does not rust like steel. Titanium is a bike frame material that has the highest strength-to-weight ratio. Titanium frames are very expensive due to the cost of the raw material (the material is very rare, and this makes it expensive) and the manufacturing process which is labour-consuming as it's a skill that not everyone possesses. These frames offer a high-quality ride to the rider (Bikecrunch, 2023). The high comfort and durability provided by titanium bike frames make many commuters and road riders like this bike frame material. The welding process of titanium is done in an oxygen-free environment which makes the manufacturing process more challenging. It's no doubt that titanium bike frames are very expensive.

Advantages of titanium bike frames.

- Titanium bike frames provide a better and more comfortable ride quality.
- Titanium bike frames are relatively lighter than frames made of steel.
- These frames have a longer durability than steel and aluminium frames, this durability can be 40-50 years if regular maintenance is made (Nehr, 2021).

Disadvantages of titanium bike frames

- Its manufacturing process is labour-intensive.
- Titanium is a very rare metal, and this makes it to be very expensive.
- Titanium welding must be carried out in an oxygen-free environment which makes the manufacturing process outrageously expensive.

2.14. Mechanical properties of bike frame materials.

Table 1: Mechanical properties of most common bike frame materials and their mechanical properties (Shaw, Dwyer, & Tombarelli, 2012)**.** The current conversion from US Dollars to Euros is $(\mathbf{1\$ = 0.94\ €})$**,** updated on 12th April 2024 at 03:02 PM.

	Modulus of Elasticity (GPa)	Yield Strength (MPa)	Tensile Strength (MPa)	Fatigue Strength at 50,000 Cycles (MPa)	Density (kg/m^3)	Weldability and Machinability	Cost (USD pe kg)
Aluminum – 6061-T6	72	193-290	241-320	75	2,700	Excellent	$2.42
Aluminum – 7005-T6	72	290	350	~75	2,780	Excellent	$2.87
Steel - 4130	205	800-1,000	650	250	7,800	Excellent	$0.95
Titanium – Grade 9	91-95	483-620	621-750	250	4,480	Fair	$57.40
Carbon Fiber	275-415	Varies	Varies	Varies	1,800	Fair	Varies

Table 1 above shows the mechanical properties of materials which are most frequently used for making bicycle frames. Young's modulus, yield strength, tensile strength, fatigue strength, density, weldability machinability, and unit cost are all shown in this table. It can be seen **Table 1** that titanium has the highest unit cost which is more than that of steel by a factor of 60.42. On the other hand, carbon fibre has the highest stiffness. Amongst all these materials, the strongest is steel. In the material selection process, extreme care must be taken with all these mechanical properties when selecting the right material for the bicycle frame depending on its area and field of application.

3. METHODOLOGY.

3.1. Prototype selection.

In the bicycle industry, each company does a prototype selection which is based on the structural requirements that the bike frame is required to meet according to the results generated by its finite element analysis. Bike frame prototypes and designs exist in many forms depending on the terrain of usage, what the bike will be used and the type of rider who will be using the bike. Some bike frame prototypes are suitable for roads, others are suitable for mountain rides, some are suitable to be used on gravel meanwhile others are hybrid. Other than the structural design of the various bike frames, the materials that is used to manufacture these frames vary from one design to another. The bike frame prototype that has been selected for this study is the diamond shape that is shown on **Figure *13*** above.

3.2. Selecting an ideal material for the frame by using Ashby charts.

Up to this section, we've been looking at the various material properties of bike frame materials. First and foremost, a standard bike frame shown in **Figure 14** is considered to have a lot of forces acting on it. The forces exerted by the truss members are either tensile or compressive. Therefore, the frame will need a material that has. In this bike frame, the proper material needed should be able to withstand what might occur during an accident or during impact with a surface. A series of simulations are always carried out by engineers to establish the material that meets the design requirements of the structure.

The practical considerations for choosing the right material include.

- A high strength (the frame should not yield when the design load has not been exceeded).
- A high stiffness (to minimize the deflection).
- Low price per unit volume (it should be commercial).
- Mass (the rider shouldn't apply a lot of force to move both his weight and that of the bike)

Table 2: Defining design requirements.

Function	**Bike frame**
Constraints	• High strength: Should not fail under design loads. • High stiffness: Should not deflect a lot under design loads. • Low cost
Objectives	Minimize material cost
Free variables	Choice of material

Material index.

The material index is another word used for the material performance index. It is the combination of all material properties during the material selection process (IGI Global , 2015).

The figure below shows how the forces acting on a bike can be compared to the forces acting on a beam that has been supported at both ends. It can be seen from the figure that the bike can be considered as a beam with two supports at both ends and a force acting in the middle.

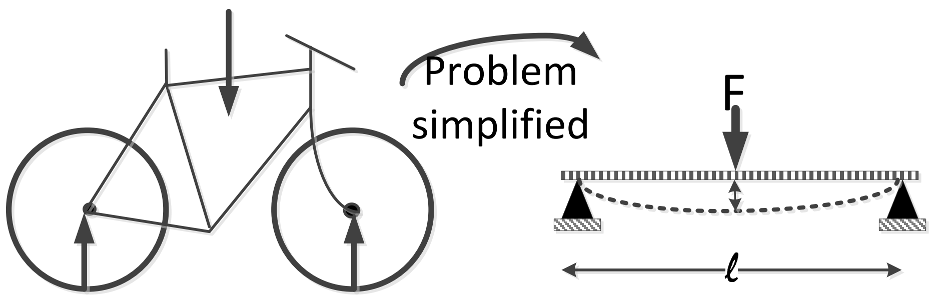


Figure 17: Similarity between the forces acting on a beam supported at both ends and central load with that of a bicycle frame.

Among all common bike frames such as carbon fibre reinforced composite, aluminium alloys, steel and titanium alloys, the material that is both stronger and cheaper will be preferable. So, the material that has the highest strength-to-relative cost ratio is preferred.

According to the 2nd Edition of CES (2009) Edupack Materials and Process Selection charts ${\sigma_f}^{2/3}/C_v$ is the material index which is suitable for selecting materials for the minimum cost design of strong beams and shafts. Let's consider the Ashby plot which is used for selecting materials by looking at two material properties against each other. If the suitable performance index for the right material is $P = {\sigma_f}^{2/3}/C_v$.

Taking logs of both sides and rearranging the equation so that it can take the form of the equation of a straight line $y = mx + c$ gives.

$$P = {\sigma_f}^{2/3}/C_v$$

$$\log P = \frac{2}{3}\log \sigma_f - \log C_v$$

$$\frac{2}{3}\log \sigma_f = \log P + \log C_v$$

$$\log \sigma_f = \frac{3}{2}\log P + \frac{3}{2}\log C_v$$

$$\log \sigma_f = \frac{3}{2}\log C_v + \frac{3}{2}\log P$$

The suitable material can be selected by drawing a line with a gradient $\frac{3}{2}$ as shown in Figure 18.

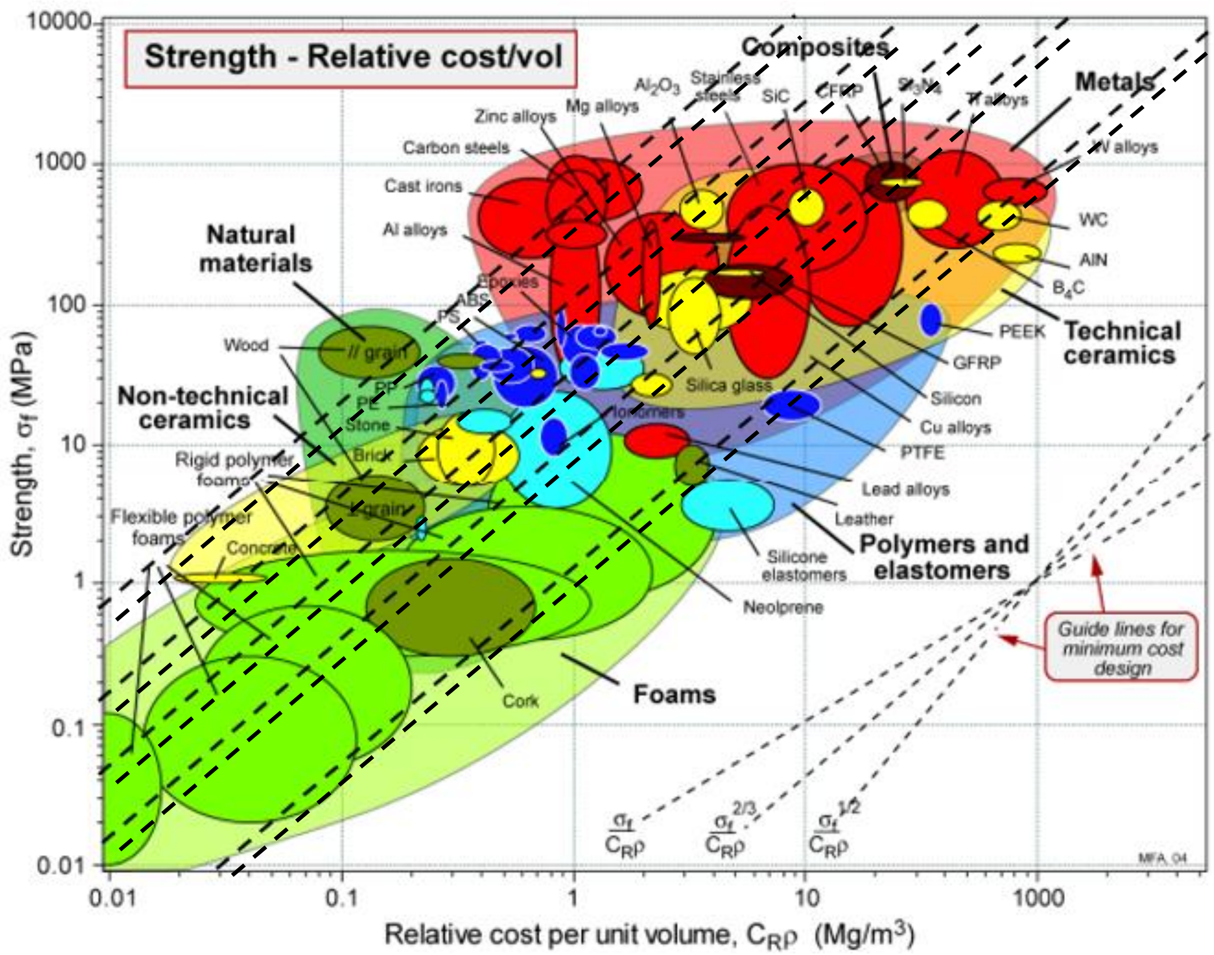


Figure 18: Asby plot of strength against relative cost per unit volume *(Edupack, 2009)*.

From the Asby plot of strength against relative cost per unit, it can be seen steel alloys are the best material that can be used to minimize the manufacturing cost of the frame. The steel alloy that is preferred for the bike frame in this study is AISI 4130 steel.

3.3. 3-Dimensional solid modelling of the bicycle frame in SolidWorks.

The main tool in SolidWorks that was used to design the bike frame was the weldment tool. SolidWorks weldments tools/tab is used for building a weldment structure such as a tube from a sketch. Alongside SolidWorks Weldments, other sketch tools such as circles, splines, tangent arcs, ellipses, centrelines, and straight slots were used in different planes which were added by reference geometry.

The Weldments tools as shown in Figure 19 were used to define the basic framework and profile of the bike frame and all its structural members such as the top tube, head tube, down tube, chain stays, seat stays, bottom bracket and seat tube.

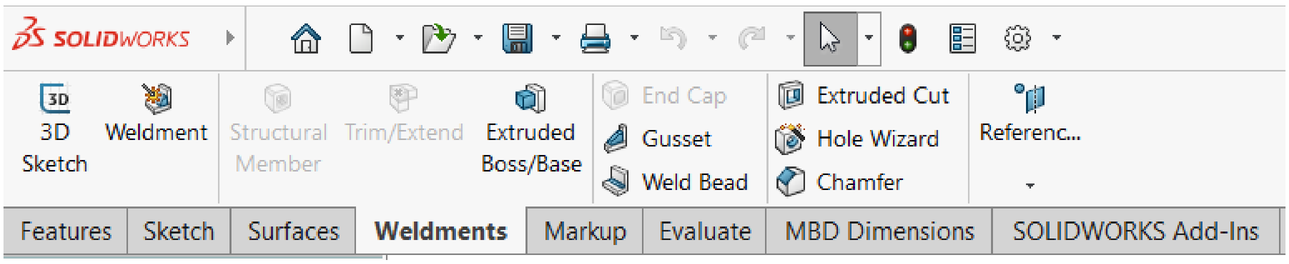


Figure 19: The Weldments toolbar in SolidWorks 2023

The sketch toolbar shown Figure 20 has a wide range of sketch tools which were used to make 2-dimensional sketches of the parts of the bike frame.

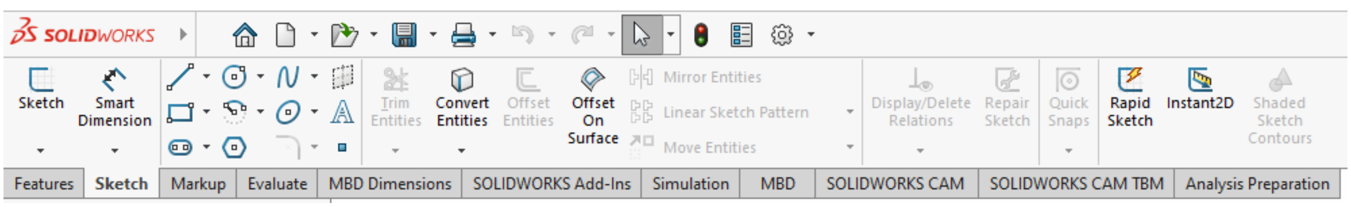


Figure 20: The Sketch toolbar in SolidWorks 2023

The features toolbar as shown Figure 21 contains tools such as Extruded Boss/Base, Extruded Cut, Sept Boss/Base, fillets and other tools which were used to model the 3Dimensional features of the bike frame. The Extrude Boss/Base tool is used to generate thickness to an already existing 2D sketch in the third dimension. This Extruded Boss/Base feature is made up of several conditions, however, the condition which was mostly used was the "blind" condition which is used to extrude the sketch at a specific distance from the sketch plane and this extrusion stops whenever that thickness has been met (Schnaars, 2026).

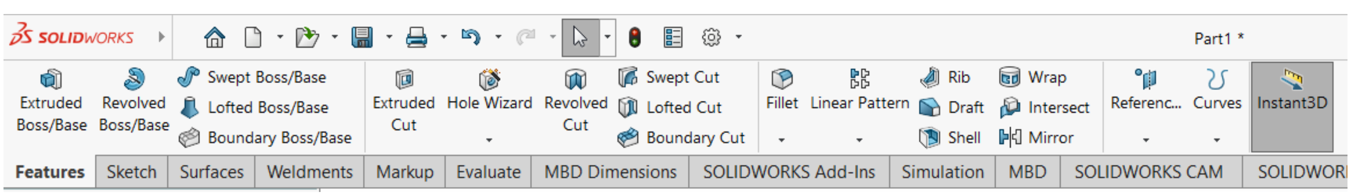


Figure 21: The Features toolbar in SolidWorks 2023

The main features used to design the bike frame are.

- **Extruded Boss/Base:** This is one of the most important tools in SolidWorks which is used to add a third dimension to a 2D sketch, this third dimension is also known as the thickness. This feature extrudes the sketch by making it have the desired thickness to form the 3-dimensional model.
- **Extruded Cute:** This is a SolidWorks tool that instead of adding material to the sketch like the Extruded Boss/Base command does, it instead subtracts material from an existing solid. When designing the bike frame, the Extruded Cut command was used to cut and create the holes in some of the sections of the frame tubing.
- **Swept Boss/Base:** This SolidWorks command was used to design the seat stays and chain stays of the bike frame by first making a 3D sketch of the desired profile and then later the swept command is used to create the solid rods along the sketch profile.
- **Smart dimensioning:** This tool is used to correct the dimensions in SolidWorks to the desired one which is on paper. In SolidWorks 2023, the smart dimensioning tool can be found on the Sketch Toolbar Manager.

Figure 22 Below is the final design of the bike frame in SolidWorks showing the front, left, right and isometric views.

