DE-41 (DME)

YEAR 2023

# NUST COLLEGE OF ELECTRICAL & MECHANICAL ENGINEERING

# Design and Fabrication of Hollow Structured Flat-Free Non-Pneumatic Tyres for Bicycle

A PROJECT REPORT

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***Submitted by***


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**PESHAWAR ROAD, RAWALPINDI**

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# ACKNOWLEDGEMENT

We want to acknowledge the faculty and HOD of Department of Mechanical Engineering CEME NUST for delivering quality educational knowledge, equipping us for this bachelor's thesis. We want to extend our gratitude to our worthy supervisor, Asst. Prof. Rehan Ahmed Khan & Dr. Sajid Ullah Butt for guiding us through every aspect of this project.

# ABSTRACT

Non-Pneumatic Tyres (NPT) are a single entity which replaces the conventional pneumatic tyres in transportation applications. Major research has been conducted to design and fabricate a working prototype of such tyre which can replace the pneumatic tyres in all type of vehicles. However, so far only NPT designed and tested are targeted in the heavy machinery and military transportations to replace the presence of air in the tyre. Design and prototyping of a non-pneumatic tyre for high-speed automobiles, three-wheelers and bikes remains a challenge till now. Major cause of this is the shearing of the material of non-pneumatic tyres which occurs at high-speed maneuvering of vehicle. Air causes potential problems linked with puncture, leaks, thermal stresses, and high internal pressure. This research focuses on the analysis, and study of materials and hollow structural elements which can form the basis of a fully functional non-pneumatic tyre, design of NPT targeted to be used in a bicycle and fabrication of a pair of NPTs which can replace a conventional air-tyre in a utility bicycle.

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# Chapter 1

# INTRODUCTION

## 1.1 Tyres

A tyre is a ring-shaped automobile part that surrounds the rim of the wheel in order to protect it and improve the vehicle's performance. Tyre is the main component of any dynamic system spanning from a simple cart to an eighteen-wheeler trailer. It is the only contacting component between the vehicle and the surface on which that vehicle is moving. This implies that they oversee acceleration, braking, steering, and absorbing any bumps the road may present. Propulsion of the vehicles moving on land usually comes from the friction between the tyres and the surface. Most tyres, including those for cars and bicycles, offer friction between the vehicle and the road while also acting as a flexible cushion to absorb shocks. This friction plays a vital role in the dynamics of the whole vehicle, ultimately defining the performance of the vehicle too. The friction is affected by many factors from which the condition of the surface and the design of the tyres is important. It becomes clear that having good tyres will greatly improve your driving experience. There are numerous varieties of tyres on the market, and not all of them offer the same performance levels. While some tyres roll more smoothly at high speeds for better fuel efficiency and lower noise, others offer significantly superior grip in wet or snowy conditions. This attribute of tyres makes them the most critically designed and engineered constituent in dynamic systems.

## 1.2 Tyre Mechanics

Mechanics is the field of practical applied physics which focuses on the study of forces, energy and their effects on different bodies under influence. Keeping this definition under view, tyre mechanics primarily deals with the study of different forces which affect the motion, formation and properties of tyres. Now, tyres can be in motion as well as stationary when the dynamic system is not in motion, so the tyre mechanics can be further divided into the field which deals with the statics of the tyre and the field which deals with the dynamics of the tyre i.e. tyre dynamics. The study of tyres is an important subject in overall vehicle dynamics. The forces acting on tyres play an important role in the handling, stability, performance and comfort of the vehicle itself.

### 1.2.1 Tyre Terminologies

The performance of tyres greatly depends on various characteristics of the tyre. These characteristics define how the tyre will respond under different environments and applications. For instance, one of the most significant characteristics is the balance of the tyre. When a wheel and tyre are rotating, they provide centrifugal force on the axle depending on where their centre of mass is located and which way their moment of inertia is oriented. The term "balance or imbalance wheel" is used to describe this. At the point of manufacture, tyres must be inspected for excessive static and dynamic unbalance.

There are some terms associated with the tyres when it comes to the in-depth study of how tyres behave under static and dynamic loadings in a system. These terms are broadly explained in the sub-headings as under.

#### 1.2.1.1 Slip Angle

The first concept you must comprehend in order to completely comprehend tyre dynamics is slip angle. This is referred to as the angle (in degrees) formed between the wheel's actual direction of movement and its "pointing" direction (perpendicular to the axis of rotation). When a vehicle experiences lateral acceleration, there is always an angle between the two.

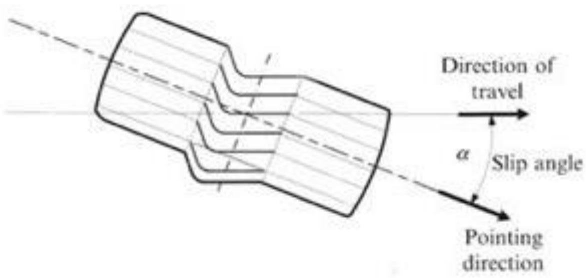


*Figure 1.1 Slip Angle*

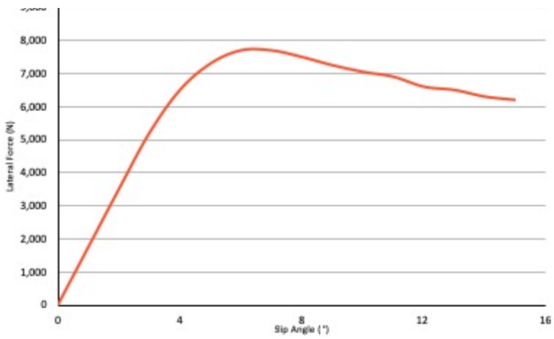


*Figure 1.2 Lateral Force vs Slip Angle*

The diagram demonstrates how the components of the contact patch have been moved to correspond with the direction of movement. As the response force decreases, these components then revert to the neutral position nearer the back of the contact patch. The contact patch deforms whenever slip angle is present because of lateral forces acting on the tyre. This deformation causes strain (elongation) within the tyre rubber's molecular structure. In addition, the tyre compound's elasticity resists this strain, creating a force perpendicular to the axis of rotation Every revolution, the tyre goes through a stretch-relaxation cycle that also produces internal friction and heat inside the tyre, improving grip. Up until a certain point, this increases until the tyre rubber has been overworked and grip dramatically decreases, often known as the "cliff."

### 1.2.1.2 Cornering Stiffness

The cornering stiffness of a tyre is a crucial indicator of its lateral grip capacity. The force produced per degree of slip angle (N/°) is used to express this. A tyre with a higher cornering stiffness will result in a stronger lateral acceleration for a given slip angle, and this is a crucial performance indicator of any tyre.

### 1.2.1.3 Slip Ratio

Only lateral force production is addressed by the idea of slip angle. The slip ratio is the term used to describe this in a longitudinal sense. Like slip angle, slip ratio describes how much slip a tyre suffers in relation to a sliding state rather than being recorded in angular displacement. For instance, a tyre with a slip ratio of 0 is free rolling, whereas one indicates that the tyre has lost grip. The longitudinal force peak in tyres typically occurs at a slip ratio of between 0.3 and 0.4.

### 1.2.1.4 Friction Circle

The friction circle, often known as the g-g diagram, is the last fundamental of tyre dynamics that needs to be understood. The friction circle helps drivers comprehend how the vehicle is being driven in relation to these constraints by graphically illuminating the tyre's ability to generate simultaneous longitudinal and lateral acceleration.

The g-g diagram actually resembles an ellipse rather than a perfect circle, but the lesson to be learned from this is that it is obvious that a driver cannot demand acceleration/braking while also expecting the kind of lateral acceleration generated in pure cornering.

### 1.2.1.5 The Coefficient of Friction

The frictional force and the response force between two objects in contact are related by the coefficient of friction (COF), also known as mu (μ). It's crucial to realize that the COF does not rise proportionally as the response force increases (vertical tyre load). In other words, the COF does not double when the response force doubles, and vice versa for the tyre grip level. The contact patch can be thought of as a matrix of distinct elements. For a given vehicle weight, a wider tyre reduces the contact pressure at each element, raising the COF. As a result, each element of the tyre can provide a little less force, but the presence of more parts outweighs this balance (contact area). The result is an overall improvement in tyre grip.

### 1.2.1.6 Contact Patch

The portion of a tyre's tread that contacts a surface when it is forced against one is known as the tyre contact patch. Each contact patch is typically no bigger than the size of your hand overall.

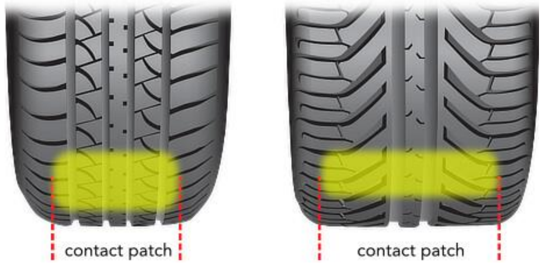

*Figure 1.3 Contact Patch*

The contact patch area for a tyre with a grooved tread pattern is made up of both contact patches and void sections where the rubber tread elements are forced up against the ground. It's crucial to realize that the tyre contact patch is not something that is added to a tyre after it has been made. Instead, it happens as a result of numerous intricately developed parts that are set up and designed to control loading during stop-start and cornering actions. The contact patch of a tyre changes along with the forces acting on it. Utilizing the prescribed tyre inflation pressure by the vehicle's manufacturer ensures an acceptable load carrying capability and optimal vehicle handling and performance. When tyres are correctly inflated, the best contact patch is realized.