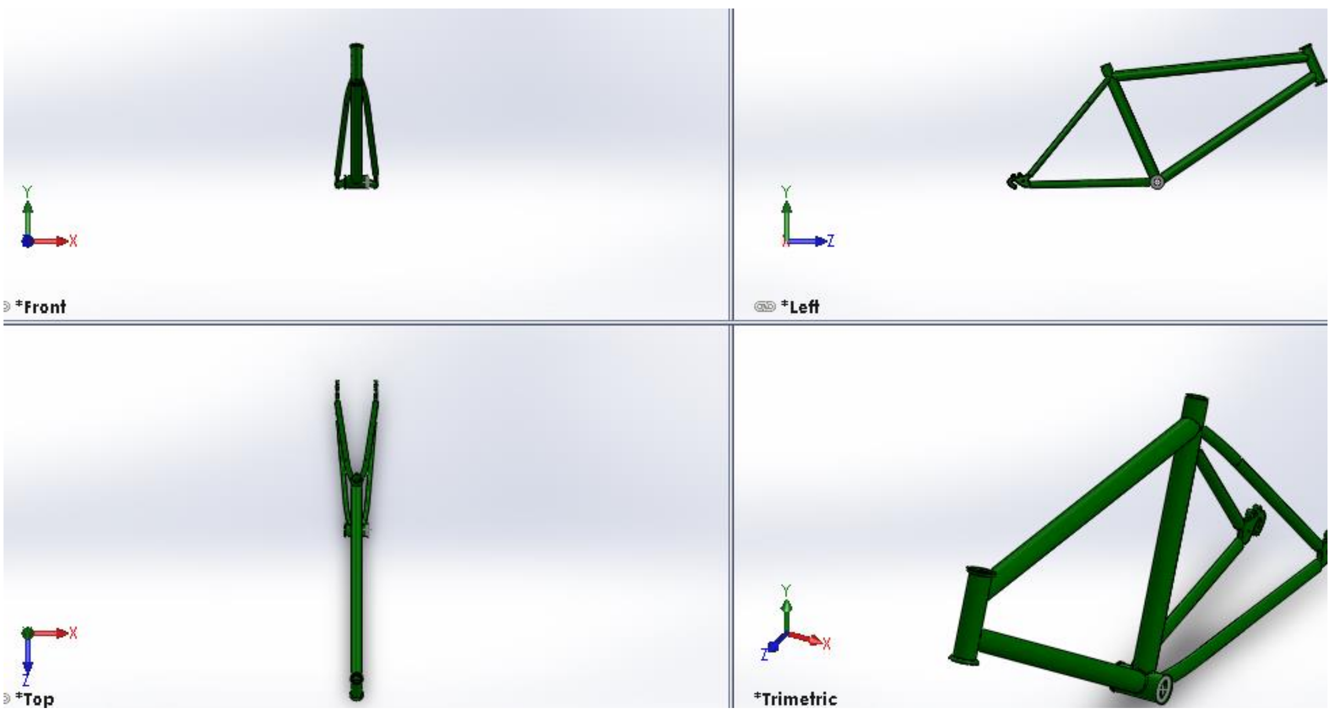


Figure 22: Final design of the bike frame showing the various views in SolidWorks.

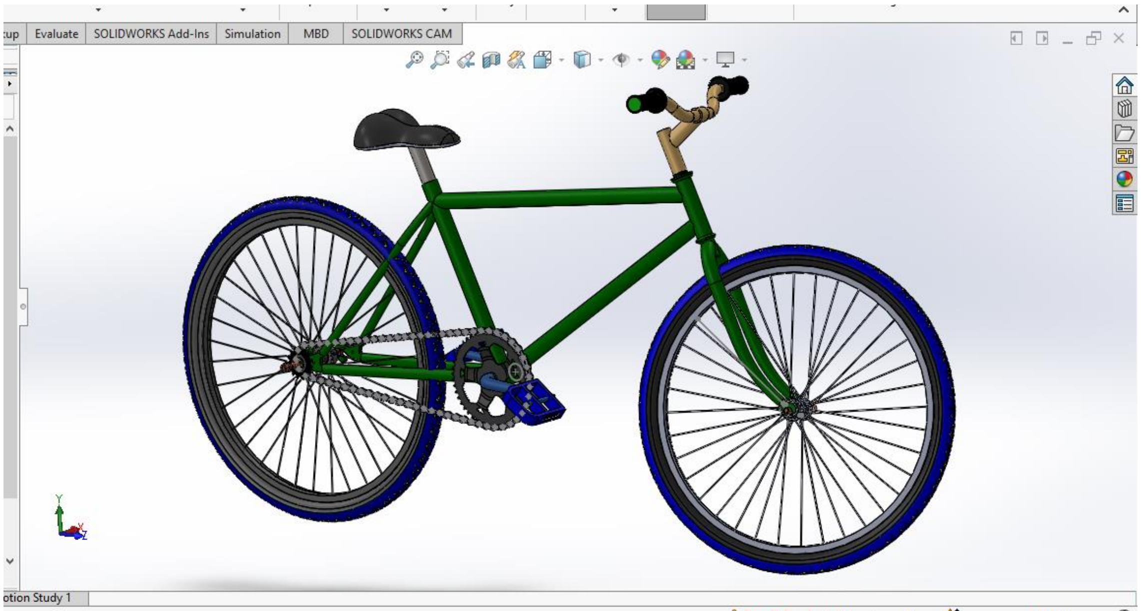


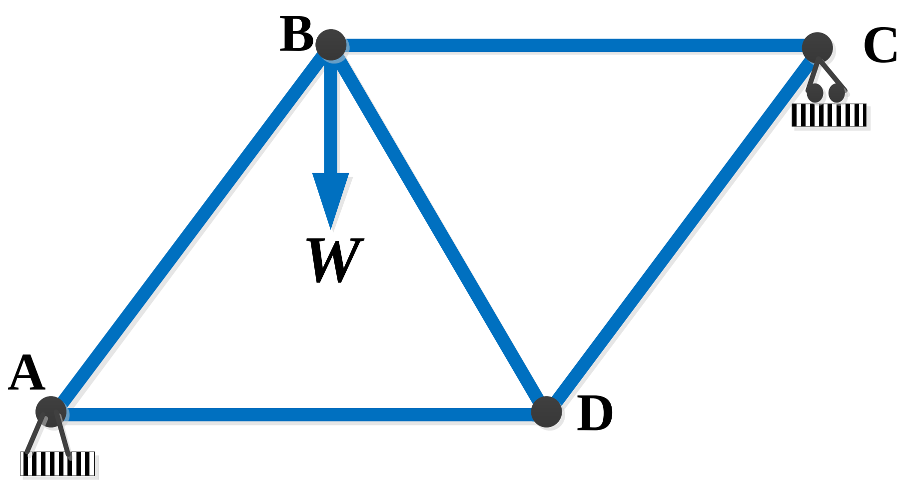
Figure 23: Complete bike design with frame in SolidWorks.

Table 3: Design parameters of bicycle frame.

Design parameter	**Length (mm)**	**Outer diameter (mm)**	**Wall thickness (mm)**
Seat tube	**420**	**32**	**1.9**
Top tube	**643.28**	**31**	**1.9**
Bottom bracket	**68**	**40**	**1.9**
Down tube	**620.75**	**31**	**1.9**
Head tube	**120**	**32**	**1.9**
Chain stays	**410.10**	**17**	**1.9**
Seat stay	**410**	**16**	**1.9**

3.4. Calculation of forces and stresses in the bike frame by using the governing equations.

Let it be assumed that the bike frame has the structure of a truss. To find the internal forces acting in each member of the bike frame, let's assume that all joints are hinges and that all members have equal lengths. To calculate the internal forces acting in the members of the truss can be calculated by two methods, either the method of section or the method of joints. The method that is more convenient to analyse this truss is the method of sections.



The truss has up to four joints, and by using the method of joints, it must be assumed that the net force in all joints is zero. The method of joints is based on the principle that if the entire truss is in equilibrium, this implies that all joints of the truss are in equilibrium. So, the free-body diagram of the whole truss needs to be drawn showing the internal forces which are acting in each of the joints. Each joint is subjected to coplanar (forces acting on the same plane) and concurrent forces (forces whose lines of action all intersect at a particular point).

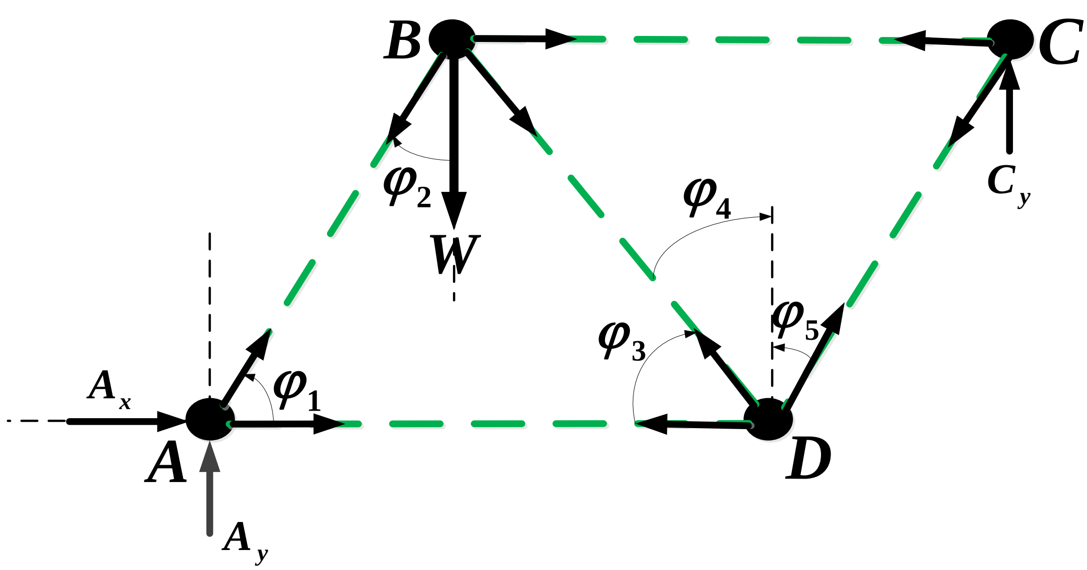


Figure 24: Analysis of forces in frame members by method of joints.

At joint A:

$$\sum F_x = A_x + F_{AD} + F_{AB} \cos\varphi_1 = 0 \quad \textbf{(3.1)}$$

$$\sum F_y = A_y + F_{AB} \sin\varphi_1 = 0 \quad \textbf{(3.2)}$$

At Joint B:

$$\sum F_x = F_{BC} + F_{BD} \cos\varphi_3 - F_{AB} \sin\varphi_2 = 0 \quad \textbf{(3.3)}$$

$$\sum F_y = -F_{AB} \cos\varphi_2 - F_{BD} \sin\varphi_3 - W = 0 \quad \textbf{(3.4)}$$

At joint C:

$$\sum F_x = -F_{BC} - F_{CD} \sin\varphi_5 = 0 \quad \textbf{(3.5)}$$

$$\sum F_y = -F_{CD} \cos\varphi_5 + C_y = 0 \quad \textbf{(3.6)}$$

At joint D:

$$\sum F_x = F_{CD} \sin\varphi_5 - F_{AD} - F_{BD} \sin\varphi_4 = 0 \quad \textbf{(3.7)}$$

$$\sum F_y = F_{CD} \cos\varphi_5 + F_{BD} \cos\varphi_4 = 0 \quad \textbf{(3.8)}$$

Deriving the internal forces

To derive the internal forces and reaction forces from the diamond frame, the matrix method and Cramer’s rule have to be used to avoid complex procedures. These equations will also help determine the relationship between internal forces.

From joint B,

$$F_{AB} \sin\varphi_2 - F_{BD} \cos\varphi_3 = F_{BC}$$

$$F_{AB} \cos\varphi_2 + F_{BD} \sin\varphi_3 = -W$$

These two equations of equilibrium for the horizontal and vertical forces acting in joint B can be represented in matrix form on the matrix shown below.

$$\begin{bmatrix} \sin\varphi_2 & -\cos\varphi_3 \\ \cos\varphi_2 & \sin\varphi_3 \end{bmatrix} \begin{bmatrix} F_{AB} \\ F_{BD} \end{bmatrix} = \begin{bmatrix} F_{BC} \\ -W \end{bmatrix}$$

Finding the inverse of the matrix, the simultaneous equation can be solved to find the expressions for F_{BC}` and F_{BD} .

$$\begin{bmatrix} F_{AB} \\ F_{BD} \end{bmatrix} = \begin{bmatrix} F_{BC} \\ -W \end{bmatrix} \frac{1}{\sin\varphi_2 \sin\varphi_3 + \cos\varphi_2 \cos\varphi_3} \begin{bmatrix} \sin\varphi_3 & \cos\varphi_3 \\ -\cos\varphi_2 & \sin\varphi_2 \end{bmatrix}$$

$$F_{AB} = \frac{(F_{BC} \sin\varphi_3 + W\cos\varphi_3)}{\cos(\varphi_2 - \varphi_3)} \quad \textbf{(3.9)}$$

$$F_{BD} = -\frac{(F_{BC} \cos\varphi_2 + W\sin\varphi_2)}{\cos(\varphi_2 - \varphi_3)} \quad \textbf{(3.10)}$$

From joint D,

$$\sum F_x = F_{CD} \sin\varphi_5 - F_{AD} - F_{BD} \sin\varphi_4 = 0$$

$$\sum F_y = F_{CD} \cos\varphi_5 + F_{BD} \cos\varphi_4 = 0$$

$$F_{CD} \sin\varphi_5 - F_{AD} = F_{BD} \sin\varphi_4$$

$$F_{CD} \cos\varphi_5 = -F_{BD} \cos\varphi_4$$

$$\begin{bmatrix} \sin\varphi_5 & -1 \\ \cos\varphi_5 & 0 \end{bmatrix} \begin{bmatrix} F_{CD} \\ F_{AD} \end{bmatrix} = \begin{bmatrix} F_{BD} \sin\varphi_4 \\ -F_{BD} \cos\varphi_4 \end{bmatrix}$$

$$\begin{bmatrix} F_{CD} \\ F_{AD} \end{bmatrix} = \frac{1}{\cos\varphi_5} \begin{bmatrix} 0 & 1 \\ -\cos\varphi_5 & \sin\varphi_5 \end{bmatrix} \begin{bmatrix} F_{BD} \sin\varphi_4 \\ -F_{BD} \cos\varphi_4 \end{bmatrix}$$

$$F_{CD} = \frac{-F_{BD} \cos\varphi_4}{\cos\varphi_5} \quad \textbf{(3.11)}$$

$$F_{AD} = \frac{-F_{BD}(\cos\varphi_5 \sin\varphi_4 + \cos\varphi_4 \sin\varphi_5)}{\cos\varphi_5} \quad \textbf{(3.12)}$$

From equation 3.5, $F_{CD} = \dfrac{-F_{BC}}{\sin\varphi_5}$ and from equation 3.11, $F_{CD} = \dfrac{-F_{BD}\cos\varphi_4}{\cos\varphi_5}$

Equating both equations give, $-F_{BC}\cos\varphi_5 = -F_{BD}\cos\varphi_4 \sin\varphi_5$ **(3.13)**

Substituting equation (3.5) in (3.13) gives

$$-F_{BC}\cos\varphi_5 = \frac{(F_{BC}\cos\varphi_2 + W\sin\varphi_2)}{\cos(\varphi_2-\varphi_3)}\cos\varphi_4 \sin\varphi_5$$

$$-F_{BC}\cos\varphi_5\cos(\varphi_2-\varphi_3) + F_{BC}\cos\varphi_2\cos\varphi_4\sin\varphi_5 = W\cos\varphi_4\sin\varphi_2\sin\varphi_5$$

$$F_{BC} = \left[\frac{W\cos\varphi_4\sin\varphi_2\sin\varphi_5}{\cos\varphi_2\cos\varphi_4\sin\varphi_5 - \cos\varphi_5\cos(\varphi_2-\varphi_3)}\right] \quad \textbf{(3.14)}$$

Substitute equation (2.14), in $F_{CD} = -\frac{F_{BD}\cos\varphi_4}{\cos\varphi_5}$ gives.

$$F_{CD} = \frac{\left(\frac{(F_{BC}\cos\varphi_2 + W\sin\varphi_2)}{\cos(\varphi_2-\varphi_3)}\right)}{\cos\varphi_5}\cos\varphi_4$$

$$F_{CD} = \frac{\cos\varphi_4\left(\left(\frac{W\cos\varphi_4\sin\varphi_2\sin\varphi_5}{\cos\varphi_2\cos\varphi_4\sin\varphi_5 - \cos\varphi_5\cos(\varphi_2-\varphi_3)}\right)\cos\varphi_2 + W\sin\varphi_2\right)}{\cos\varphi_5\cos(\varphi_2-\varphi_3)}$$

$$F_{CD} = \frac{\cos\varphi_4\left(\left(\frac{W\cos\varphi_4\sin\varphi_2\sin\varphi_5}{\cos\varphi_2\cos\varphi_4\sin\varphi_5 - \cos\varphi_5\cos(\varphi_2-\varphi_3)}\right)\cos\varphi_2 + W\sin\varphi_2\right)}{\cos\varphi_5\cos(\varphi_2-\varphi_3)}$$

$$F_{CD} = \left[\frac{\left(\left(\frac{W\cos^2\varphi_4\sin\varphi_2\sin\varphi_5}{\cos\varphi_2\cos\varphi_4\sin\varphi_5 - \cos\varphi_5\cos(\varphi_2-\varphi_3)}\right)\cos\varphi_2 + W\cos\varphi_4\sin\varphi_2\right)}{\cos\varphi_5\cos(\varphi_2-\varphi_3)}\right] \quad \textbf{(3.15)}$$