### 1.2.2 Tyre Forces

The performance of the vehicle is significantly influenced by the contact patch between the tyre and the road. The engineer needs a precise description of the tyre-road contact phenomena in order to assess how the tyre properties affect the dynamic behaviour of the vehicle. In order to identify tyre performance characteristics and gain understanding of how a tyre's design influences the general dynamics of a vehicle, tyre forces and moment measurements are used.

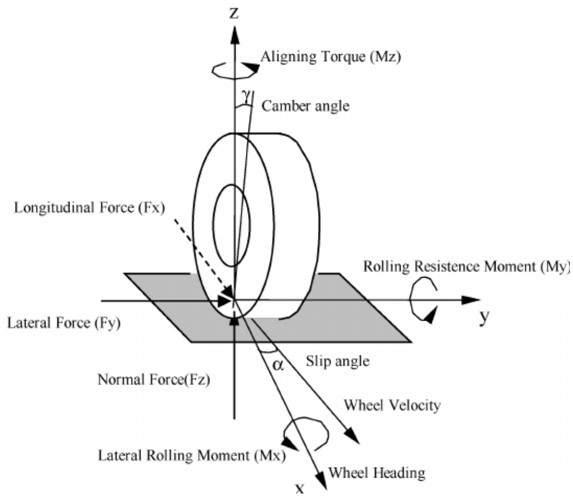

*Figure 1.4 Tyre Forces, Angles and Moments*

There are three forces and three moments acting on the tyre from the surface on which it is rolling:

1. Tractive Forces (longitudinal forces)
2. Lateral Forces
3. Normal Forces

4. Overturning Moment
5. Rolling Resistance Moment
6. Aligning Torque

## 1.3 Evolution of Tyres:

Ever since the beginning, mankind has always tried to shorten the distance between places of the world. Through inventing and evolving the means of transportation, he has always been improving the comfort in covering the immense distances across land, sea, and air. Since the invention of the wheel in the time period as early as 4200 BC to 4000 BC, this revolutionary invention found its application in horse carts for transportation. This form of transportation was improved and innovative throughout history with the introduction of axle, steering and even shock absorbers of its kind. The men's quest for comfort and capability in conquering distances took a step forward in the year 1886 when Carl Benz patented the first automobile which worked on a gas powered engine [1]. This invention set the sails of the future research, inventions, and development in the field of automotive.

### 1.3.1 Difference between Tyre and Wheel:

Through the course of history, transportation evolved depending upon their application. For example, locomotives have their application mainly in logistics and automobiles were focused on passenger mobility. There is one thing in common for all kinds of land transports, the contact between the surface of earth and the vehicle itself. This contact has been achieved most through wheels. Though recently in the last century, metal tracks have replaced wheels in heavy transportation applications, the importance and the wide usage of wheels has not been compromised. Wheels are used as primary contact points between the surface and vehicle from a small tricycle to a heavy industrial loader truck. There is a rich history of wheels and tyres which confirms the improvement in the design, material, performance, durability, and life cycle of the tyres.

### 1.3.2 The Concept of Tyre:

Because of the metal foundation at first, wheels were shaky and uncomfortable to roll on the street without any firm support. In 1839, a guy by the name of Charles Goodyear invented the first vulcanized tyre. It is manufactured from sulphur and rubber. The vulcanized rubber was incredibly robust, long-lasting, and simple to mould. The vulcanized tyre has drawbacks of its own as well. On the street, it was difficult to roll the tyres due to their weight. However, it contributed to tyre models to come.

### 1.3.3 First Commercial Pneumatic Tyre:

Due to its four key benefits over solid wheels, the first commercial bicycle tyre was introduced by Dunlop in 1888, and it has since controlled the global tyre industry for more than 100 years. Low vertical stiffness, minimal contact pressure, low energy loss on uneven surfaces, and low weight are all contributing factors. The tyre does, however, have a number of drawbacks: the potential for catastrophic damage, such as bursting while driving, the requirement to maintain the proper internal air pressure, and a challenging manufacturing process.

### 1.3.4 Cross-ply Tyres:

The tyre started to really find its stride after this. Detachable pneumatic tyres were invented by the Michelin brothers in 1891, and businesses like DuPont worked to synthesize rubber, which helped increase the performance potential of tyres. At this time, tyres were often built using the cross-ply design, which involved crisscrossing layers of material for the tyre's outer casing. To offset the industry's reliance on oil, the US-based Goodyear Tyre Company, which was founded by vulcanization pioneer Charles Goodyear, developed the tubeless tyre in 1947.

### 1.3.5 Radial Tyres:

The next significant development was the development of radial tyres. On the grounds that its constantly laterally coiled (and hence radial) casing offers better performance and fuel efficiency, this technological improvement replaced cross-ply construction. Nowadays, radials are used almost exclusively on vehicle and truck tyres in Western countries. Cross-ply tyres are more durable and more immune to overloading, according to some, nonetheless. Cross-ply tyres are still preferred in several specialized, agricultural, and industrial applications. However, it must be noted that altogether, these continue to be a relatively small minority.

### 1.3.6 Drawbacks:

Despite being in use for more than a century, the conventional, air pressure, pneumatic tyres still have drawbacks, including high rolling resistance, poor longevity, a tendency to go flat due to punctures, and the requirement for routine air pressure checks to maintain proper air pressure.

### 1.3.7 Non-Pneumatic Tyres:

In order to provide a good tyre and ensure safety, attempts were undertaken to create a flexible wheel starting in the early 1920s by adding wire spokes. Michelin suggested a non-pneumatic tyre design to solve these issues [2]. Since then, a number of engineers have also tried to create non-pneumatic tyres (NPTs) by adding elastomer to the inside or making polygonal spokes to replace the tyre's air. Recent advancements in airless tyres include the appearance of NPTs, which contain flexible polygonal spokes and an elastomeric layer with an inner and outer ring [3].

Over the past few years, research has been conducted at Clemson University in cooperation with Michelin to produce numerous analytical and numerical models as well as prototypes to examine the various NPT features. The critical pneumatic tyre properties of mass, stiffness, durability, contact pressure, and rolling resistance serve as the basis for NPT design. As it affects how much gasoline a vehicle uses or how much a bicycle rider needs to use energy, rolling resistance is one of the key qualities of interest. Other crucial characteristics to consider while building an NPT include stiffness and contact pressure distribution.

## 1.4 Coordinate System:

To solve a problem a coordinate system is needed for 3D visualization of the problem. In case of vehicles the coordinate system used is usually referred as Vehicle Coordinate System. This coordinate system is used to calculate the vehicle dynamic and position problems in the 3D visualization environment.

### 1.4.1 Vehicle Coordinate System:

The vehicle coordinates system axes ($X_V$, $Y_V$, $Z_V$) are fixed in a reference frame attached to the vehicle. The origin is at the vehicle's sprung mass.

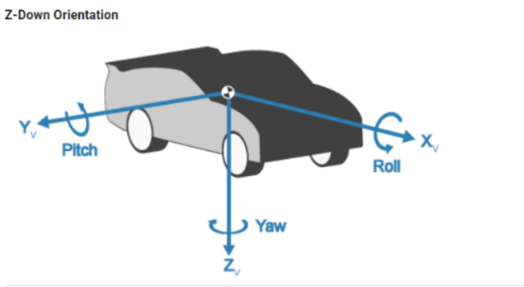


*Figure 1.5 Vehicle Coordinate System*

## 1.4.2 Earth-Fixed Coordinate System:

The axes of the earth-fixed coordinate system are fixed in an inertial reference frame. The linear, angular, accelerations are all zero in the inertial reference frame. The earth is an inertial reference in Newtonian physics.

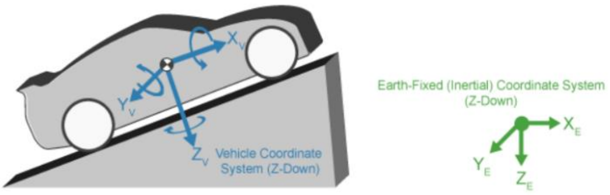


*Figure 1.6 Earth-Fixed Coordinate System*

## 1.4.3 Tyre and Wheel Coordinate Systems:

The tyre coordinate system axes ($X_T$, $Y_T$, $Z_T$) are fixed in a reference frame attached to the tyre. The origin is at the tyre contact with the ground.

The wheel coordinate system axes ($X_W$, $Y_W$, $Z_W$) are fixed in a reference frame attached to the wheel. The origin is at the wheel centre.