From equation (3.8), $F_{BD} = \frac{F_{CD}\cos\varphi_5}{\cos\varphi_4}$

$$F_{BD} = \frac{\left(\dfrac{W\cos\varphi_4 \sin\varphi_2 \sin\varphi_5}{\cos\varphi_2 \cos\varphi_4 \sin\varphi_5 - \cos\varphi_5 \cos(\varphi_2 - \varphi_3)}\right)\cos\varphi_5}{\cos\varphi_4}$$

$$F_{BD} = \left(\frac{W\cos\varphi_4 \cos\varphi_5 \sin\varphi_2 \sin\varphi_5}{\cos\varphi_4\left(\cos\varphi_2 \cos\varphi_4 \sin\varphi_5 - \cos\varphi_5 \cos(\varphi_2 - \varphi_3)\right)}\right)$$

$$F_{BD} = \left(\frac{W\cos\varphi_5 \sin\varphi_2 \sin\varphi_5}{\left(\cos\varphi_2 \cos\varphi_4 \sin\varphi_5 - \cos\varphi_5 \cos(\varphi_2 - \varphi_3)\right)}\right) \tag{3.16}$$

From equation (3.7),

$$F_{CD}\sin\varphi_5 - F_{AD} - F_{BD}\sin\varphi_4 = 0$$

$$F_{AD} = F_{CD}\sin\varphi_5 - F_{BD}\sin\varphi_4$$

Substituting equations (3.15) and (3.16) in equation (3.7) gives.

$$F_{AD} = \left[\frac{\left(\left(\dfrac{W\cos^2\varphi_4 \sin\varphi_2 \sin\varphi_5}{\cos\varphi_2 \cos\varphi_4 \sin\varphi_5 - \cos\varphi_5 \cos(\varphi_2 - \varphi_3)}\right)\cos\varphi_2 + W\cos\varphi_4 \sin\varphi_2\right)}{\cos\varphi_5 \cos(\varphi_2 - \varphi_3)}\right]$$

$$-\left(\frac{W\cos\varphi_5 \sin\varphi_2 \sin\varphi_5}{\left(\cos\varphi_2 \cos\varphi_4 \sin\varphi_5 - \cos\varphi_5 \cos(\varphi_2 - \varphi_3)\right)}\right)\sin\varphi_4 \tag{3.17}$$

From equation (3.6),

$$-F_{CD}\cos\varphi_5 + C_y = 0$$

Substituting equation 3.15 in equation 3.6 gives,

$$-\left[\frac{\left(\left(\dfrac{W\cos^2\varphi_4 \sin\varphi_2 \sin\varphi_5}{\cos\varphi_2 \cos\varphi_4 \sin\varphi_5 - \cos\varphi_5 \cos(\varphi_2 - \varphi_3)}\right)\cos\varphi_2 + W\cos\varphi_4 \sin\varphi_2\right)}{\cos\varphi_5 \cos(\varphi_2 - \varphi_3)}\right]\cos\varphi_5 + C_y = 0$$

$$C_y = \left[\frac{\left(\left(\left(\frac{W \cos^2 \varphi_4 \sin \varphi_2 \sin \varphi_5}{\cos \varphi_2 \cos \varphi_4 \sin \varphi_5 - \cos \varphi_5 \cos(\varphi_2 - \varphi_3)} \right) \cos \varphi_2 + W \cos \varphi_4 \sin \varphi_2 \right) \right)}{\cos(\varphi_2 - \varphi_3)} \right] \quad \textbf{(3.18)}$$

From equation (3.4),

$$-F_{AB} \cos \varphi_2 - F_{BD} \sin \varphi_3 - W = 0$$

Substituting equation (3.16) in equation (3.4) gives;

$$-F_{AB} \cos \varphi_2 - \left(\frac{W \cos \varphi_5 \sin \varphi_2 \sin \varphi_5}{(\cos \varphi_2 \cos \varphi_4 \sin \varphi_5 - \cos \varphi_5 \cos(\varphi_2 - \varphi_3))} \right) \sin \varphi_3 - W = 0$$

$$F_{AB} = -\frac{1}{\cos \varphi_2} \left[\left(\frac{W \cos \varphi_5 \sin \varphi_2 \sin \varphi_5}{(\cos \varphi_2 \cos \varphi_4 \sin \varphi_5 - \cos \varphi_5 \cos(\varphi_2 - \varphi_3))} \right) \sin \varphi_3 + W \right] = 0 \quad \textbf{(3.19)}$$

From equation (3.2),

$$A_y + F_{AB} \sin \varphi_1 = 0$$

$$A_y = -F_{AB} \sin \varphi_1$$

$$A_y = \frac{\sin \varphi_1}{\cos \varphi_2} \left[\left(\frac{W \cos \varphi_5 \sin \varphi_2 \sin \varphi_5}{(\cos \varphi_2 \cos \varphi_4 \sin \varphi_5 - \cos \varphi_5 \cos(\varphi_2 - \varphi_3))} \right) \sin \varphi_3 + W \right] = 0 \quad \textbf{(3.20)}$$

From equation (3.1),

$$\sum F_x = A_x + F_{AD} + F_{AB} \cos \varphi_1 = 0$$

$$A_x = -F_{AD} - F_{AB} \cos \varphi_1$$

$$A_x = -\left[\frac{\left(\left(\frac{W\cos^2\varphi_4 \sin\varphi_2 \sin\varphi_5}{\cos\varphi_2\cos\varphi_4\sin\varphi_5 - \cos\varphi_5\cos(\varphi_2-\varphi_3)}\right)\cos\varphi_2 + W\cos\varphi_4\sin\varphi_2\right)}{\cos\varphi_5\cos(\varphi_2-\varphi_3)}\right]$$

$$+\left(\frac{W\cos\varphi_5\sin\varphi_2\sin\varphi_5}{\left(\cos\varphi_2\cos\varphi_4\sin\varphi_5 - \cos\varphi_5\cos(\varphi_2-\varphi_3)\right)}\right)\sin\varphi_4$$

$$+\frac{\cos\varphi_1}{\cos\varphi_2}\left[\left(\frac{W\cos\varphi_5\sin\varphi_2\sin\varphi_5}{\left(\cos\varphi_2\cos\varphi_4\sin\varphi_5 - \cos\varphi_5\cos(\varphi_2-\varphi_3)\right)}\right)\sin\varphi_3 + W\right] = 0 \qquad \textbf{(3.21)}$$

Let it be assumed that an average rider has a mass of $100\ kg$, and assuming acceleration due to gravity as $9.81\ m/s^2$, this gives an average weight $981\ N$. Calculating the numerical values and nature of the forces can be done in Microsoft Excel by using the governing equations and this will generate the results shown on **Table 4**. In this calculation $\varphi_1 = 40°$, $\varphi_2 = 29°$, $\varphi_3 = 50°$, $\varphi_4 = 40°$, $\varphi_5 = 30°$.

Table 4: Numerical values of forces in members of bike frame and nature of forces.

Internal force	Value [N]	Nature of force
Force in the down tube F_{CD}	131.82	Tension
Force in the top tube F_{BC}	-384.72	Compression
Force in the seat tube F_{BD}	-434.93	Compression
Force in the seat stays F_{AB}	-771.47	Compression
Force in the chain stays F_{AD}	345.47	Tension
Horizontal reaction at the chain stays A_x	-860.00	Compression
Vertical reaction at the chain stays A_y	495.89	Tension
Reaction at the head tube C_x	114.15	Tension

To calculate the stresses in the truss members of the bike frame, the cross-sectional areas of the various bike frame members are needed. With the data that is found **Error! Reference source not found.**, the c ross-sectional areas of the various members can be calculated in Microsoft Excel while assuming that all members of the bike frame have a cylindrical shape.

Table 5: Cross-sectional areas of truss members

Frame member	Shell thickness $[mm]$	Outer diameter $[mm]$	Outer Area $[mm^2]$	Inner Area $[mm^2]$	Shell area $[mm^2]$
Seat tube	1.9	32	804.25	624.58	179.67
Top tube	1.9	31	754.77	581.07	173.70
Down tube	1.9	31	754.77	581.07	173.70
Chain stays	1.9	17	226.98	136.85	90.13
Seat stays	1.9	16	201.06	116.90	84.16

Table 6: Stresses in the truss members.

Frame member	Shell area $[mm^2]$	Force $[N]$	Stress $[MPa]$
Seat tube	179.67	-434.926	-2.420724699
Top tube	173.70	-384.715	-2.214841524
Down tube	173.70	131.813	0.758859635
Chain stays	90.13	345.472	1.916470155
Seat stays	84.16	-771.467	-4.58315739

The factor of safety of design.

If it's assumed that the bike frame is made up of Steel alloy steel 4130, which is a ductile material and has a yield strength 435 MPa, then the factor of safety can be calculated by using the formula.

Factor of safety $FOS = \dfrac{Yields\ strength}{Working\ or\ Design\ stress}$

$$FOS = \frac{435\,MPa}{4.58\,MPa} = 94.98$$

This factor of safety is not for the whole bike frame. However, it's for the truss members, because if other parts of the bike frame such as the bottom brackets and the dropouts are to be taken into consideration in this section, the factor safety will be lower or closer to 2 especially when the design has been optimized in SolidWorks. The stresses in the dropouts and the joints that connect the truss members are always very high due to stress concentrations around these joints.

Analysis of the bike frame by the method of sections.

The method of sections is used to determine the forces in the members of the truss by breaking down the truss into two sections and carrying out analysis on each of the sections as if it were a separate rigid body. One of the advantages of this method of section is that the only internal forces that are exposed are the ones through which the cut has been made the other internal forces that are not exposed by the cut are ignored (Baker & Haynes, 2024). The truss of the bike frame can be analysed by using the following steps.

- Support reactions.
- Cut truss by passing a cut through the members of interest.
- Free body diagram of parts.
- Equilibrium equations.

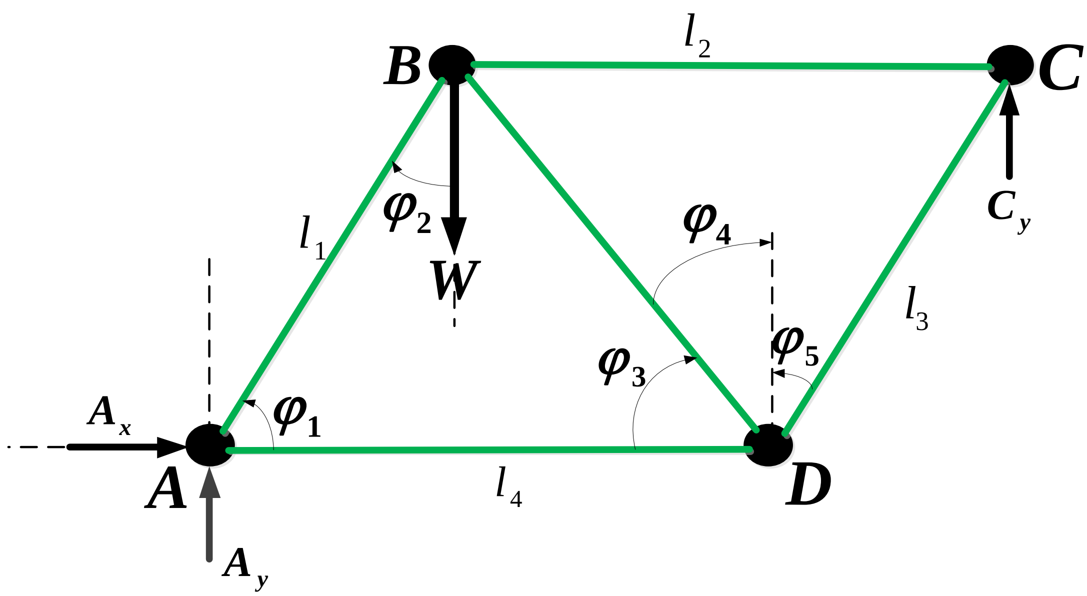


Figure 25: Bike frame showing support reactions.

- **Support reactions (external forces).**

Finding the reactions at the supports is the first step that is to be done when analysing a truss by the method of sections because this will generate boundary conditions that will ease the progress of the analysis. It can be seen in Figure 25 that there are two reactions at support A (both vertical and horizontal) because it acts as a pin connection. It can also be seen that there is just a vertical reaction at support B because it acts as a roller.

Equilibrium of horizontal reactions at the supports.

$$\sum F_x = 0$$

$$A_x = 0$$

Equilibrium of horizontal reactions at the supports.

$$\sum F_y = 0,$$

$$A_y + C_y = 0$$

$$A_y = -C_y \quad \textbf{(3.22)}$$

- **Cutting the truss through the member of interest (internal forces).**

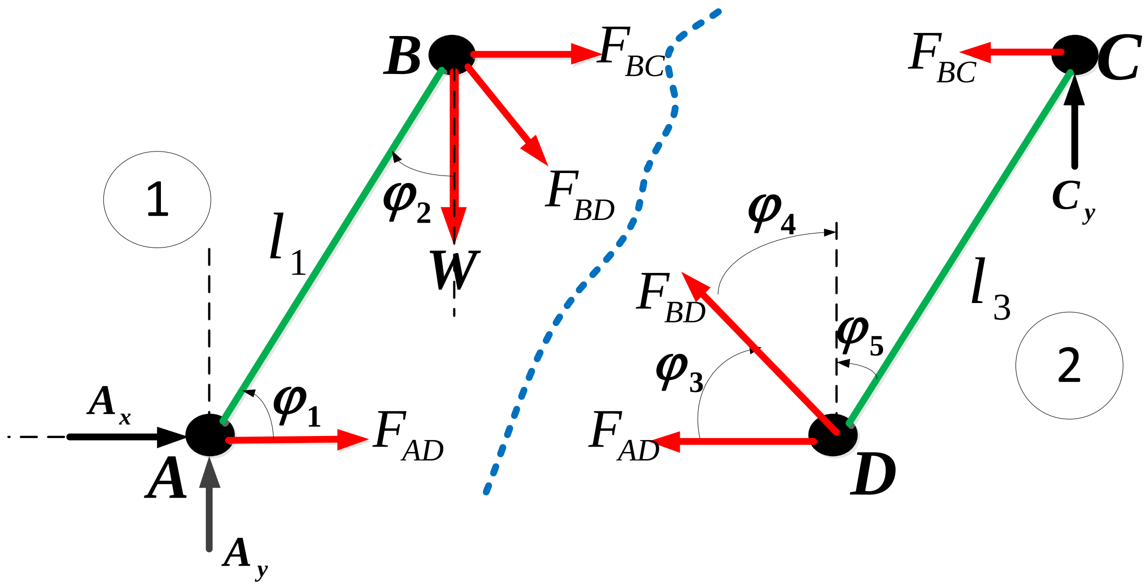


Figure 26: Free body diagram of parts of the truss by using the method of sections.

Summing moments about $\boldsymbol{A}$ eliminates the forces $\boldsymbol{A_x}$, $\boldsymbol{A_y}$ **and** $\boldsymbol{F_{AD}}$.

From body 1.

$\sum M_A = 0;$ (Assuming that the anticlockwise moments are positive)

$$-Wl_1 \cos\varphi_1 - F_{BC} l_1 \sin\varphi_1 - F_{BD} \cos\varphi_3 l_1 \sin\varphi_1 - F_{BD} \sin\varphi_3 l_1 \cos\varphi_1 = 0 \quad \textbf{(3.23)}$$

$\sum M_B = 0;$ (Assuming the anticlockwise moments to be positive).

$$A_x l_1 \sin\varphi_1 + F_{AD} l_1 \sin\varphi_1 - A_y l_1 \cos\varphi_1 = 0 \quad \textbf{(3.24)}$$

From body 2.