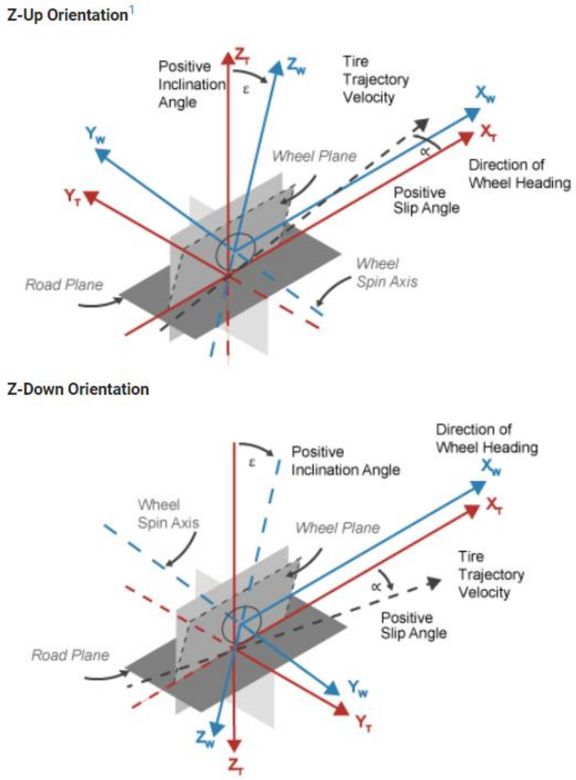


*Figure 1.7 Wheel Coordinate System*

# Chapter 2

# LITERATURE REVIEW

This chapter discusses the literature involving non-pneumatic tyres, different proposed designs for these tyres, and the presented analysis provided alongside the aforementioned designs.

A composite ring with at least two circumferential reinforcements spaced apart radially makes up the NPT idea. Shear beam is the name given to the composite ring that is sandwiched between the reinforcements and has a low modulus material. The material between the reinforcements is shear loaded during rolling and largely deforms in pure shear. The spoke pairs that join the ring to the wheel hub are distributed uniformly but discreetly, and they bend owing to buckling [1].

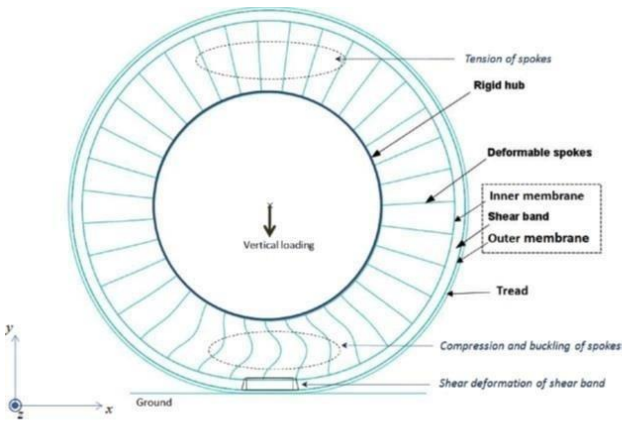


*Figure 2.1 Radial Tyre with components*

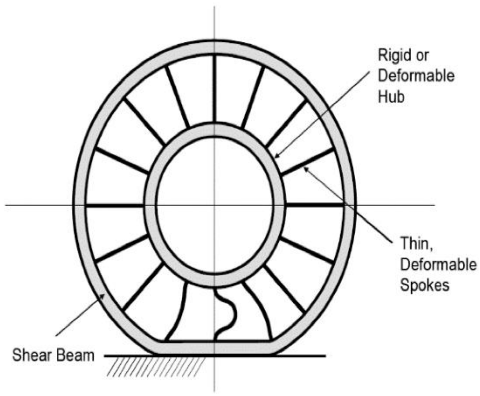


*Figure 2.2 Radial Tyre (Michelin)*

## 2.1 Design and Structure:

### 2.1.1 Spokes:

C. Manibaalan, Balamurugan S., Keshore and Dr. Joshi C. Haran elaborated on the various aspects to be considered in the design and manufacture of non-pneumatic tyres in their research [2]. The work provides that flexible spokes used with the shear band and rubber tread can replace the functionality of air in a tyre, allowing the design of an efficient airless tyre.

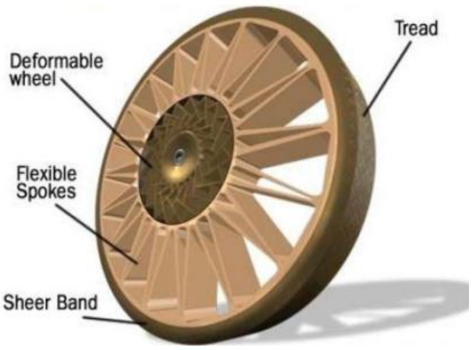


*Figure 10 Part components of airless tyre*

### 2.1.2 Honeycomb:

The term "honeycombs" refers to prismatic two-dimensional cellular materials with a periodic microstructure. In lightweight sandwich constructions that demand a high out-of-plane rigidity, honeycombs have predominantly been utilized.

By adjusting the cell angle, cell wall thickness, and cell length, hexagonal honeycombs may be readily modified to have desired in-plane characteristics. As a result, certain hexagonal constructions may have structurally sound designs [3].

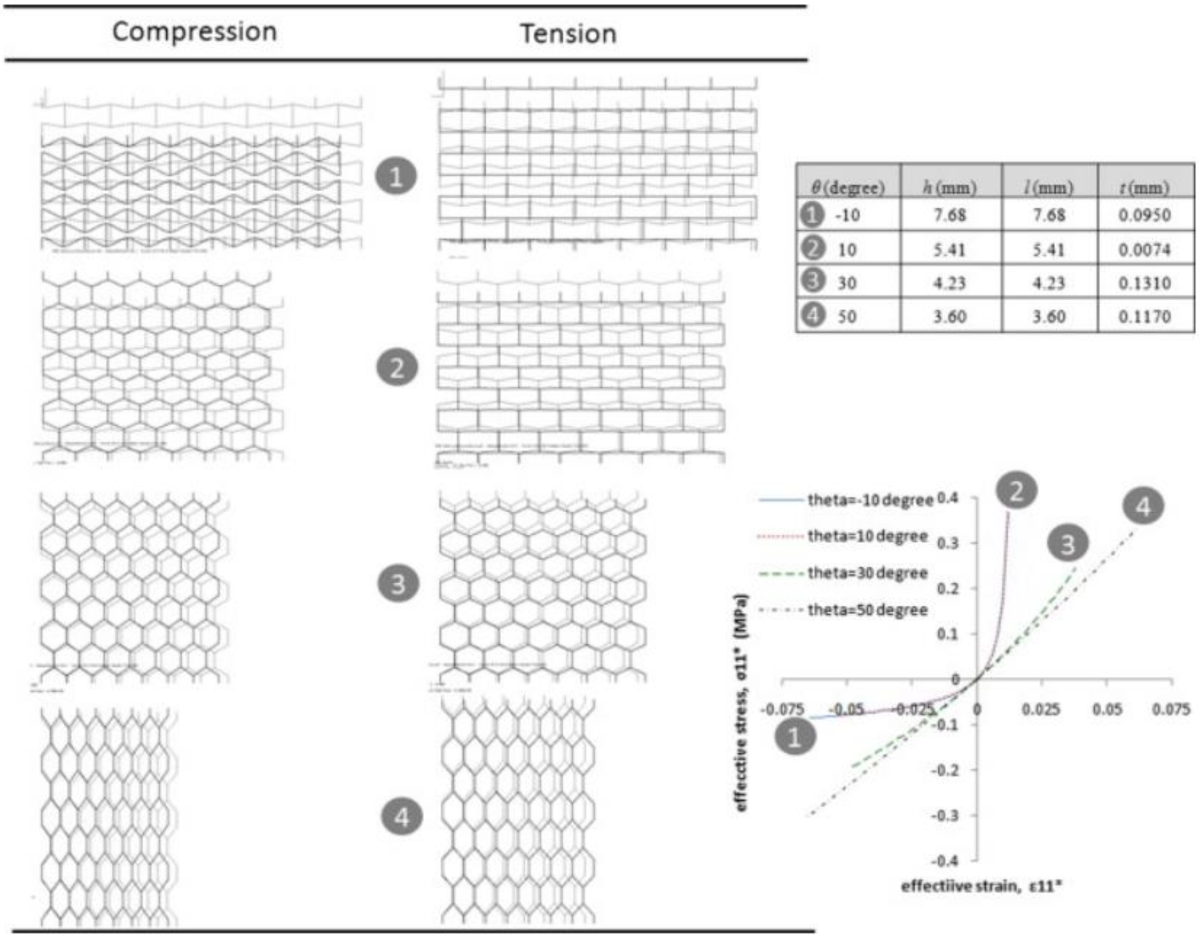


*Figure 11 In-plane characteristics via adjusting cells*

Each structure has further types into which it can be divided. Jaehyung Ju, Doo-Man Kim and Kwangwon Kim have done an extensive study on the various types of honeycomb structures for airless tyres [3]. In this work, researchers examined various hexagonal spokes in honeycomb shape for a configuration with higher resistance against fatigue, aiming to obtain a reliable hexagonal structure with minimal local stresses.Jayanthi Srivatsa Sharma, Y Srinivas, R. Sabari Vihar and D. Govardhan conducted research, and reported their results on the design of airless tyres incorporating re-entrant structure [4]. While this design was limited to a small aircraft, Cessna 172, the approach provides a good insight on using spokes with a re-entrant structure.