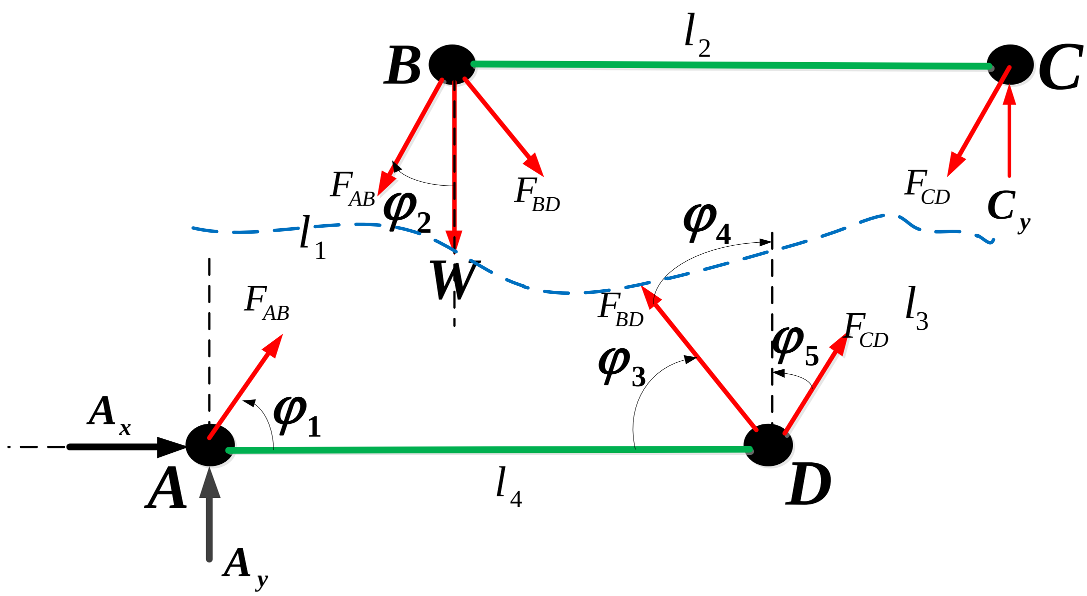
$$\sum M_C = 0;$$

$$-F_{AD}l_3\cos\varphi_5 - F_{BD}\cos\varphi_3 l_3\cos\varphi_5 - F_{BD}\sin\varphi_3 l_3\sin\varphi_5 = 0 \quad \textbf{(3.25)}$$

$$\sum M_D = 0;$$

$$C_y l_3\sin\varphi_5 + F_{BC}l_3\cos\varphi_5 = 0 \quad \textbf{(3.26)}$$

Making a horizontal cut through the truss gives the sketch show below.



Considering the lower body and taking moments of point A, gives.

$$\sum M_A = 0;$$

$$F_{BD}\sin\varphi_3 l_4 + F_{CD}\cos\varphi_5 l_4 = 0 \quad \textbf{(3.27)}$$

Considering the lower body and taking moments of point D, gives.

$$\sum M_D = 0$$

$$-A_y l_4 - F_{AB}\sin\varphi_1 = 0 \quad \textbf{(3.28)}$$

Considering the upper body and taking moments of point B, gives.

$$\sum M_B = 0;`$$

$$C_y l_2 - F_{CD}\cos\varphi_5 = 0 \quad \textbf{(3.29)}$$

Considering the upper body and taking moments of point C, gives.

$$\sum M_C = 0;$$

$$F_{BD}\cos\varphi_4 l_2 + Wl_2 + F_{AB}\cos\varphi_2 l_2 = 0 \quad \textbf{(3.30)}$$

From equation **[3.23]**,

$$F_{BD} = \frac{Wl_1\cos\varphi_1 + F_{BC}l_1\sin\varphi_1}{l_1\cos\varphi_3\sin\varphi_1 + l_1\cos\varphi_1\sin\varphi_3} \quad \textbf{(3.31)}$$

From equation **[3.24],**

$$F_{AD} = \frac{A_y l_1\cos\varphi_1}{\sin\varphi_1} \quad \textbf{(3.32)}$$

From equation **[3.26],**

$$F_{BC} = \frac{C_y l_3\sin\varphi_5}{l_3\cos\varphi_5} \quad \textbf{(3.33)}$$

From equation **[3.28],**

$$-A_y = Cy = \frac{F_{AB}\sin\varphi_1}{l_4} \quad \textbf{(3.34)}$$

From equation **[3.30]**

$$F_{AB} = -\frac{F_{BD}l_2\cos\varphi_4 + l_2 W}{l_2\cos\varphi_2} \quad \textbf{(3.35)}$$

From equation **[3.29],**

$$Cy = \frac{F_{CD}\cos\varphi_5}{l_2} \quad \textbf{(3.36)}$$

3.5. Design simulation and Finite Element Analysis (FEA) in SolidWorks Environment.

Finite Element Analysis (FEA) involves using calculations, design simulations and models to make a reliable prediction and understand how designs and structures will behave under certain physical conditions such as pressure, forces and loadings, stresses, temperature etc, so that this will help engineers to determine how vulnerable the design prototype might be. The FEA is a numerical and computational method that involves splitting an object into small and simpler pieces or elements to find a solution to a boundary value problem. During Finite Element analysis, the structure is first meshed, and the meshing produces up to millions of smaller parts. The results are obtained as a sum of all calculations that have been individually performed on the meshed elements. (Brush, 2019).

In this study, the Finite Elements Analysis will generate the following results,

- Stress.
- Displacement.
- Strain.

3.5.1. Load cases.

The bicycle frame is modelled and manufactured to be applied to several load cases as part of the study on the bike frame. All these cases will be studied to examine the stress, displacement, and strain response of the bike frame. Five different load cases will be used in this study. The load cases include,

- **Static start-up:** In this condition, the bike is assumed to be ridden by a rider whose mass is 100 kg (981 N) and this load is placed on the saddle. One of the assumptions taken here is that the effect of air resistance is neglected during the analysis. In this case, the bicycle is stationary, and the rider sits on the saddle with his feet resting on the pedal.
- **Steady state pedalling:** In this condition, the rider is assumed to be weighing $981N$. It will be assumed that the rider is riding with a steady pedalling force $200N$ which will be applied horizontally on the bottom bracket pedal of the bike frame. It's also assumed that the ground is frictionless and that the rider maintains this force consistently throughout the ride (Akhyar, Husaini, & Husanuddin, 2019).
- **Vertical impact:** The vertical loading condition takes place when the bike suddenly gets into a hole or pothole which is deep to the extent that the frame impacts a hard load that transfers a lot of energy to the truss structure, or when it falls from a small height to a rigid surface. This condition is represented by twice the weight of the bike rider and the gravity load of the bike itself due to gravity. Here the rider's weight will be multiplied by some of the G constant. In this case, it will be multiplied by a factor of 2 (P, Deepak, H, & Sara, 2021).
- **Horizontal impact:** In the horizontal loading condition, a load of $981N$ is applied horizontally on the front head tube of the bicycle frame.
- **Rear wheel breaking:** In the rear wheel breaking condition the ridder pedals the bike, and it reaches a steady speed until it stops. A force of $981N$ will be given to the rear seat stays, this force is considered to originate from the braking action. All these forces will be concentrated on the rear wheels (P, Deepak, H, & Sara, 2021).

3.5.1.1. Static start-up.

- **Fixtures.**

  Figure *27* shows the fixtures that were applied in this load case during the simulation. The first fixture is the lower end of the top tube, and the second fixture is the combination of all two rear wheel dropouts.

Figure 27: Fixtures in static startup.

- **Loads.**
  The weight of the rider which is assumed to be $981N$ is applied directly on the saddle as shown in **Figure 28** and a gravity load of the bike frame's weight is also applied on the top plane of the bike frame.

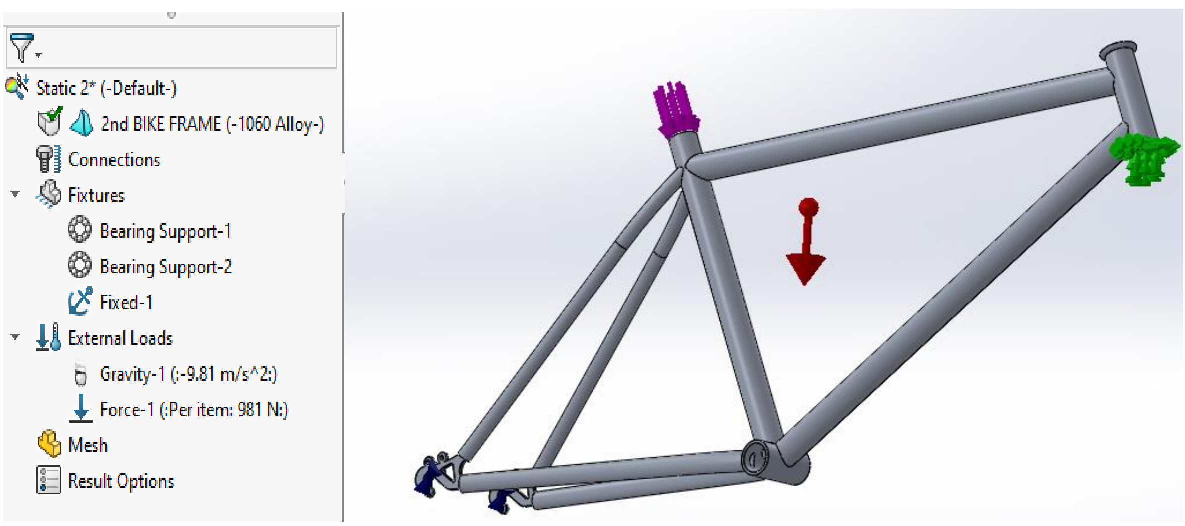


Figure 28: Loads in static startup.

- **Meshing.**
  This design is meshed by using a high-quality solid mesh with an element size of 1.416mm which generated a total of 122552 nodes and 64434 elements as shown in **Figure 29.** This mesh size was automatically selected by SolidWorks.

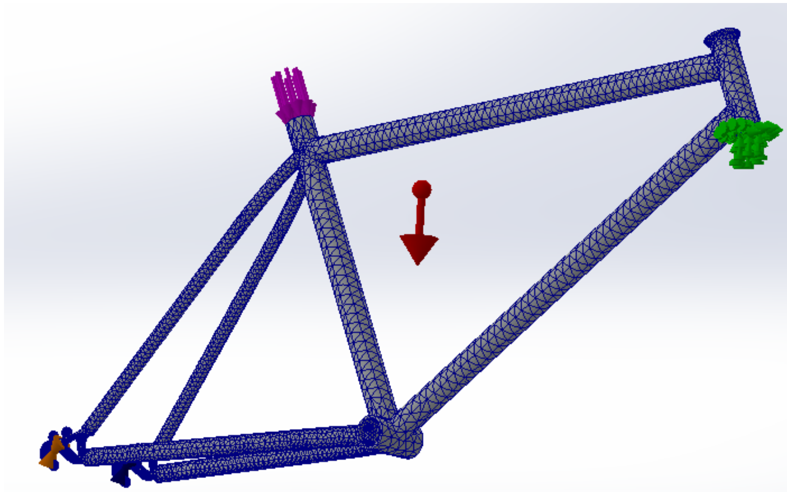


Figure 29: Meshing in the static startup.

3.5.1.2. Steady state pedalling.

- **Fixtures.**

  Figure 30 shows the fixtures that were applied in this load case during the simulation. The first fixture is the lower end of the top tube, and the second fixture is the combination of all two rear wheel dropouts.

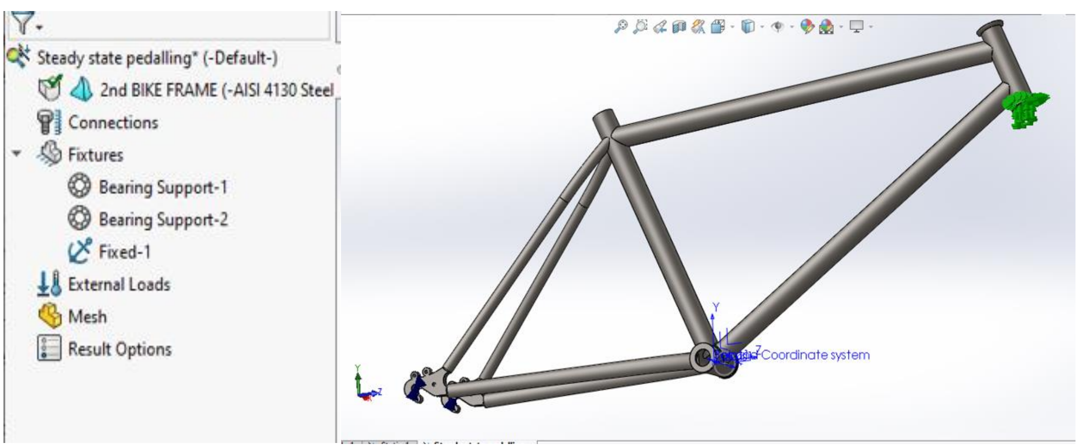


Figure 30: Fixtures in steady-state pedalling.

- **Loads.**

  The loads applied in the load case of steady-state pedalling are shown in Figure 31. The rider's weight of $981N$ is applied on the position of the saddle and a riding force of $200\ N$ is applied horizontally on the bottom bracket.

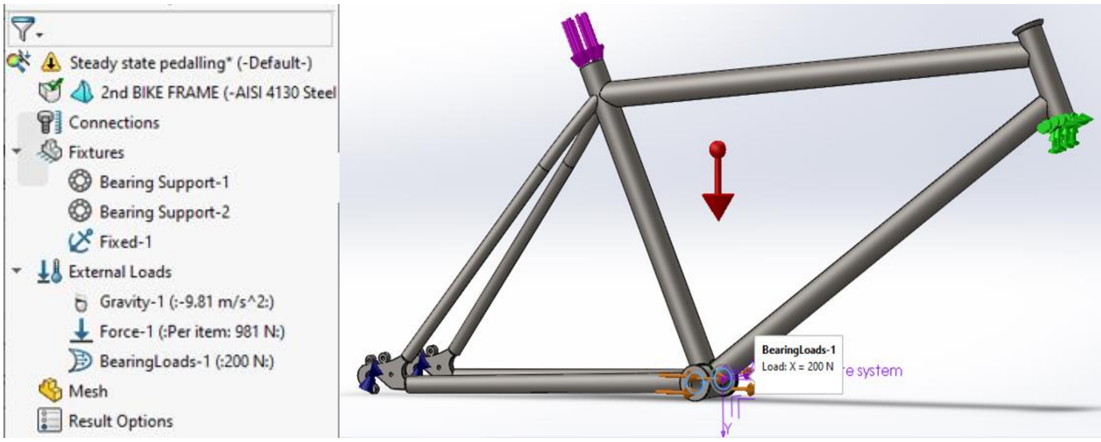


Figure 31: Loads in steady-state pedalling.

- **Meshing.**
  This design is meshed by using a high-quality solid mesh with an element size of 1.416mm which generated a total of 122552 nodes and 64434 elements as shown in **Figure 32.**

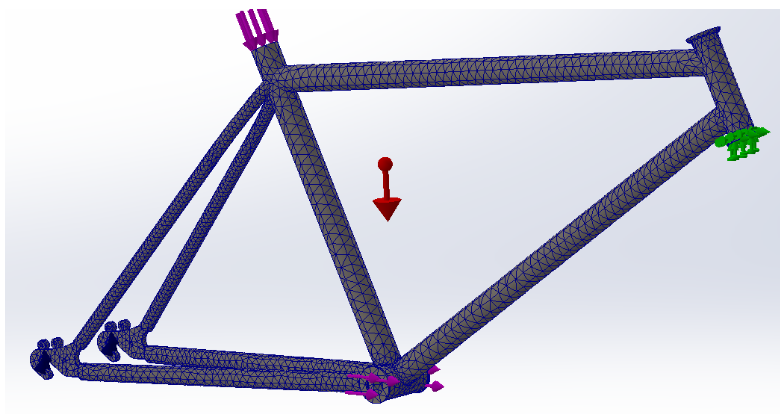


Figure 32: Meshing in steady-state pedalling.

3.5.1.3. Vertical impact.

- **Fixtures.**
  Figure 33 shows the fixtures that were applied in this load case during the simulation. The first fixture is the lower end of the top-tube, and the second fixture is the combination of all two rear wheel dropouts.

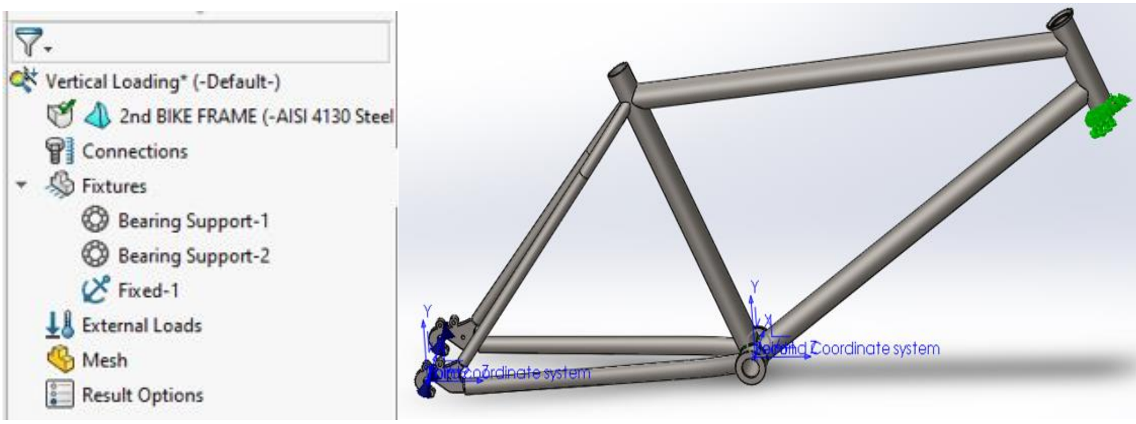


Figure 33: Fixtures in vertical impact.

- **Loads.**
  In this load case of the vertical impact, the rider's weight is increased by a factor of 2 and the weight of the bike frame itself is also increased by a factor of 2 as shown in **Figure 34.**

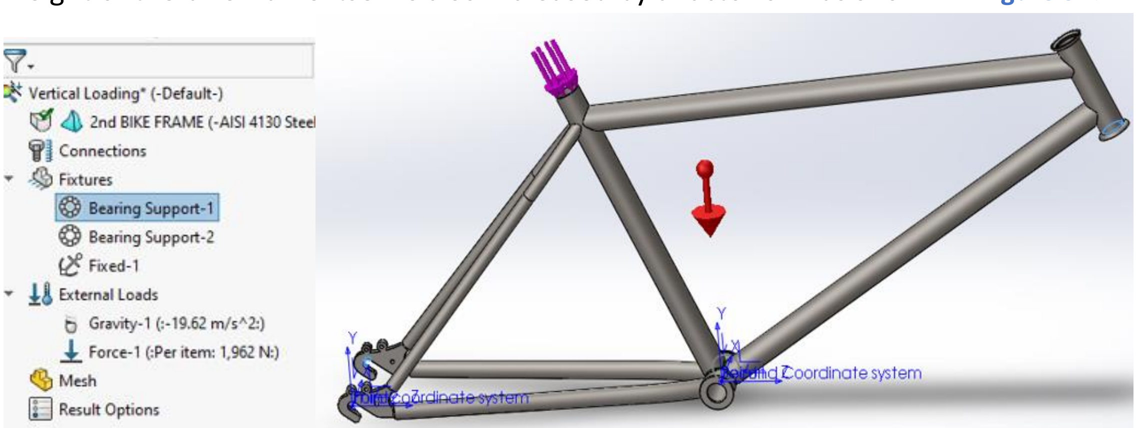


Figure 34: Loads in vertical impact.

- **Meshing.**
  This design is meshed by using a high-quality solid mesh with an element size of 1.416mm which generated a total of 122552 nodes and 64434 elements as shown in **Figure 35.**

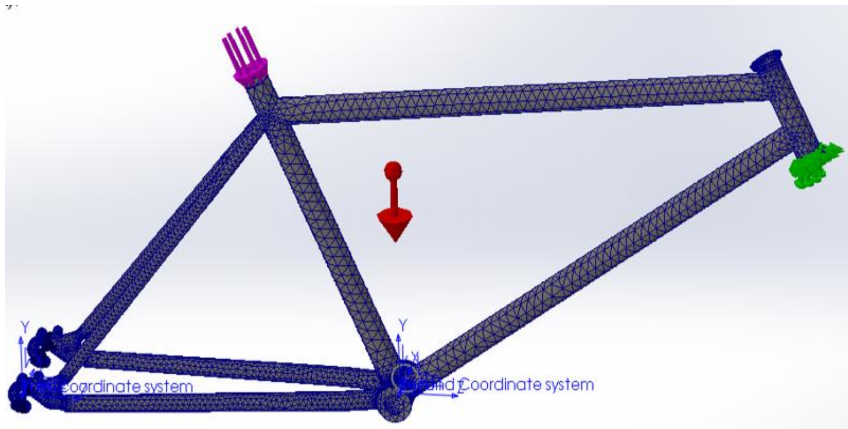


Figure 35: Meshing in vertical impact.

3.5.1.4. Horizontal impact.

- **Fixtures and loads.**

A load which is equivalent to the rider's weight of $981N$ is applied directly in the front of the head tube while the rear wheel dropouts are constrained. This is shown on **Figure 36.**

Figure 36: Loads and fixtures in horizontal impact.

- **Meshing.**

This design is meshed by using a high-quality solid mesh with an element size of 1.416mm which generated a total of 122552 nodes and 64434 elements as shown in **Figure 37.**

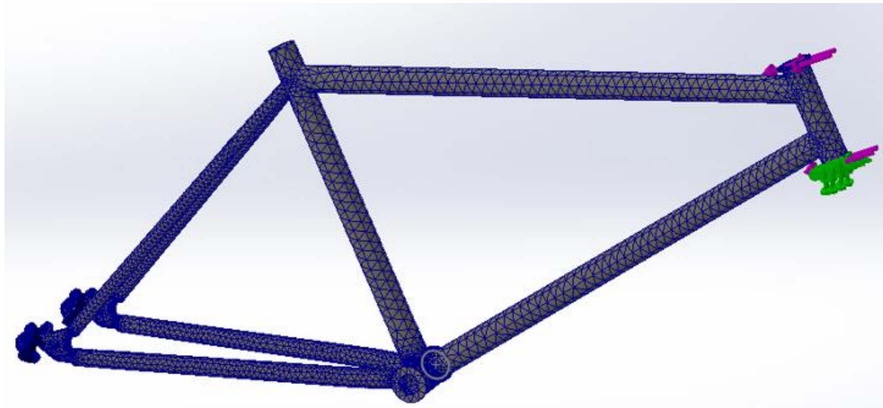


Figure 37: Meshing in horizontal impact.

3.5.1.5. Rear wheel braking.

- **Fixtures and loads.**
  A braking force of $981N$ is given to the rear wheels while the frame is constrained at the bottom face of the head tube as shown in **Figure 38.**

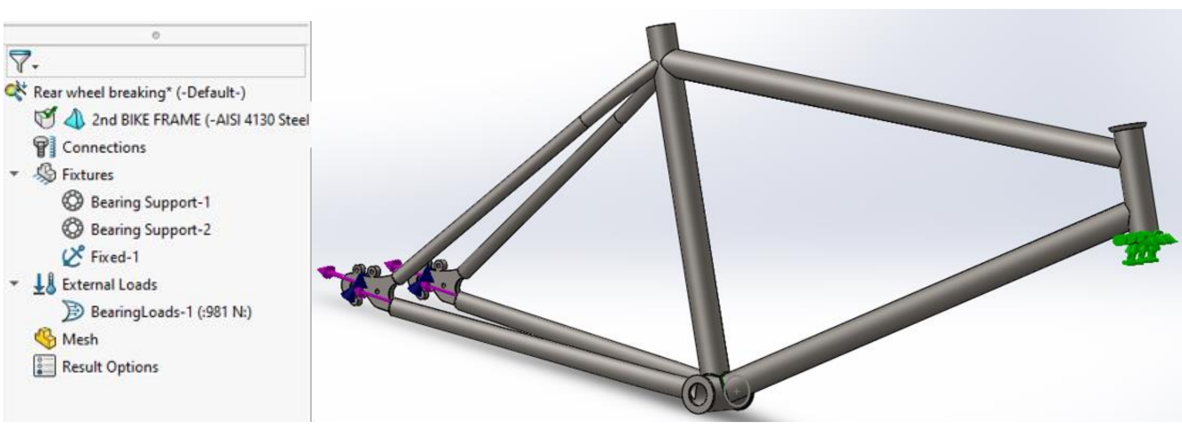


Figure 38: Fixtures and loads in rear wheel braking.

- **Meshing.**
  This design is meshed by using a high-quality solid mesh with an element size of $1.416mm$ which generated a total of 122552 nodes and 64434 elements as shown in **Figure 39.**

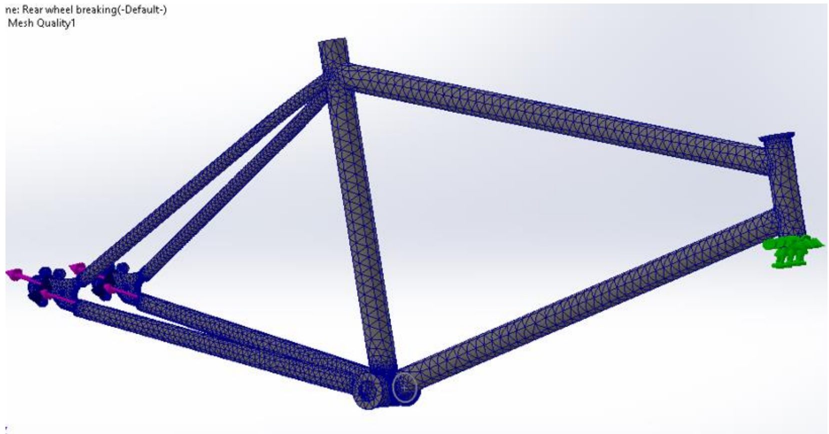


Figure 39: Meshing in rear wheel braking.

3.6. Design Optimization.

SolidWorks is a very flexible software for design analysis and optimization. SolidWorks can be installed on a wide range of operating systems. In SolidWorks, the optimization of a design is done by using the design study tool which is located both in the Simulation tab and Evaluate tab in SolidWorks.

3.6.1. Variables.

The variables are the values of the simulation that the user can modify on the design or structure that is to be optimized.

Table 7: Variables used for the design study.

Variables	Range		Steps	Units
	Minimum value	Maximum value		
Shell thickness	0.9	1.9	0.2	mm
Hole diameter	5	15	2.5	mm
Dropouts thickness	2	8	2	mm

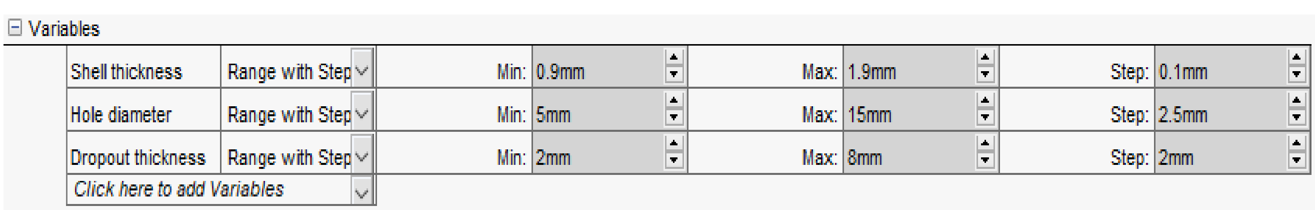


Figure 40: Variables used during design study.

3.6.2. Constraints.

The constraints here are the maximum and minimum values that are placed on various parameters which are to be optimized, they are defined by using sensors. The constraint chosen for the optimization study is the simulation data that is obtained from the simulation of the bike frame in the static study. The constraint that is chosen for this study is the stress from the simulation data. The maximum stress that is chosen for this design study is $\sigma\_\max = 260\ MPa$. done to obtain a factor of safety which is almost 2. These constraints also determine the mass that will be subtracted from the unoptimized design.

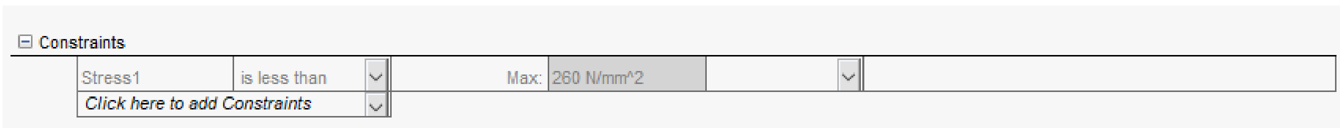


Figure 41: Constraints used during design study.

3.6.3. Goals

In every optimization, there is a parameter that is to be optimized. Depending on the main objectives of the design study, the goal can be mass, energy, temperature, cost etc. The goal of this study is to minimise the mass of the bike frame while keeping it strong and safe. Minimizing the mass of the material used in the manufacturing process will make the bike frame design to be more commercial. However, this reduction in the mass of the design can also lead to a reduction in the factor of safety of the design. The initial mass of the design is $3.879\ kg$.

3.6.4. Running study.

When these goals and constraints are input in the SolidWorks design study, the software automatically generates a particular number of iterations and scenarios according to the variables and constraints, maximum and minimum values of the constraints and according to the step size of each of the constraints that have been entered by the SolidWorks user. The computational time and number of scenarios in the design study depend on several factors such as the number of variables input, the step size of the variables and how complex the geometry of the design is. In this study, a total of 222 scenarios were generated of which 137 out of all 222 scenarios were successful. The scenarios are generated and the design study is run by the software in such a way that the maximum stress in the design should not exceed $260\ MPa$ as chosen for this design while the mass of the design is also minimized at the same time. It took up to about 8 hours and 35 minutes to be carried out by the computers in Room D399 of ARCADA UAS.

4. RESULTS.

4.1. Comparison of the Von Mises stresses obtained for different loading conditions.

It can be seen **Figure *42*** that a maximum stress 96.9 MPa in static startup occurs at the bottom bracket while the minimum Von Mises stress approximately 32 MPa occurs at the rear wheel dropouts.

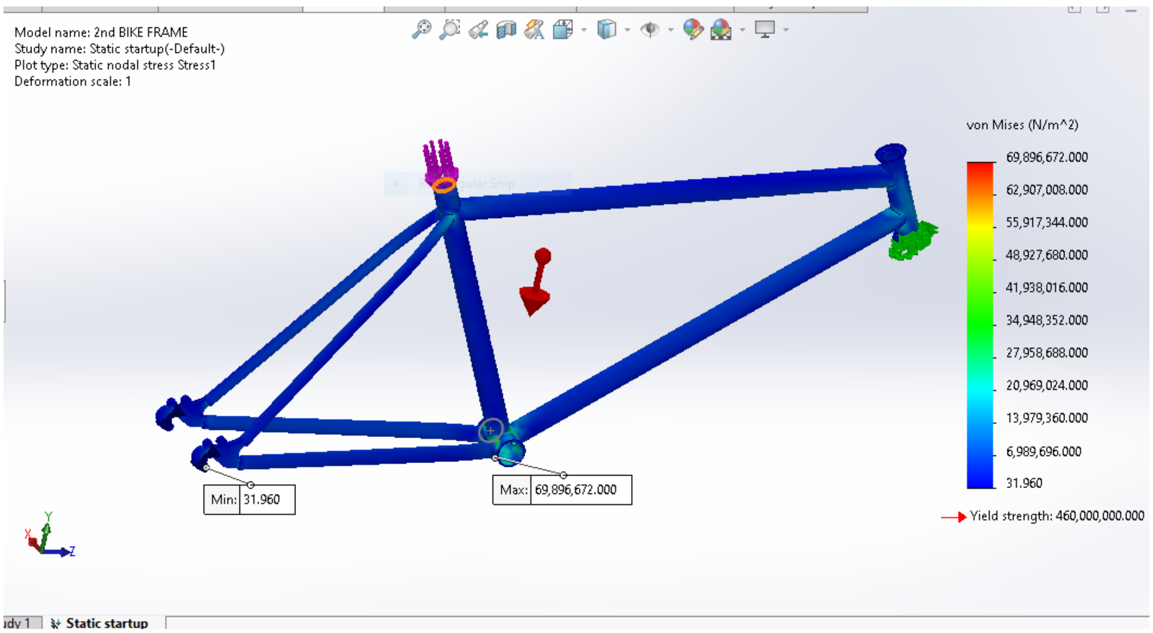


Figure 42: Equivalent Von Mises stress in static startup.

Figure 43 shows the Von Mises stress plot for steady-state pedalling and the maximum Von Mises stress of 42.3 MPa is felt at the bottom bracket while the minimum Von Mises stress is felt at the rear wheel dropouts.