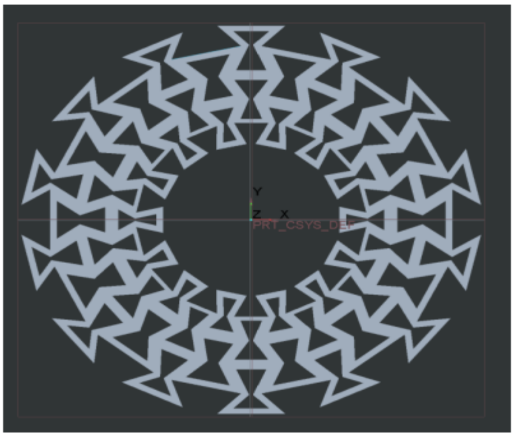

*Figure 12 Four-layered spoke*

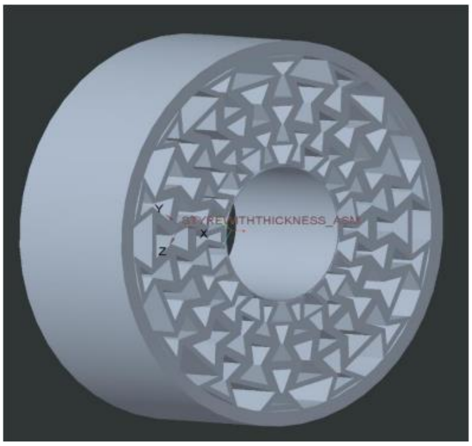

*Figure13 Assembled Spoke*

### 2.1.3 Others:

The stresses and strains experienced by airless tyres vary with the pattern of spokes used, as elaborated by Nibin J. Mathew, Dillip K. Sahoo and E. Mithun Chakravarthy in their research [5]. Initially, this research briefly details the various aspects of stress experienced by tyres, and the problems that could occur with poorly designed airless tyres.

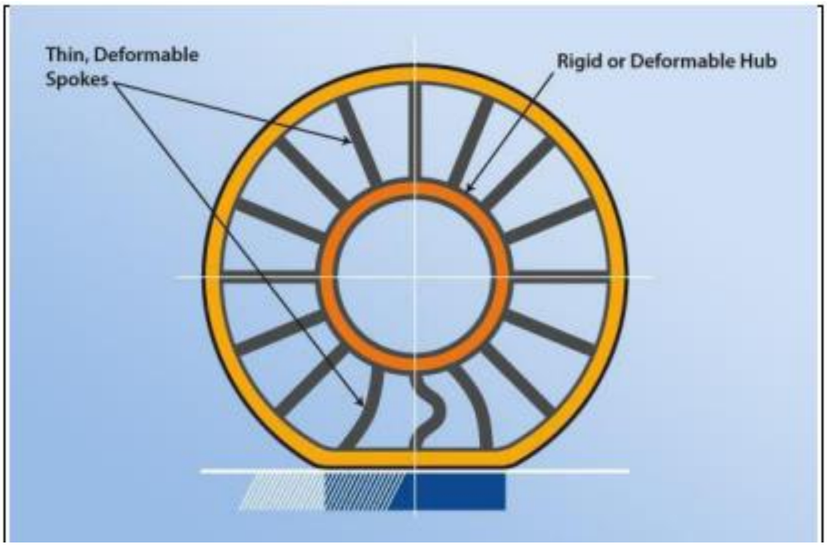


*Figure14 Deformation of Spokes*

Furthermore, the work takes four separate models of airless tyres with structures such as triangular and diamond structure, in addition to the usual spoke and honeycomb structure, each with tetrahedral mesh. The design of each of these structures is done using CREO. The tyre models designed in this work are geometrically analogous to car tyres [5].


*Figure15 Various Structures of Airless Tyres*

## 2.3 Results:

The results of these designs were obtained by performing analyses of the above elaborated designs. The analyses were performed taking into account that tyres undergo cyclic deformation and stresses. The geometry and materials were attempted to be adjusted so that such designs could be achieved that allowed the optimum values for rigidity and stiffness.

Most of the analyses on the designs were performed using the FEA (finite element analysis) program ANSYS. The loads were applied with necessary supports set, and the resulting deformations and stresses were clearly elaborated and illustrated.

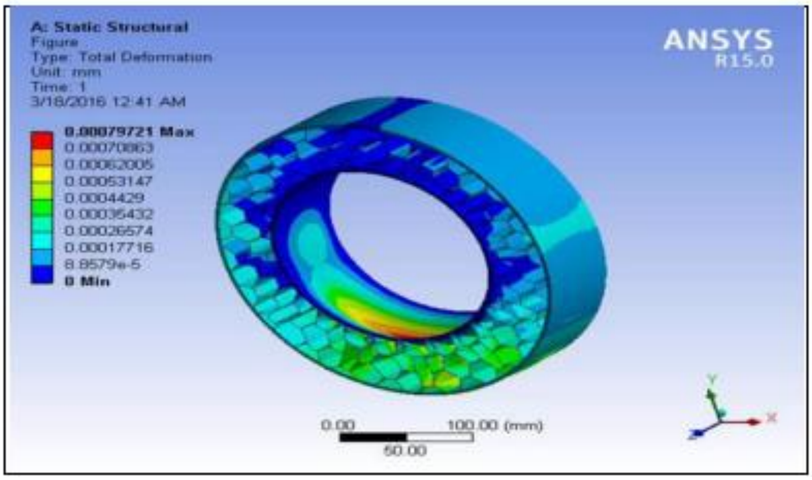


*Figure16 Deformation of Airless Tyre with Honeycomb structure*

## 2.3.1 Spokes:

The design illustrated in the research could perform adequately in controlled environments due to lack of shearing load, as compared with the requirements on regular roads. [2]

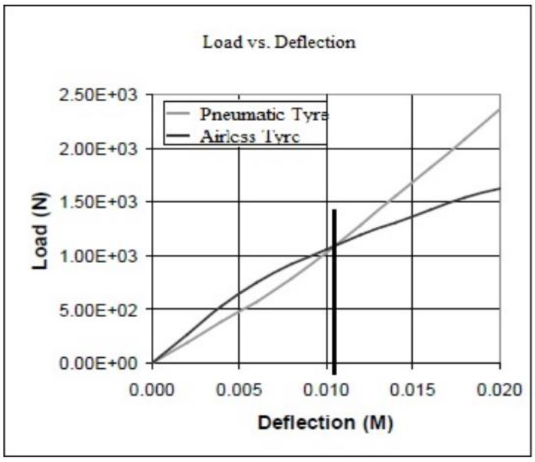


*Figure17 Comparison of Load Deflection*

## 2.3.2 Honeycomb:

Jaehyung Ju, Doo-Man Kim and Kwangwon Kim have provided in their conclusion that in terms of similar vertical load bearing capabilities, lower local stresses are exhibited by honeycomb spokes with a higher cell angle magnitude. This is good for fatigue resistance and makes the design more feasible. These types of honeycomb structures are the types C and F in the research. Type C has a lower mass design, and it also has a higher manufacturing feasibility, due to the lower design complexity as compared to type F [3].