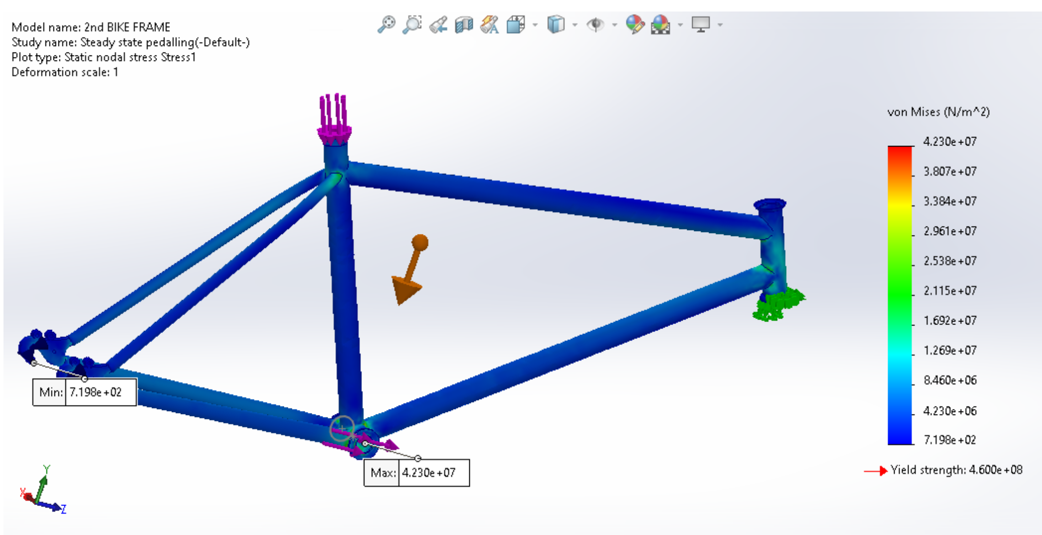


Figure 43: Equivalent Von Mises stress in steady-state pedalling.

During vertical impact, the frame is subjected to a maximum Von Mises stress of 96.7 MPa and a minimum Von Mises stress of 68.7 Pa as shown in **Figure 44**. This load causes the chain stays and the seat stays to twist and appear as if they seem to be intersecting each other.

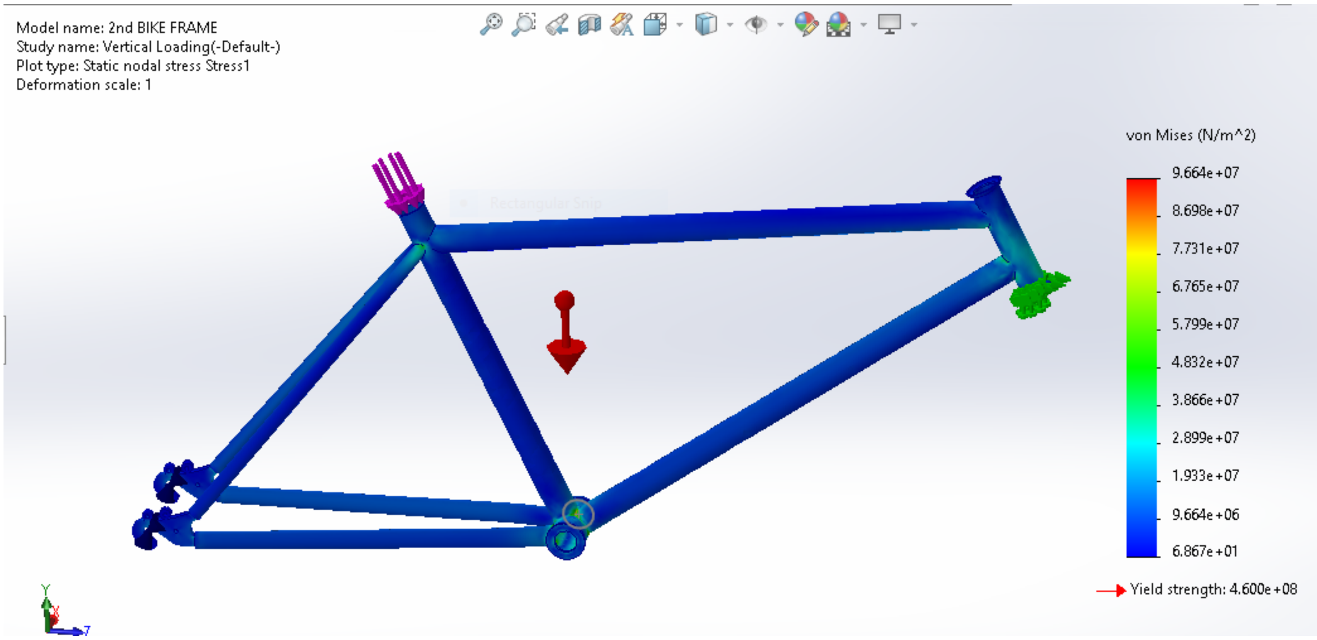


Figure 44: Equivalent Von Mises stress in vertical impact.

During horizontal impact simulation, the bike frame is subjected to a maximum Von Mises stress of 46.7 MPa that occurs at the head tube and a minimum Von Mises stress of 21 MPa that occurs at the rear wheel dropouts as shown in **Figure *45***.

Figure 45: Equivalent Von Mises stress in horizontal impact.

The Von Mises stress plots for rear wheel braking is shown in **Figure *46*** with the dropouts and bottom bracket subjected to maximum and minimum stresses $73.49 MPa$ and $4.82\ Pa$ respectively.

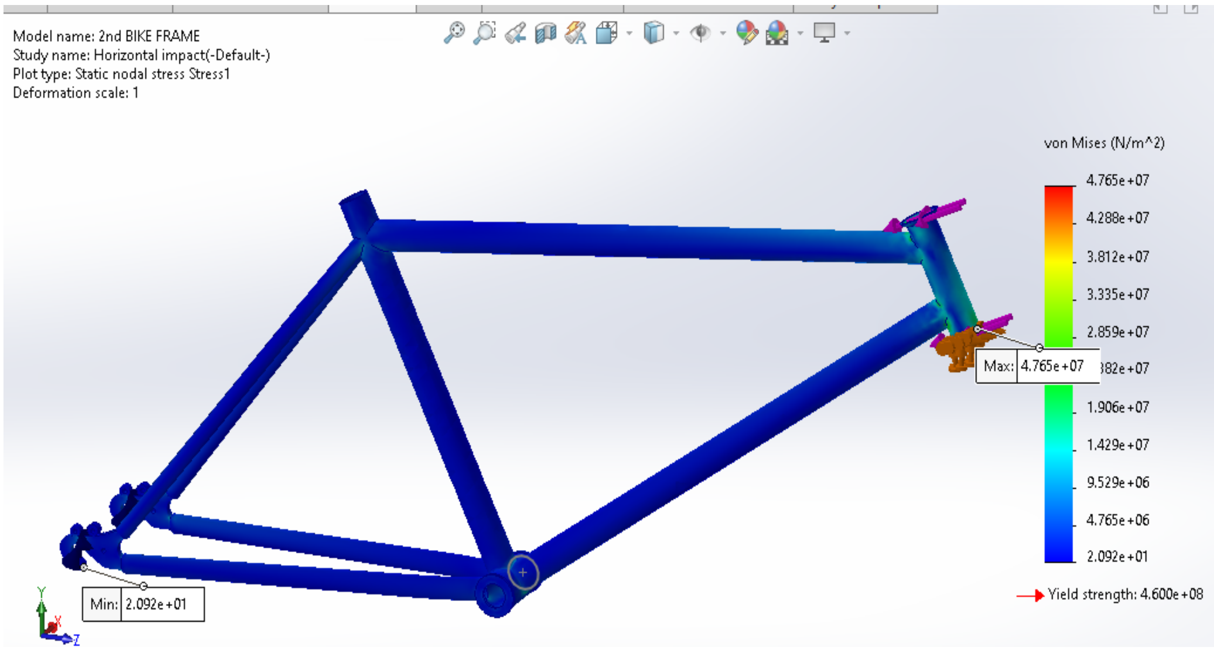


Figure 46: Equivalent Von Mises stress in rear wheel breaking.

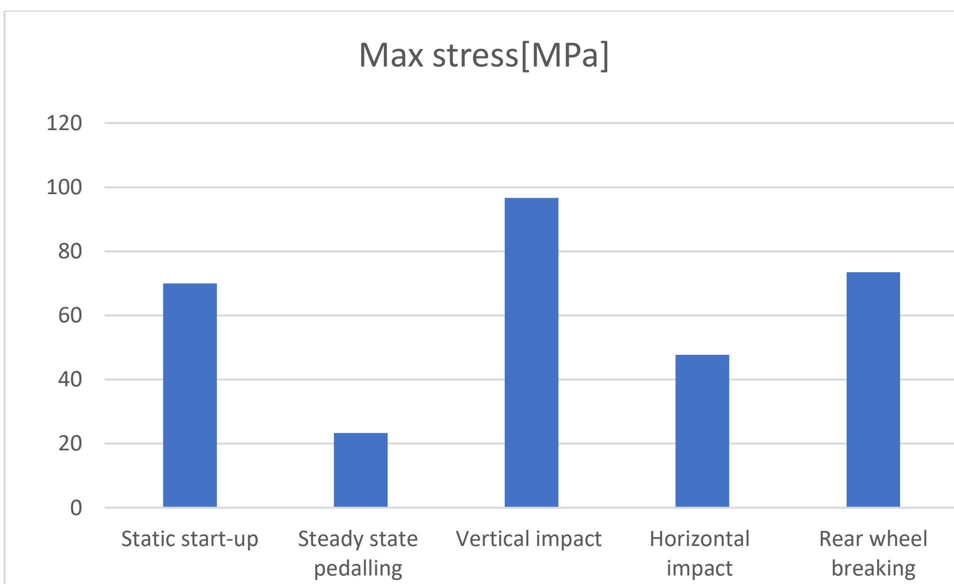


Figure 47: Comparison of Von Mises stresses for all five load cases.

Figure 47 gives a detailed summary of the maximum Von Mises stress in all five load cases. It can be seen from this figure that the load case with the maximum Von Mises stress is the vertical impact with a maximum value of $96.64\ MPa$ followed by rear wheel braking with a maximum Von Mises stress of

$73.49 MPa$ and the load case with the least maximum Von Mises stress value is steady state pedalling with maximum Von Mises stress of $23.3\ MPa$.

4.2. Comparison of displacements obtained for different loading conditions.

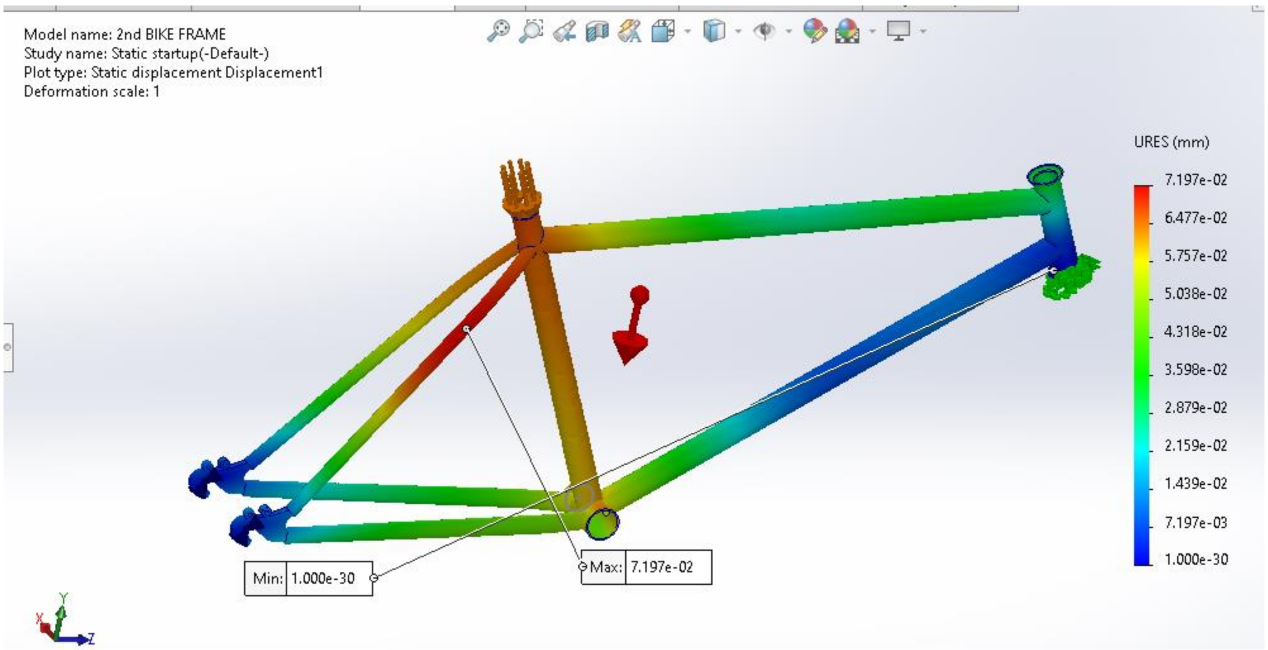


Figure 48: Equivalent displacement in Static startup.

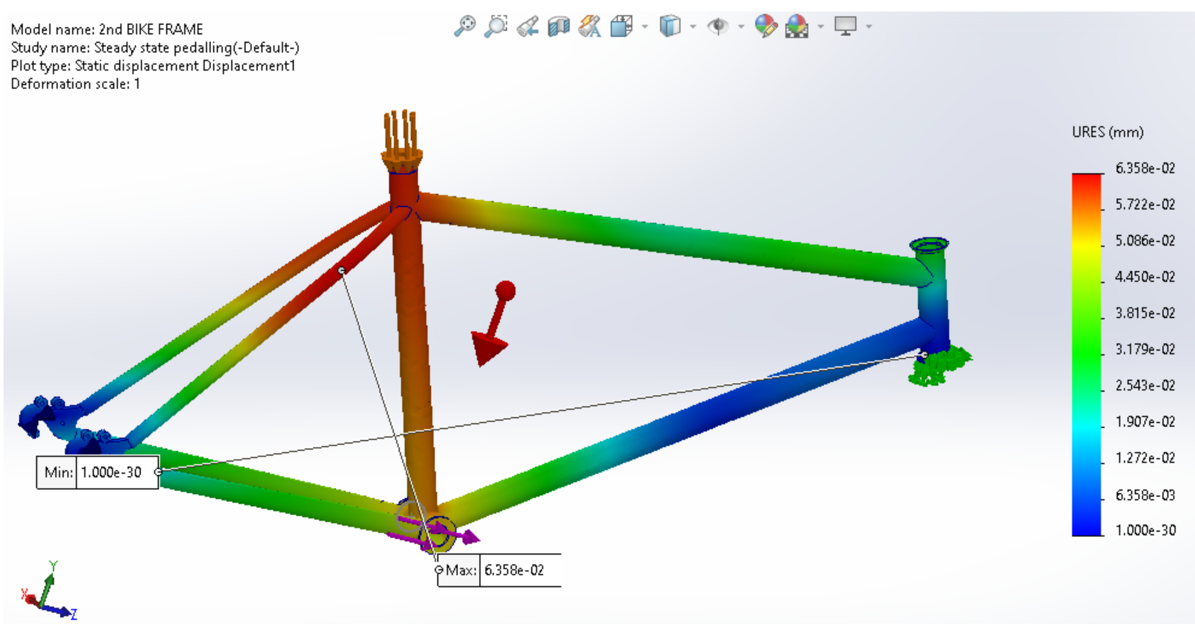


Figure 49: Equivalent displacement in steady state pedalling.

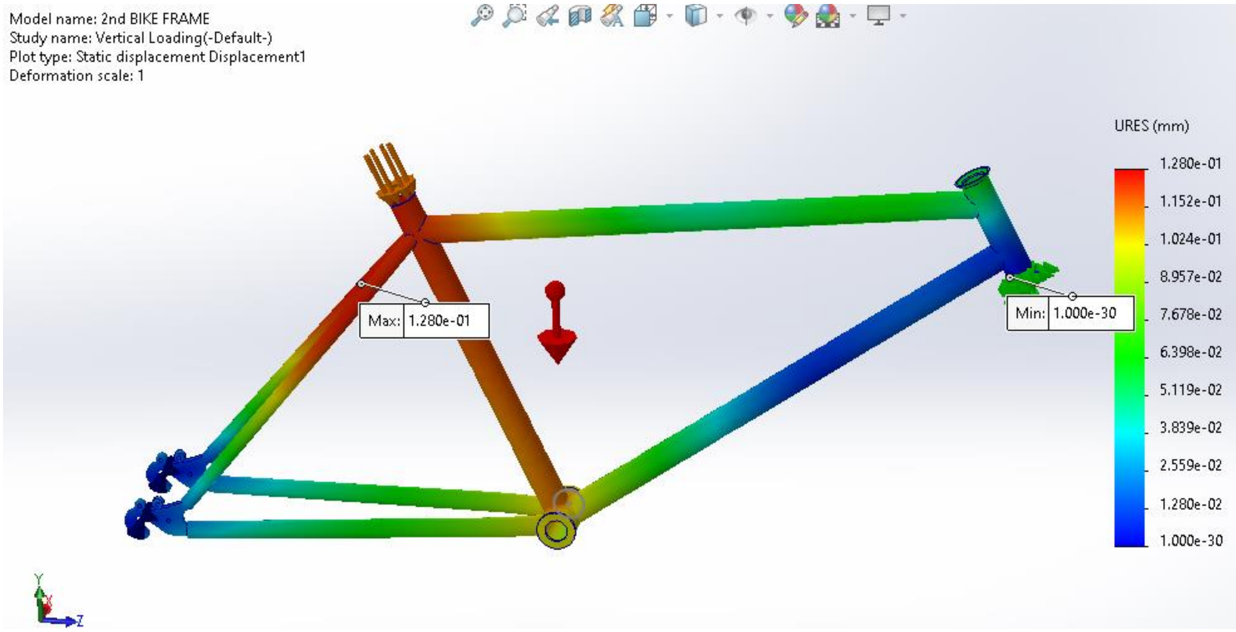


Figure 50: Equivalent displacement in vertical loading.