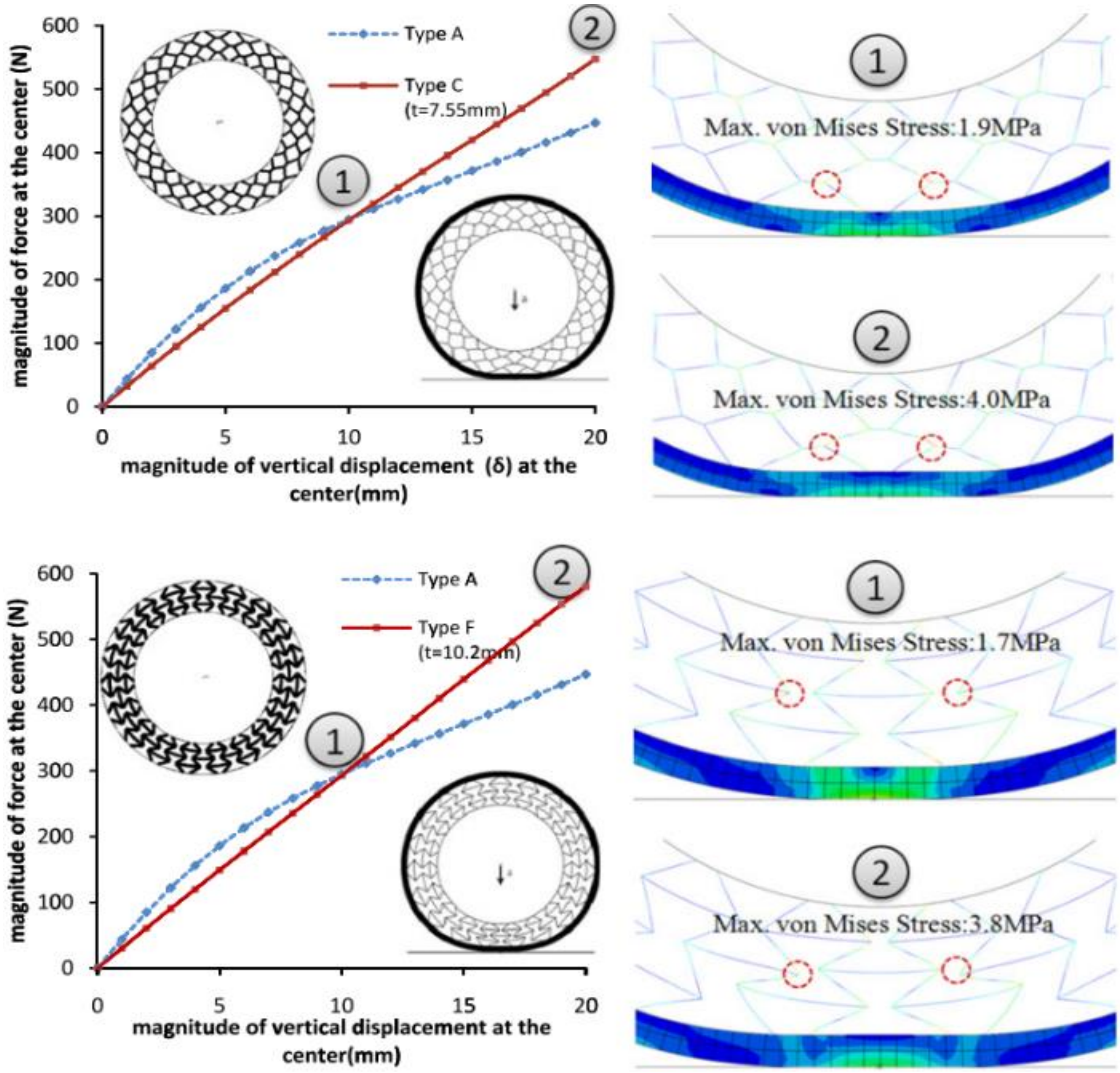


*Figure 18 Force vs Vertical Displacement*

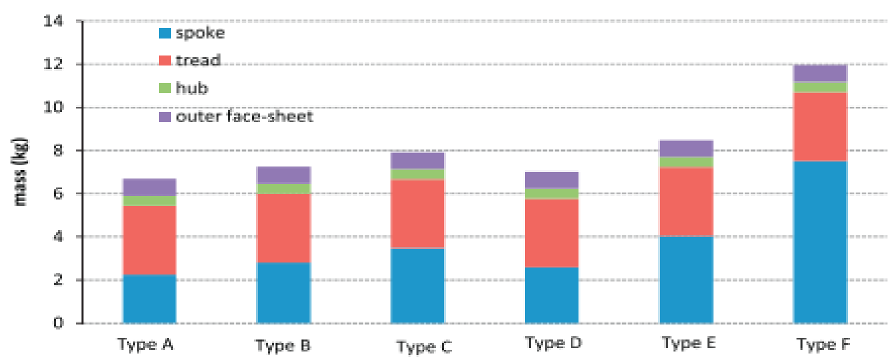


*Figure 19 Mass of Components in Designs*

As for the re-entrant structure, this design seems to only be applicable on large vehicles, it has been reported that experimentation with the prototype has not been done and most importantly, the design is unfeasible for manufacture, especially on a smaller scale. It is too intricate, and the necessary equipment for manufacture, even via molding, is unavailable [4].

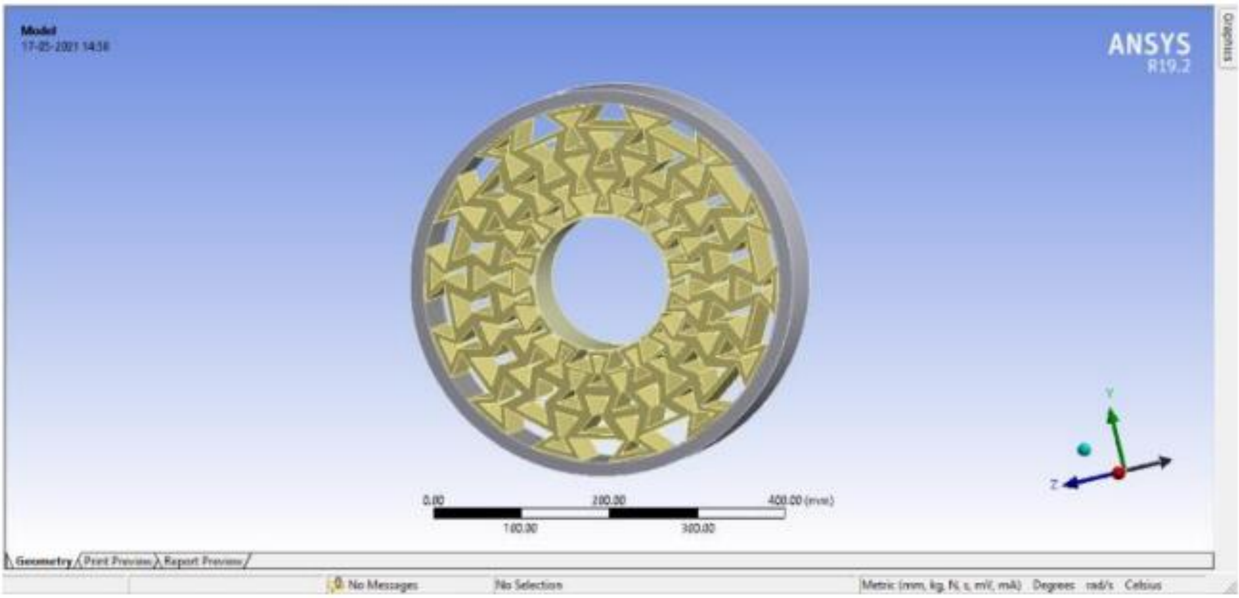


*Figure 20 Analysing Type F Structure*

| S.no | Type | Result |
|---|---|---|
| 1 | Total Deformation | 0.00178 m |
| 2 | Von-Mises Stress | 108750000 pa |
| 3 | Von-mises Strain | 0.11192 |
| 4 | Maximum Principal Stress | 115540000 pa |

*Table 2.1 Analysis Results*

### 2.3.3 Others:

The results of this research provide that both the honeycomb and diamond structure are more suitable than the standard-spoke or triangular structure, due to their high load carrying capacity [5].

| S. No | Structure | Force Applied(N) | Total Deformation (Existing Material) mm | Total Deformation (Existing Material) mm |
|---|---|---|---|---|
| 1 | Honeycomb | 1200 | 0.00079721 | 1.0608e-007 |
| 2 | Spokes | 1200 | 4.6483e-7 | 2.8606e-007 |
| 3 | Triangular | 1200 | 8.2519e-6 | 1.3521e-007 |
| 4 | Diamond | 1200 | 0.016874 | 1.0498e-007 |

*Table 2.2 Analysis Results for Multiple Designs*

# Chapter 3

# DESIGN PARAMETERS

## 3.1 Tyre Suitability:

The above covered literature review has illustrated the performance and behavior of different types of tyres. It allows us to analyze the suitability of a certain NPT design against various design parameters.

Gauging the design against design parameters of a tyre will allow us to validate its capability.

## 3.2 Design Parameters:

### 3.2.1 Radial Stiffness:

This parameter is the stiffness that indicates the amount of deformation the tyre will experience along the direction of the spokes due to the component of the force in the same direction. The following figure illustrates this parameter for a tyre. [6]

The radial stiffness of a tyre is not required to be specifically high or low, but at a nominal level for a good performance and rider comfort. The average value of radial stiffness for a bicycle tyre ranges between 100N/mm – 200N/mm [7].

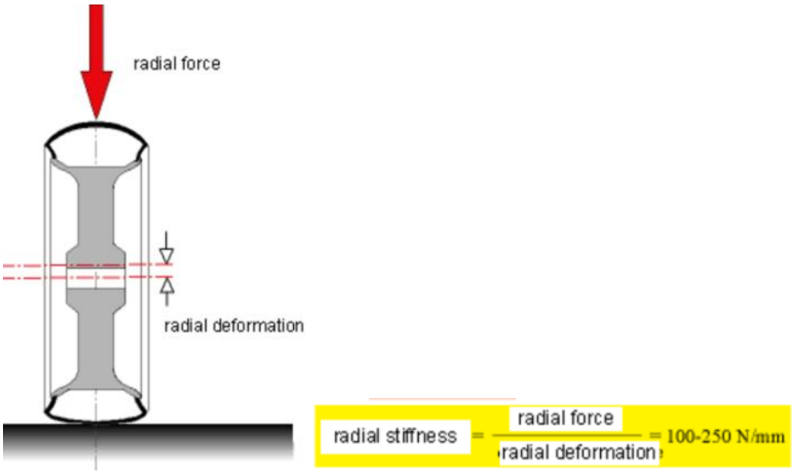


*Figure 3.21 Radial Stiffness*

### 3.2.2 Lateral Stiffness:

This parameter is the stiffness that indicates the amount of deformation the tyre will experience in the lateral direction, perpendicular to the spokes due to the component of the force in the same direction. The following figure illustrates this parameter for a tyre. [6]

The lateral stiffness of a tyre is preferred to be high for off-roading purposes, often the case for mountain bikes and dirt bikes. With increased lateral stiffness, the tyre is less likely to deform or fold under lateral forces, allowing for more precise handling and improved traction [8]. This means it helps in maintaining better control and responsiveness when riding on uneven terrain, such as trails, rocky surfaces, or off-road tracks. It improves the tyre's resistance to sidewall flex, which can enhance stability during aggressive maneuvers like cornering or quick direction changes. [9]

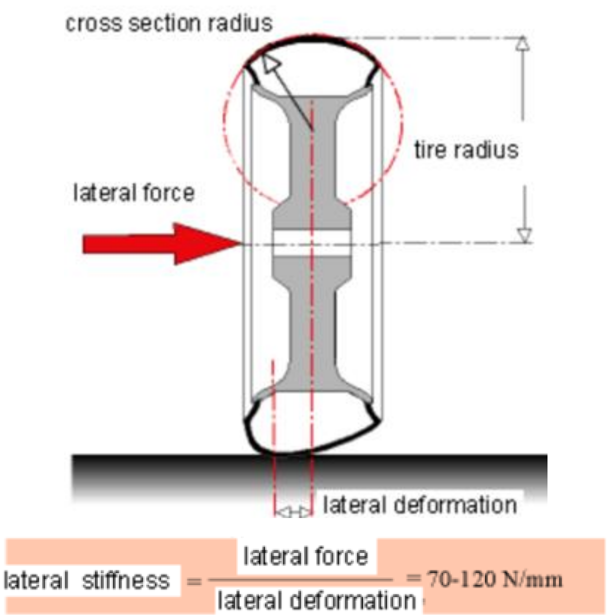


*Figure 22 Lateral Stiffness*

### 3.2.3 Torsional Stiffness:

This parameter is the stiffness which occurs due to the force around the perpendicular symmetry axis of the tyre. It occurs when we are turning the tyre, such as manoeuvring at a standstill. [10] Torsional stiffness is the ratio of the torque acting on the tyre to the torsional angle. [9]

It is given by the equation: $k_s = M/\alpha$

Where, $k_s$: torsional stiffness (Nm/rad), M: torque moment loading the tyre (Nm) and finally, α: torsional angle (rad).

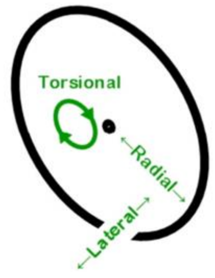


*Figure 23 Torsional Stiffness*

## 3.2.4 Camber Stiffness:

This type of stiffness is encountered by the bicycle as it turns a corner, and exhibits a camber angle. This can be seen in the figure 3.4.

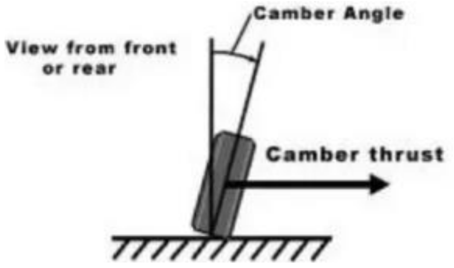


*Figure 24 Camber*

It can be calculated via the camber angle, the normal load, the tyre tread, and material of the tyre, among many other factors. [11] [7]

It refers to its ability to resist deformation when subjected to forces that cause it to flatten or bulge along its width. It plays a crucial role in maintaining stability and control during cornering or leaning maneuvers. [6] Thus, camber stiffness plays an important role in cornering stability, traction, steering or turning response and energy efficiency for the rider. [10]

## 3.2.5 Weight

The weight of the tyre is an essential design parameter, as it determines the speed and control of the bicycle, as well as the effort required by the bicycler to accelerate the bicycle.

It can be calculated simply by using a weight measurement device, or if we know the material of the tyre (in particular, its density), volume of the material used per tyre, then we can calculate an approximate mass of the tyre, using which we can obtain its weight. We can use these methods as our designed tyre will not be like a factory-made one, which are marked with numbers, indicating their weight. [7]

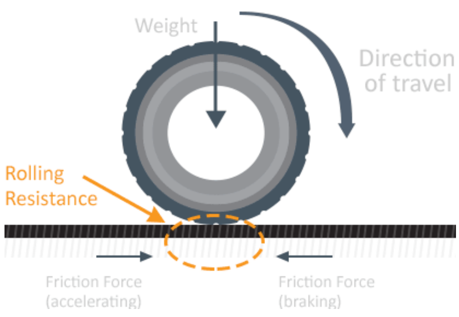


*Figure 25 Weight Acting Direction*

### 3.2.6 Yaw

Yaw is basically referred to as the rotation of the bicycle about the vertical axis. A yaw rotation is a movement around the yaw axis of a rigid body that changes the direction it is pointing, to the left or right of its direction of motion. [7]

The yaw rate or yaw velocity is the angular velocity of this rotation, or rate of change of the heading angle when the aircraft is horizontal. It is commonly measured in degrees per second or radians per second.

**tangential speed*yaw velocity = lateral acceleration = tangential speed^2/radius of turn**

It is important for the stability of the bicycle, its handling, maintaining balance and control while riding, turning corners as well as the traction of the bicycle tyre. Furthermore, for bike riding at higher speeds, it is also an important determinant in aerodynamic drag. [12]

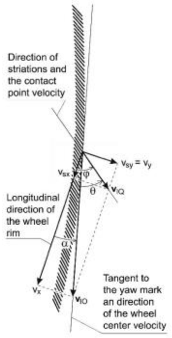


*Figure 26 Yaw*

### 3.2.7 Load-Bearing

This property of the tyre determines the overall load that it can tolerate while still operating without significant damage per revolution. The load on the tyre is contributed by the bicycle frame, weight of the rider and other accessories. [11]

It is important to know the load-bearing capability of the tyre [10] mainly for the safety of the rider. Other than this, the load-bearing capability of the tyre also contributes to the comfort provided to the rider, the durability of the bicycle in general and its on-ground performance. [8]

Calculations for the load-bearing of a bicycle by its tyres has been covered via analytical modeling in Chapter 6→Methodology.

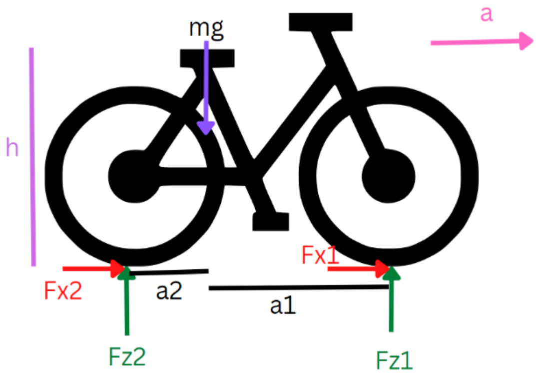


*Figure 27 Load Calculation*

### 3.2.8 Rolling Contact

By contact of the tyre with the ground, we are referring to the tread of the tyre, the dynamic friction of the contact patch and its road-holding capability. A larger friction, while improving the handling and rolling contact, can reduce the speed and vice versa. [8] [6] [13] [12]

Rolling contact plays a vital role in all tyres, including bicycle tyres. It determines the efficiency, speed, traction, comfort, stability, control and how rapidly the tyre wears over time with usage. Rolling contact of a tyre is determined mainly by tyre design and the tread pattern. [13]

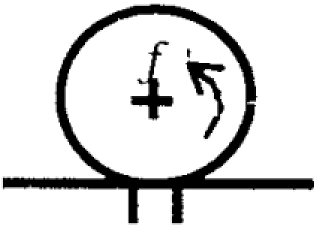

*Figure 28 Rolling Contact*

### 3.2.9 Cushioning

Cushioning in bicycle tyres refers to the ability of the tyre to absorb and dampen shocks and vibrations from the road or trail surface. If the rebound is too low or too high, it can prove to be quite uncomfortable for the rider. [6] This property is important because it contributes to the comfort, handling and impact protection of the bicycle, while increasing the tyre longevity and improving performance. [11] [8]

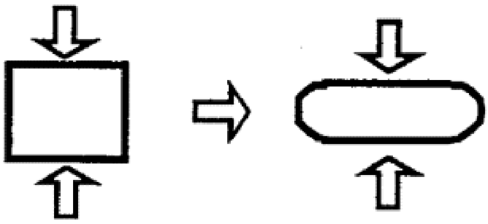

*Figure 29 Cushioning*

# Chapter 4

# DESIGN INSPIRATION

## 4.1 General Analysis:

### 4.1.1 Concept:

Upon analyzing the simplest design of NPTs, which would be Michelin's Tweel [2], we can identify that some sort of structure must be employed in order to replace the air in the tyre. These structures can have various designs, which include but are not limited to honeycomb structure, re-entrant structures, simple spokes, or even just solid material such as rubber, with optional holes in it of a suitable geometry, optimally spaced.

### 4.1.2 Designs:

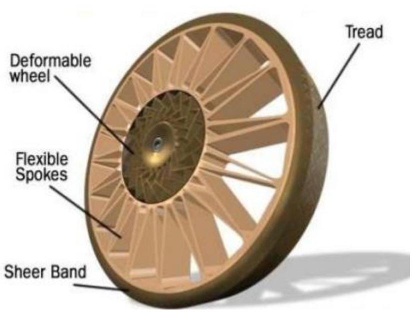


*Figure 30Michelin Tweel (Simple Spokes) [2]*

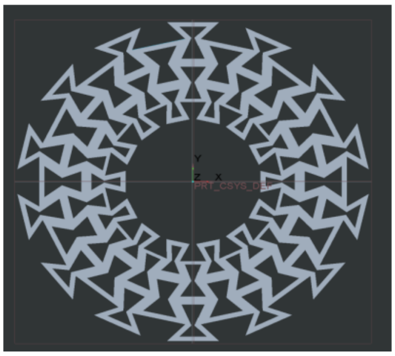

*Figure 31 Re-entrant Structure [4]*

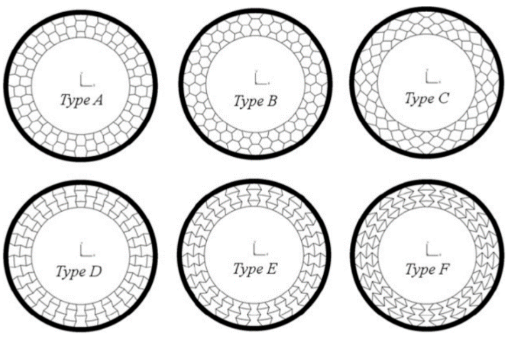


*Figure 32 Various designs of Honeycomb Structure [3]*

## 4.2 Tyre Suitability:

The above covered literature review has illustrated the performance and behavior of different types of tyres. It allows us to analyze the suitability of a certain NPT design against various design parameters.