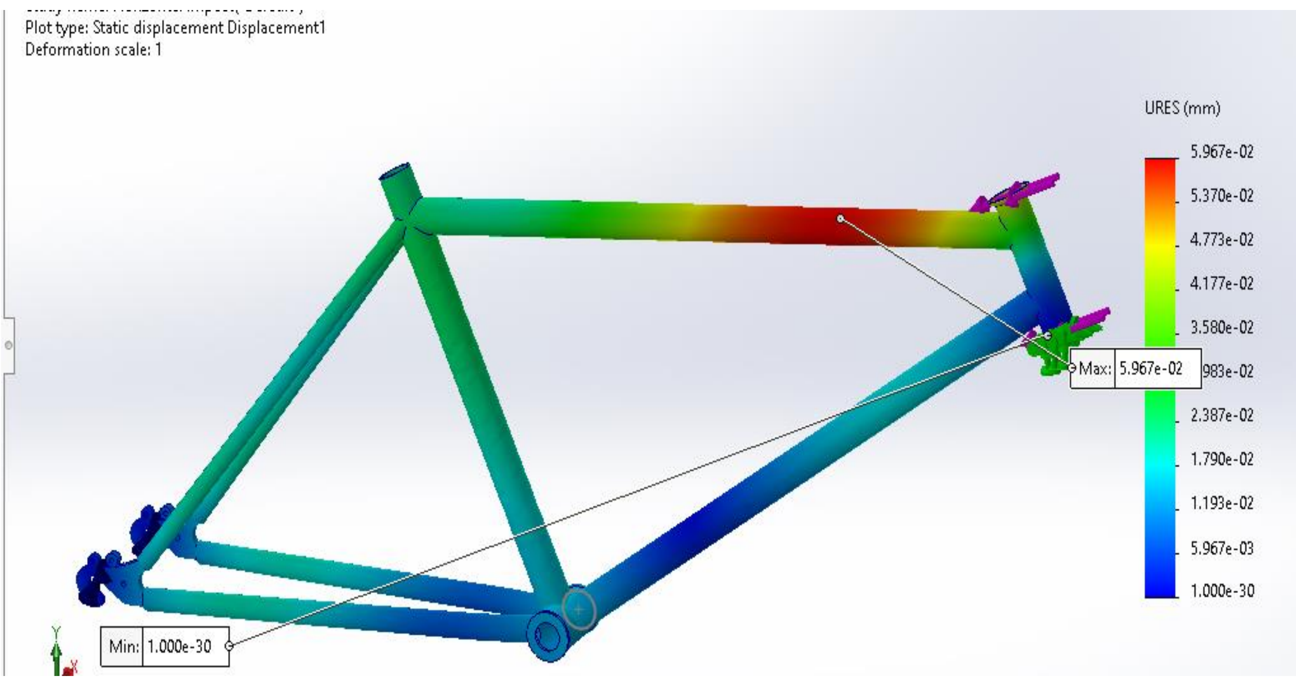


Figure 51: Equivalent displacement in horizontal impact.

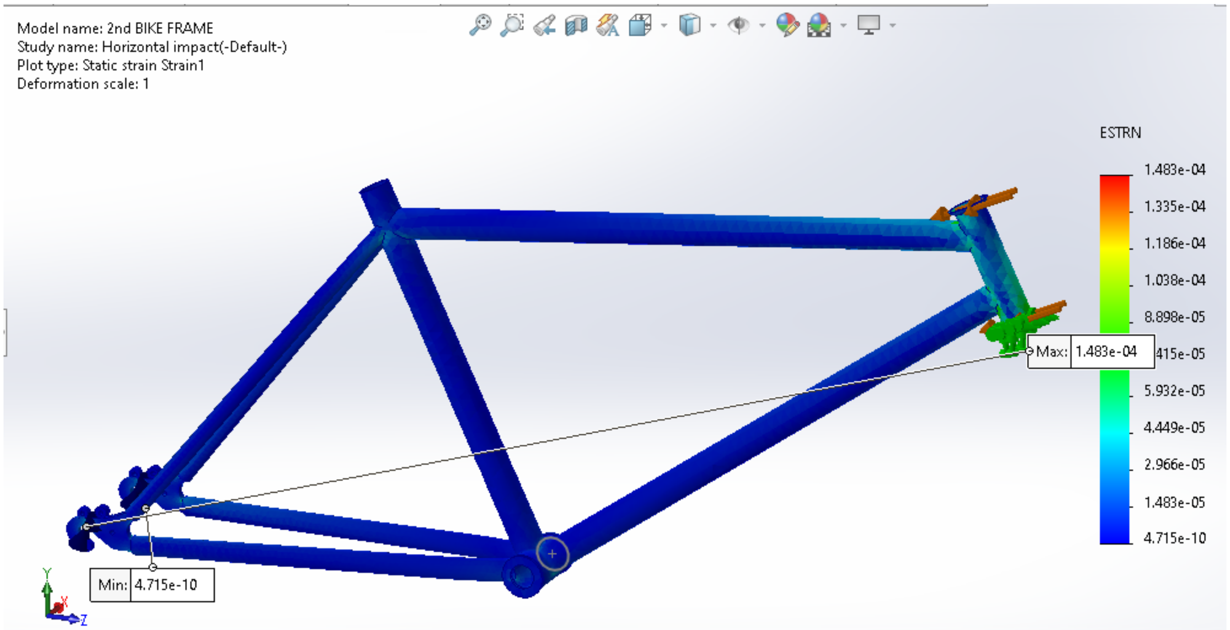


Figure 52: Equivalent displacement in rear wheel breaking.

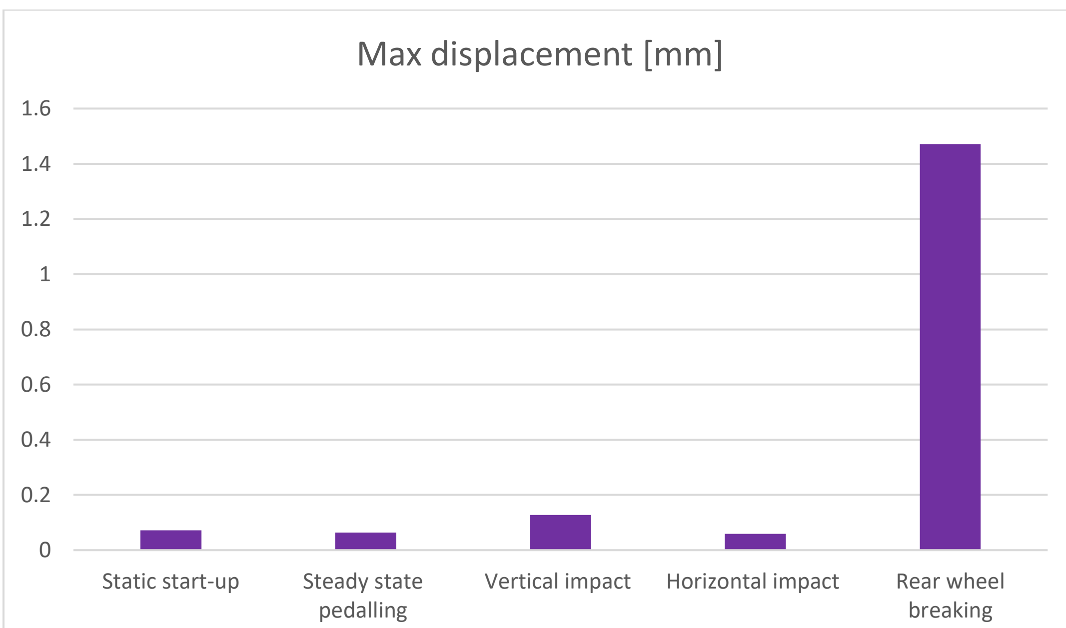


Figure 53: Comparison of maximum displacements from all five load cases.

Figure *53* summarizes the comparison of the deformation of the bike frame in all five load cases. It can be seen from the figure that the load case with the highest deformation is rear wheel braking with a maximum displacement of $1.472mm$ and the load case with the least deformation is horizontal impact with a maximum displacement of $0.05967\ mm$. The reason for the maximum deformation in the rear wheel braking case is due to the high stresses which are acting in the rear dropouts.

4.3. Comparison of strains obtained for different loading conditions.

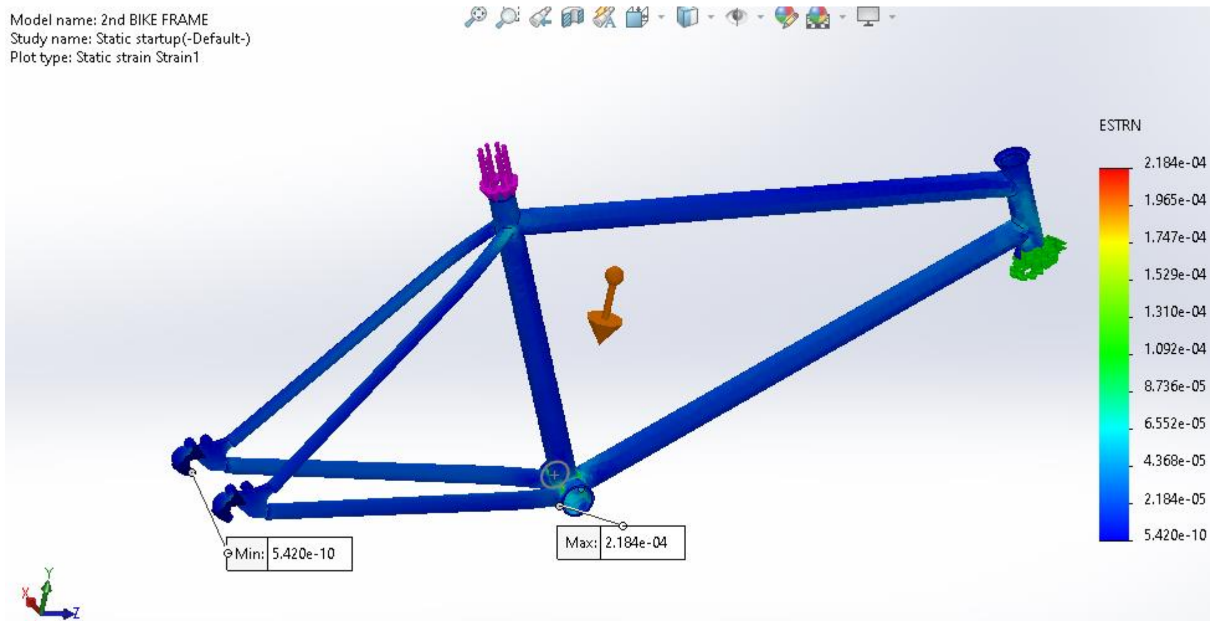


Figure 54: Equivalent strain in Static-startup.

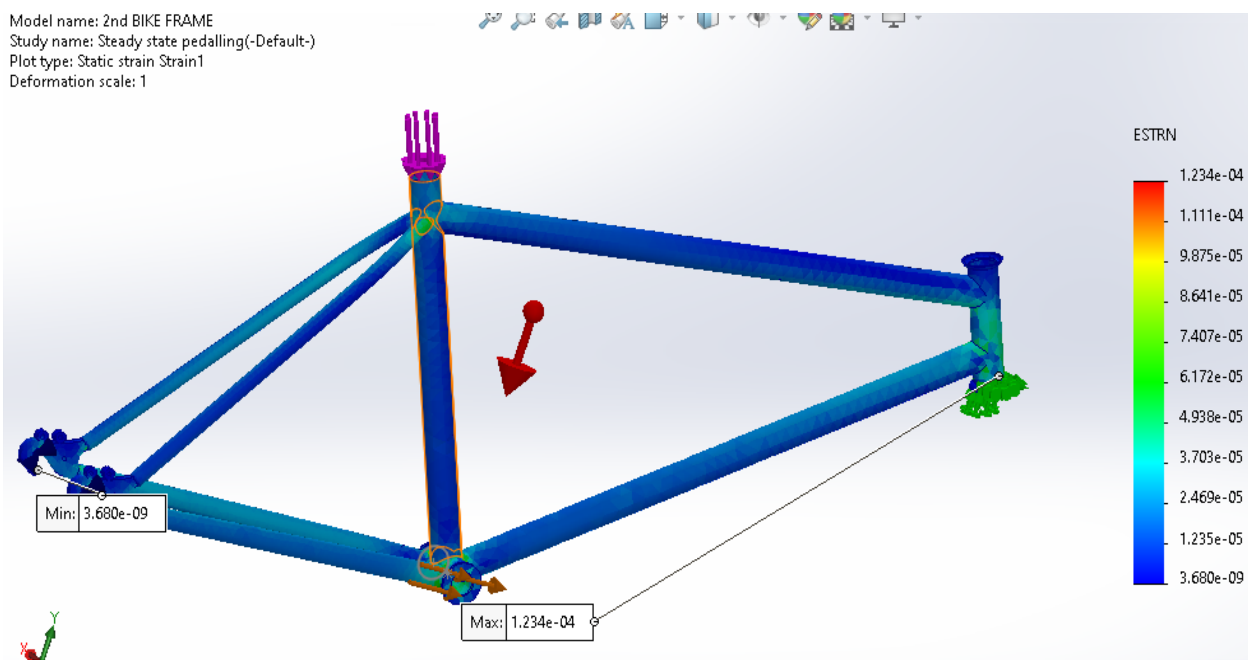


Figure 55: Equivalent strain in steady state-pedalling.

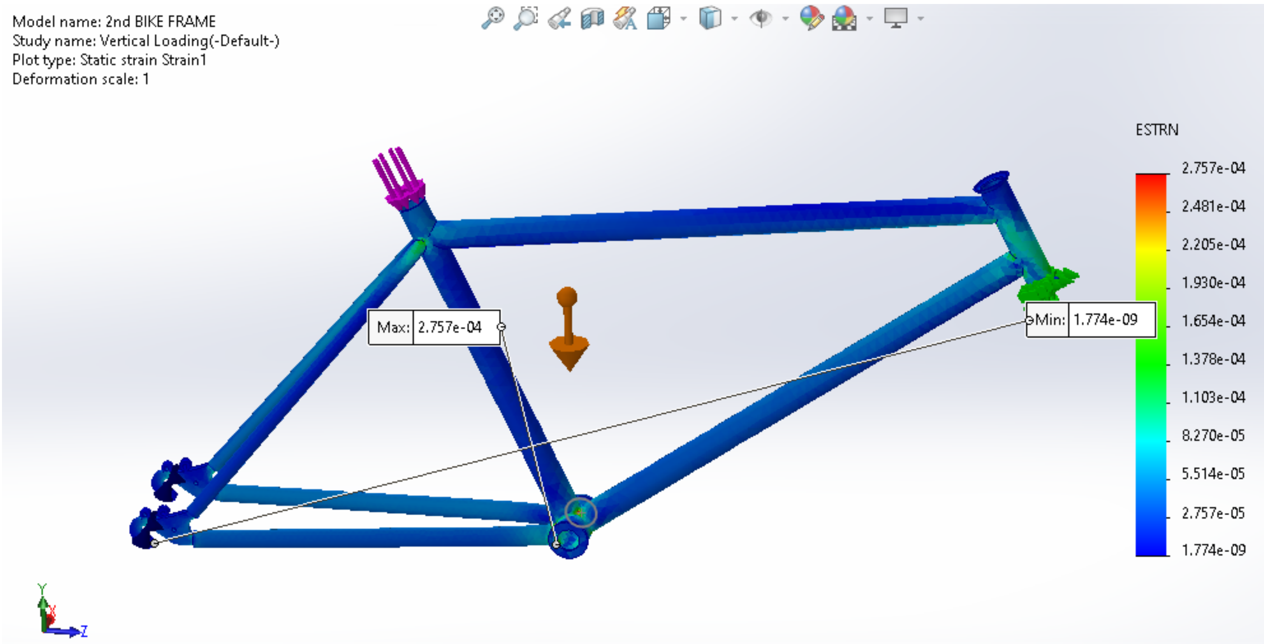


Figure 56: Equivalent strain in vertical impact.

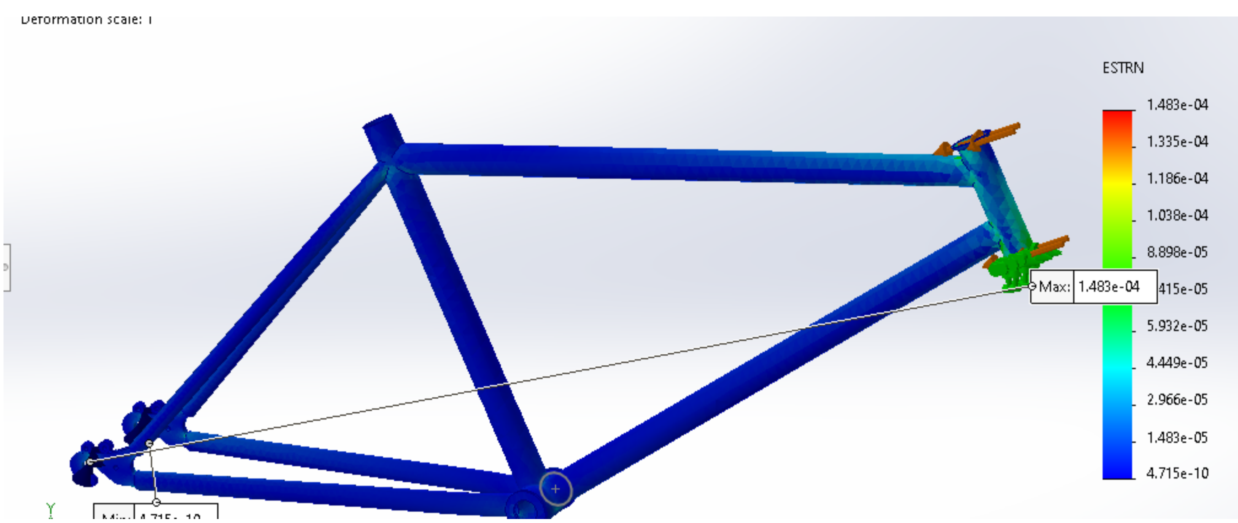


Figure 57: Equivalent strain in horizontal impact.

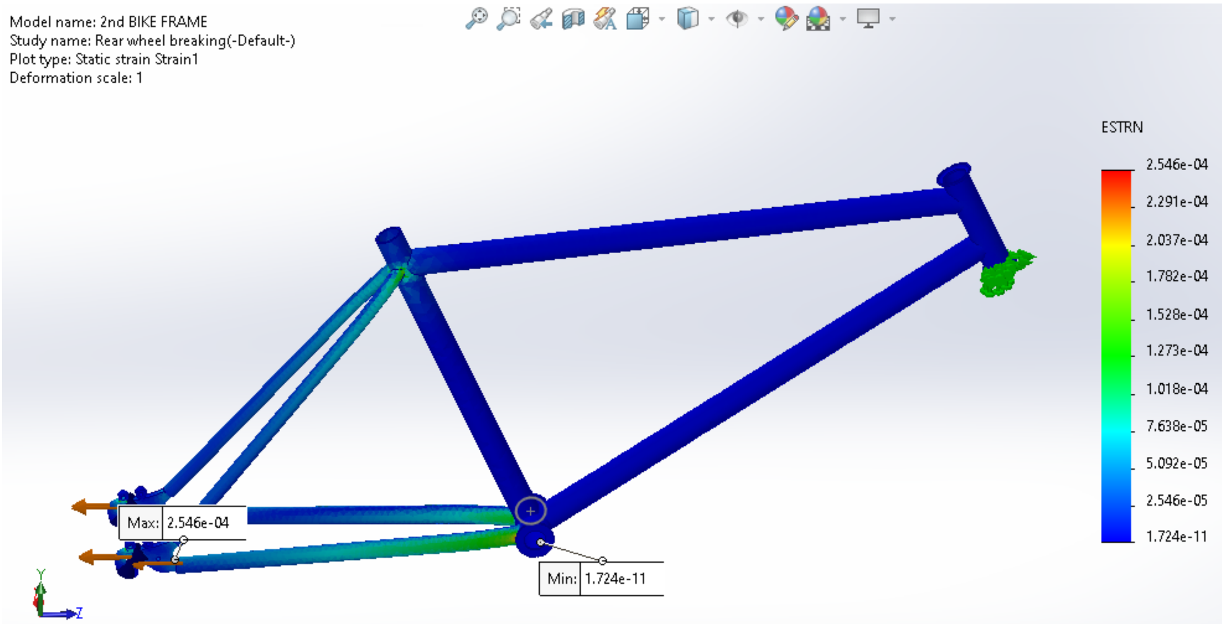


Figure 58: Equivalent strain in rear wheel braking.

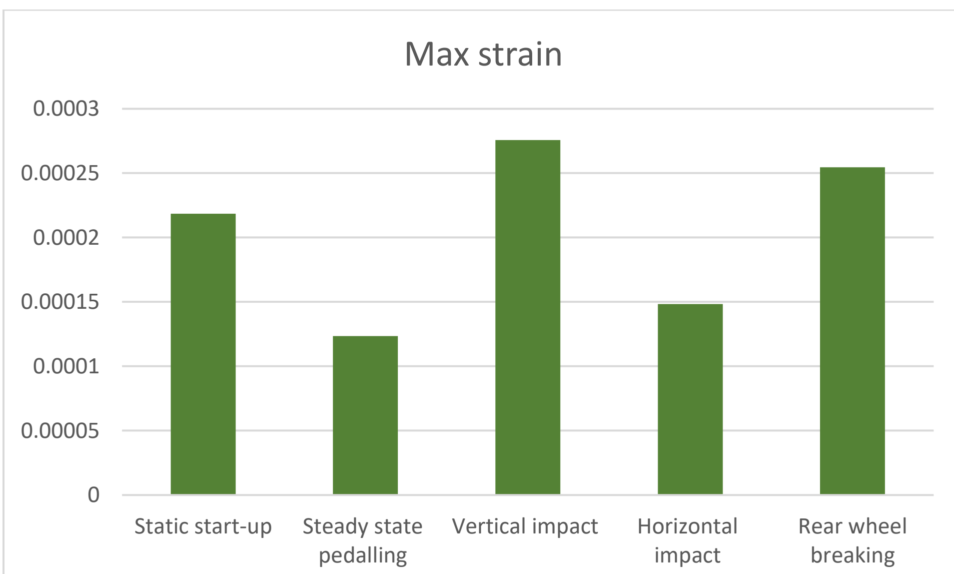
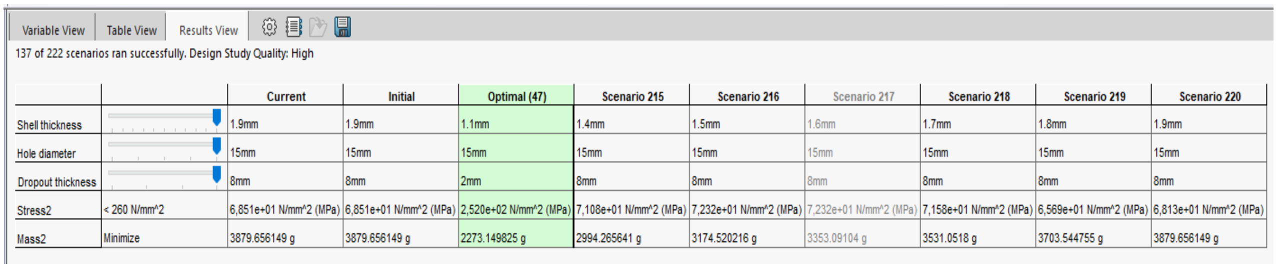


Figure 59: Comparison of equivalent strains in all five load cases.

Figure 59 summarizes the strains of the bike frames for all five load cases, the maximum strain 0.0002757 occurs in the vertical impact due to the extremely high stresses because of the 2G factor during the vertical impact.

4.4. Result for Design optimization.

After running the design optimization in b using the Design study tool in SolidWorks, this software optimised the design by using three constraints as shown in **Figure 60** below. Weight reduction is needed in this bike frame to minimize the manufacturing cost of the bicycle chassis because this will increase the quantity of material which is saved in the manufacturing process. This optimization process has not just minimized the mass of the design but has also made the design meet its structural requirements such as meeting up with the reliable factor of safety. It can be seen from the mass optimization result in **Figure 60** that the mass of the design has been optimized in such a way that there is a decrease in mass from 3.880 kg to 2.273 kg which gives a 41.42 % decrease in mass. It can also be learnt that decreasing the shell thickness, decreasing the rear wheel dropout thickness and increasing the diameter of the hole in the rear wheel dropouts has led to a significant decrease in the mass of the standard while not cutting the edge of it's safety. Though the maximum stress of the optimized design has increased, the design remains safe to be used in all five loading conditions.


Variable View | Table View | Results View

137 of 222 scenarios ran successfully. Design Study Quality: High

		Current	Initial	Optimal (47)	Scenario 215	Scenario 216	Scenario 217	Scenario 218	Scenario 219	Scenario 220
Shell thickness		1.9mm	1.9mm	1.1mm	1.4mm	1.5mm	1.6mm	1.7mm	1.8mm	1.9mm
Hole diameter		15mm	15mm	15mm	15mm	15mm	15mm	15mm	15mm	15mm
Dropout thickness		8mm	8mm	2mm	8mm	8mm	8mm	8mm	8mm	8mm
Stress2	< 260 N/mm^2	6,851e+01 N/mm^2 (MPa)	6,851e+01 N/mm^2 (MPa)	2,520e+02 N/mm^2 (MPa)	7,108e+01 N/mm^2 (MPa)	7,232e+01 N/mm^2 (MPa)	7,232e+01 N/mm^2 (MPa)	7,158e+01 N/mm^2 (MPa)	6,569e+01 N/mm^2 (MPa)	6,813e+01 N/mm^2 (MPa)
Mass2	Minimize	3879.656149 g	3879.656149 g	2273.149825 g	2994.265641 g	3174.520216 g	3353.09104 g	3531.0518 g	3703.544755 g	3879.656149 g

Figure 60: Properties of optimized design.

Table 8: Results of stresses in the bike frame members by hand calculation.

Frame member	**Shell area** $[mm^2]$	**Force** $[N]$	**Stress** $[MPa]$
Seat tube	179.67	−434.926	−2.420724699
Top tube	173.70	−384.715	−2.214841524
Down tube	173.70	131.813	0.758859635
Chain stays	90.13	345.472	1.916470155
Seat stays	84.16	−771.467	−4.58315739

Table 9: Properties of design before and after optimization.

Quantity	**Analytical calculation**	**Value before optimization**	**Value after optimization**
Shell thickness $[mm]$	1.9	1.9	1.1
Hole diameter $[mm]$	5	5	15
Dropout thickness $[mm]$	8	8	2
Max stress $[MPa]$	4.58	68.51	252.0
Mass $[kg]$	NA	3.880	2.273
FOS	94.98	4.8	1.83

The factor of safety of the optimized design can be calculated by using the factor of safety formula which is shown in **Equation 2.1** above. The yield strength of steel 4130 is $460\ MPa$ (Matmatch, 2024).

The factor of safety FOS $= \frac{460\ MPa}{252\ MPa} = 1.83$

Even though this factor of safety is comparatively low, the design is still able to meet up with its structural requirements. It is seen on **Table *8*** that the maximum stress in the bike frame calculated by hand is far lower than the maximum stress that has been generated by the simulation software. The stress in the analytical calculations is comparatively low because the joints and other parts of the bike frame that have higher stresses in the bike frame were impossible to consider in the hand calculations. In the post-optimization, there is also a significant decrease in the factor of safety from 4.8 to 1.83 due to a reduction in the shell thickness and other optimization parameters. This optimized mass of the steel bike frame is not that far from the mass of the steel bike frames which are available in the market. However, the mass of the lightest steel bike frame is as small as $1.24\ kg$ (Unpainted weight) (Luke, 2019).

5. DISCUSSION.

Before the optimization, the minimum factor of safety of the design in SolidWorks was 4.8. After the optimization process, the factor of safety of the design decreased to 1.8 due to the decrease in shell thickness of the frame. The bike frame member that had the maximum stress in the analytical calculation was the seat stay with the stress of $4.583\ MPa$ which is not accurate because some vital parts of the bike frame were not considered during the analytical calculation. The FEA results generated by SolidWorks were more accurate, these FEA results gave a maximum stress of $96.64\ MPa$ which was in vertical loading. This result generated by FEA is more accurate because Finite Element Analysis takes the whole bike frame into account regardless of the complexity of the geometry and it also considers the areas where the highest stresses are concentrated. This accounts for the huge differences between the stresses and FOS in FEA and hand calculation. The accuracy of FEA also depends on the mesh size and the number of nodes in the discretization process, this increases the number of of calculation points and then increases the accuracy. The margin of the accuracy of FEA depends on the number of nodes and on the mesh size.

Since the factor of safety of the design calculated by using the analytical method was 94.98 which is far greater than the final factor of safety of the optimized design, what accounts for this big difference is the fact that the joints, and junctions around other parts of the bicycle frame such as the bottom bracket and the dropouts were not taken into consideration while calculating the stresses analytically. It's practically known that around these joints the stress concentrations are always very high due to the abrupt change in cross-sectional areas and geometries, in most cases some cases in failure occurs in mechanical structures, it's always due to high stress around joints.

Most bike frame manufacturing companies today use other expensive bike frame materials such as carbon fibre reinforced composites and titanium to manufacture the bike frames, however, in this study that has not been the case, using a cheaper but stronger material makes the bike frame manufacturing process more commercial.

6. CONCLUSION.

In conclusion, the main objectives of this work have been attained. One of the objectives of this study is to calculate the stresses by hand by using either the method of sections or the method of joints. This bicycle frame was analysed both manually and by using the simulation software. In the analytical method, both the method of sections and the method of joints were used to calculate the forces in all truss members of the bike frame and these forces were used to find the stresses in the truss members with the aid of Microsoft Excel. The method of joints gave the numerical values of the stresses in the various bike frame members using Microsoft Excel. The bike frame member that had the highest stress was the seat stay with stress of $4.583\ MPa$. In this thesis, the modelling of the bike frame was done in SolidWorks 2023. The bike frame is mostly composed of four different materials, that is Aluminium (specifically Al 6061), titanium alloys, steel, and carbon fibre-reinforced composites. The simulation on the bike frame was done by using five different load cases that include static startup, steady state pedalling, vertical impact, horizontal impact, and rear wheel braking. These simulations were used to analyse the Von Mises stresses, deformations, and strains of all five load cases. Comparative studies were conducted on the equivalent Von Mises stresses, deformations, and strains on all five load cases. Among all five load cases, the maximum equivalent Von Mises stress was found during vertical loading and had a value of $9.64\ MPa$. The load case with the maximum displacement was rear wheel breaking with a maximum displacement of $1.472\ mm$ and the load case that had the maximum strain was rear wheel breaking with a strain of 0.0002546.

The main objective of this thesis was also to design and optimize the bicycle chassis by using the design study tool in SolidWorks which is located both in the Simulation and Evaluate tabs in SolidWorks. Since the vertical loading case generated the maximum equivalent Von Mises stress of $96.64\ MPa$ that occurred because of stress concentrations around the bottom bracket, its simulation data was used to conduct the optimization. During the optimization, several sensors were used to run the optimization. A total of 222 scenarios were generated of which 137 of all the 222 scenarios were successful, the initial mass of the design was reduced by 41.42% while its safety and structural requirements were not compromised. The factor of safety of the final design was 1.83 which is quite acceptable in mechanical engineering.

Design optimization is important in mechanical engineering and manufacturing in several ways because it reduces the manufacturing mass hence making the manufacturers save more material which makes the manufacturing process more sustainable, this also reduces the manufacturing time of this product because if it's to be tested in real life it will take more time as compared to when using a simulation software, this will lead to less manufacturing time and less material will be consumed.

From this result analysis, it can be concluded that SolidWorks can be used by production and manufacturing industries to minimize the quantity of material needed to manufacture their final products, reducing the manufacturing time and cost while maximizing their profits without compromising the safety parameters of the design. The reduction in weight of the bike frame will also ease the riding for the rider because the bike frame has become lighter.

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