Taking inspiration from the already researched NPT designs for four-wheelers, we can obtain a functional design of NPT for two-wheelers. Gauging the design against design parameters will allow us to validate its capability. (Chapter 3)

## 4.3 Design Features:

### 4.3.1 Honeycomb (Hollow-structured):

Upon checking the honeycomb tyre design [3] for two-wheelers, it seems to have an optimally low weight, and excellent load-bearing capability [5]. However, its lateral stiffness and camber stiffness are incapable for two-wheelers, especially when turning a corner.

### 4.3.2 Tweel (Simple Spokes):

The Michelin Tweel [1] has a similar problem. Although, in this case, the radial stiffness of the tyre also becomes questionable, and highly depends on the material used, which also determines the weight of the tyre [2].

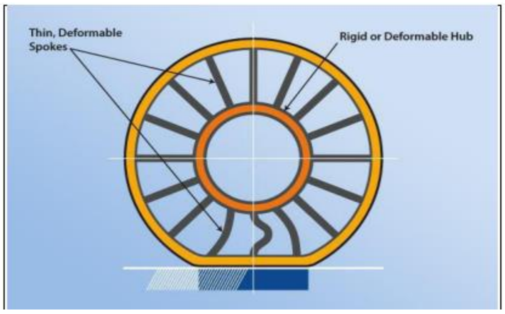


*Figure 33 Deformation of Spokes*

### 4.3.3 Solid Rubber:

Solid rubber tyres (with some hollow structures), on the other hand, seem to be quite capable for two-wheelers. These tyres have good radial and lateral stiffness. Their camber stiffness is ample for turning corners without any problems. However, the downside is their large weight. It would demand a high amount of effort from the rider to accelerate the bicycle.

*Figure 34 Solid rubber*

## 4.4 Derived Approach:

However, if we were to employ a structure, similar to the ones studied [5], in the NPT design, while using a material with sufficient rigidity and low-weight, we can acquire a design which would have acceptable performance in terms radial and lateral loads. Using suitable material and structures, or a shear band before the tyre tread would give the design significantly better camber stiffness, allowing it to turn corners without any problem. The sufficiently low-weight materials of the tyre allow suitable performance (acceleration) without demanding too much effort.

*Figure 35 NPT with Polymer*

## 4.5 Design Selection:

Taking hollow structure designs from multiple other researchers' articles [3] [5], we can design multiple such tyres with our approach, and test for the tyre with the most reasonable deformation and weight. Materials, such as polymers could be tested as the compliant material.

*Figure 36 NPT with Polymer on bike*

# Chapter 5

# Methodology

For four-wheeler vehicles extensive research has been done by different organization and group of people even fabricating the NPTs for them. But the dynamics of the two-wheeler are different from four-wheeler vehicles. That’s why there is very little research done in domain of two-wheeler dynamic systems. Sole purpose of our research is to obtain results of NPTs for two-wheeler starting from simple one ‘a bicycle’. NPTs for cars or heavy loader have life issue but works well at slow speed and under heavy loadings. This will make the idea easy for bicycle as it does not work at very high speeds and will bear the weight of the rider. But in case of two-wheeler a new issue emerges is that while riding a bicycle and cornering a turn even at very low speed very significant number of lateral forces are generated that will affect our design or may become the cause of failure.

The main issue will be to extract lateral data for some designs and optimize the design according to the results to increase the life and performance of the tyres. For this purpose, we will use Finite Element Analysis of various types to virtually analyze the behavior of the tyre under different loading. Once the results are generated those results will determine the better design for a bicycle in terms of life and performance.

## 5.1 Analytical Calculations:

Weight distribution on each tyre was needed to understand the magnitude of load a tyre will be facing when a rider mounts the bicycle. For this purpose, a bicycle model was considered, and few assumptions were taken along with bicycle related data to calculate the weight distribution on each tyre by using equilibrium equations.

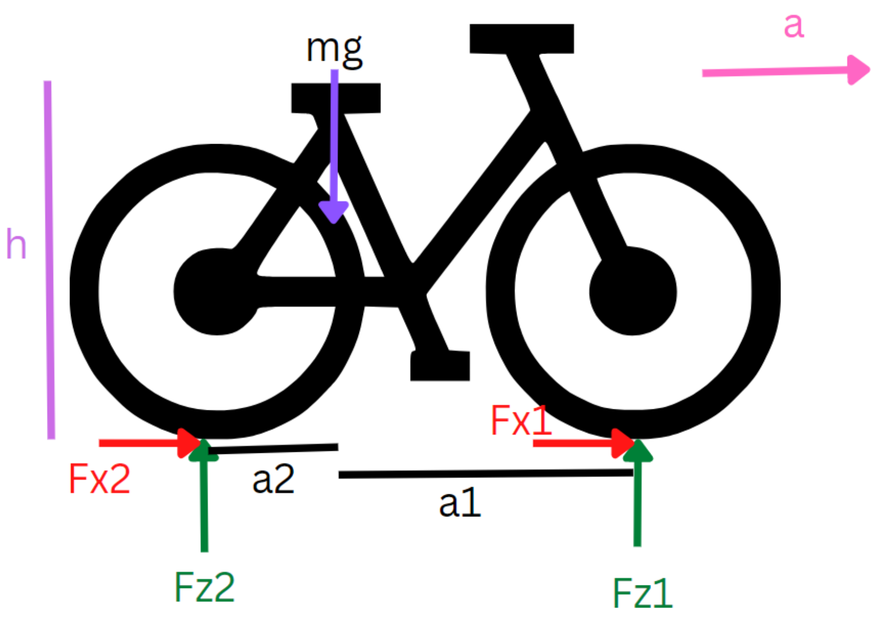


*Figure 37 Load Calculations of Tyre*

### 5.1.1 Data:

Wheelbase of the cycle = 1500mm = 1.5m

$a_1$ =900mm = 0.9m

$a_2$ =600mm = 0.6m

Mass of cycle frame = 14.6kg

Bicycle Height = 70cm = 0.7m

Center of gravity = $C_g$ = h = 75cm = 0.75m

### 5.1.2 Assumptions:

Mass of the Rider = 90kg

Center of gravity = $C_g$ = h = 75cm = 0.75m

Total mass = m = 104.6kg

Acceleration = a =2ms$^{-1}$

### 5.1.3 Equilibrium Equations:

$$\sum F_x = 0$$

$ma = F_{x1} + F_{x2}$ …….. eq i)

$\sum F_z = 0$

$0 = Fz_1 + Fz_2 - mg$ …….. eq ii)

$\sum M = 0$

$0 = -F_{z1}x_1 + F_{z2}x_2 - (Fx_1 + Fx_2)h$

Insert equation ii) in above equation:

$0 = -F_{z1}x_1 + F_{z2}x_2 - mah$ …….. eq iii)

After solving eq ii) & eq iii) simultaneously, following results were extracted:

$F_{z1} = \frac{mga_2}{a_1+a_2} - \frac{mah}{a_1+a_2}$

$F_{z2} = \frac{mga_1}{a_1+a_2} + \frac{mah}{a_1+a_2}$

$F_{z1}$ and $F_{z2}$ are the forces or weight distribution on the front tyre and rear tyre of the vehicle respectively.

### 5.1.4 Results:

Inserting the above-mentioned data into the above expression of forces the results extracted are:

$F_{z1} = 305.4N$

$F_{z2} = 719.6N$

These values provide us the forces that will act on the tyre of bicycle when a rider of mass 80kg will mount it. This data will help in performing Static Structural Analysis as it will provide the estimate of the forces that the tyres will be facing in static condition. There some exaggerated values of these forces will be used to FEA analysis to keep the factor of safety and avoid the chances of failure.

## 5.2 3D Models:

There are three designs under consideration out of which the one with best FEA results and fabrication possibility will be considered. For this purpose, 3D Model for each design is necessary. Fusion 360 is used as a CAD software to create the model for each design for further working.

### 5.2.1 Solid Tyre with circular holes:

First design modeled is solid rubber tyre with circular through holes. For this tyre the dimensions of rim are:

- Rim Diameter: 553.72 mm
- Rim Height: 11.43 mm
- Rim Width: 45.72 mm
- Number of Spokes: 36
- Spokes Diameter: 1.778 mm

The solid rubber tyre has multiple holes of circular shapes across the circumference of the rubber tyre with hole diameter of 25.4mm and gap between two holes is 8.89mm. The height of solid rubber tyre is 36.83mm.

The material used for the spokes, outer ring and the hub of the rim is Aluminium Alloy. The solid tyre is made of Rubber (Butyl) which is a common material used for making tyres by many OEMs around the world.

The CAD model of this design is shown in the renders attached. Note that this model is the first iteration of the design which will be improved in the next iteration depending on the results of FEA. The final design may vary.

*Figure 38 Solid Rubber NPT with through holes*

### 5.2.2 PVC Rings Tyre

The second design modelled is PVC rings tyre. This design has a wider rim as compared to the solid tyre rim and has three parallel chains of PVC rings along the periphery of the rim. A tyre tread holds the structure firmly attached to the rim and provides a contact between the wheel and the road surface. For this tyre the dimensions of rim are:

- Rim Diameter: 558.8 mm
- Rim Height: 12.7 mm

- Rim Width: 82.55 mm
- Number of Spokes: 36
- Spokes Diameter: 1.778 mm

The PVC rings used between tyre tread and rim have rings diameter of 88.9mm with a wall thickness of 5.5mm. Total PVC rings in each chain are 22 which exhibit a major portion of the load bearing capability of the tyre.

The material used for the spokes, outer ring and the hub of the rim is Aluminium Alloy. The tyre tread is made of Rubber (Butyl) which is a common material used for making tyres by many OEMs around the world. The PVC rings are made of U-PVC Grade 80 material which is a common U-PVC schedule 80 used in pipes.

The CAD model of this design is shown in the renders attached. Note that this model is the first iteration of the design which will be improved in the next iteration depending on the results of FEA. The final design may vary.

*Figure 39 PVC NPT Design*

### 5.2.3 Metallic Loops Tyre:

The third and last design under consideration to be modelled is Metallic Loops Tyre inspired by the Mars Rover tyre concept under work by NASA. This design has a similar rim to that of solid rubber tyre. It has multiple metallic loops along the periphery of the rim inner surface. A tyre tread holds the structure firmly attached to the rim and provides a contact between the wheel and the road surface. For this tyre the dimensions of rim are:

- Rim Diameter: 553.72 mm

- Rim Height: 11.43 mm
- Rim Width: 45.72 mm
- Number of Spokes: 36
- Spokes Diameter: 1.778 mm

The metallic loops are of elliptical shape with height of 30.48mm and width of 50.8mm. The thickness of the sheet metal used to make the loops is kept at 0.762mm and the total number of metallic loops are 60 which exhibit a major portion of the load bearing capability of the tyre.

The material used for the spokes, outer ring and the hub of the rim is Aluminium Alloy. The tyre tread is made of Rubber (Butyl) which is a common material used for making tyres by many OEMs around the world. The metallic loops are made of galvanized mild steel sheet commonly available for sheet metal applications.

The CAD model of this design is shown in the renders attached. Note that this model is the first iteration of the design which will be improved in the next iteration depending on the results of FEA. The final design may vary.

*Figure 40 Metallic Loops NPT Design*

## 5.3 FEA Analysis:

After creating 3D model for each design, the weight distribution calculated using vehicle dynamics will be used to perform different types of analysis on these designs. As the maximum force distribution was on rear tyre of value 720N so to keep some factor of safety value of 800N will be used in analysis. The analysis performed on each design will be Static Structural Analysis.

### 5.3.1 Static Structural Analysis:

In this analysis, tyre will be experiencing forces at different points and direction which will provide deformation, stresses, and strains on the model [14] which will be used to calculate different types of stiffness that are main parameters of our designs. A contact patch made of concrete is made under the tyre so that the results are obtained at the contact patch of the tyre [15]. This denotes that when a person mounts the bicycle, how much of the tyre will deform standing in a static position and what types of stresses will be generated at contact patch.

#### 5.3.1.1 Solid Rubber Tyre with through holes Analysis:

First analysis shows the resulting deformation and stresses on the Solid Structured Tyre. The forces applied and fixed supports used have been elaborated via the given table. The deformation and the stresses generated at the contact patch are also shown.

In performing this Finite Element Analysis (FEA), the mesh size was kept at 10mm, the element types a tetrahedral shape, and the number of nodes cumulated to 132,730.

**Vertical Loading:**

For vertical loading, the fixed support was set at the contact patch of the tyre, a force of 800N was applied along the z-axis, and the simulation gave a result of maximum deformation of 10.9mm and a maximum stress of 17MPa.

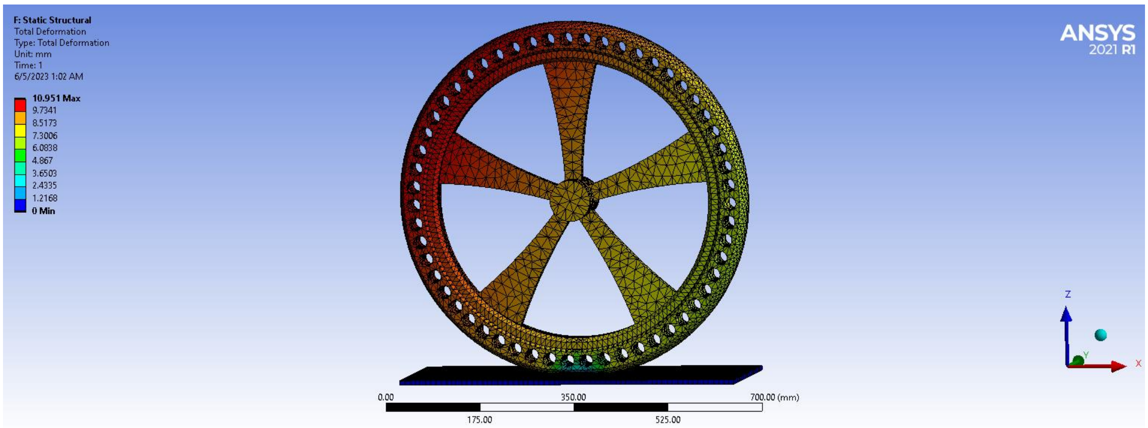


*Figure 41 Vertical Total Deformation*

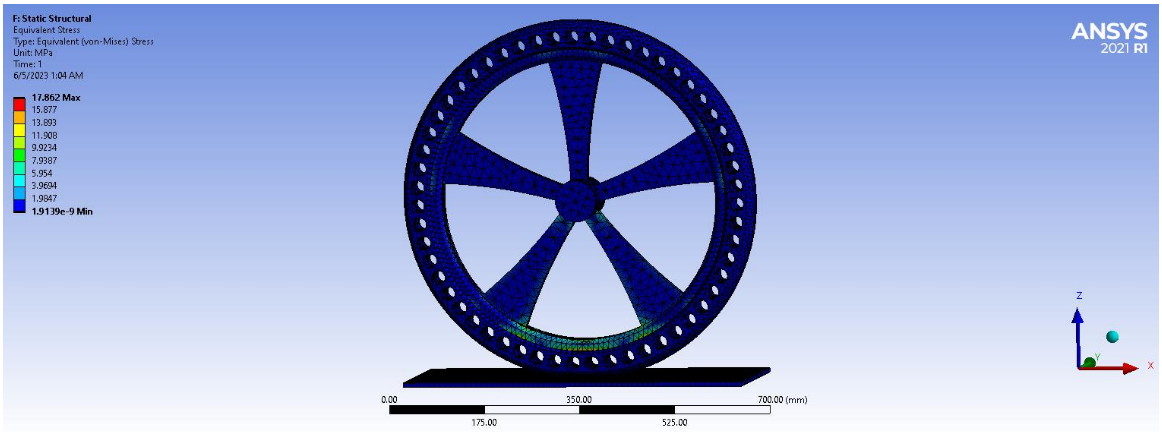


*Figure 42 Vertical Stress*

**Lateral Loading:**

For lateral loading, the fixed support was set at the contact patch of the tyre, a force of 400N was applied along the yz-plane at $45^0$, and the simulation gave a result of maximum deformation of 84.7mm and a maximum stress of 2.65MPa.

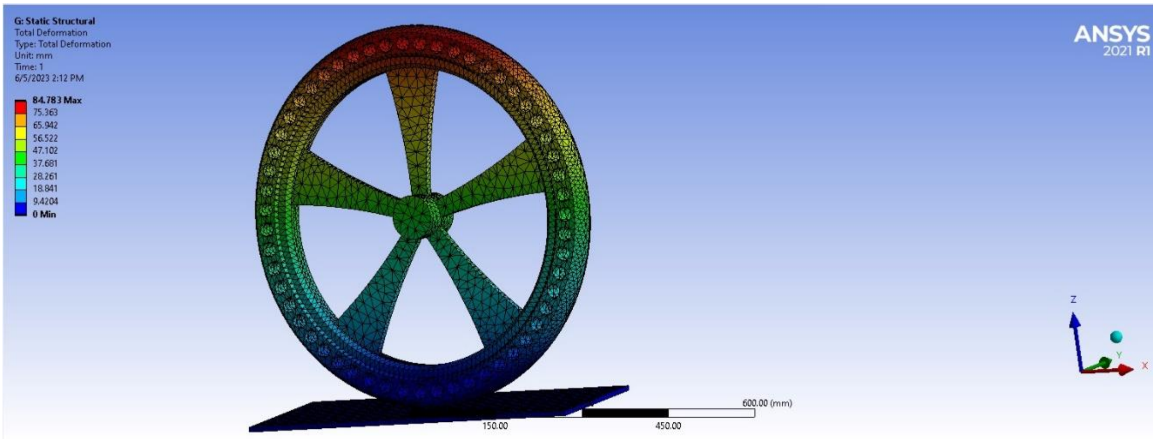


*Figure 43 Lateral Total Deformation*

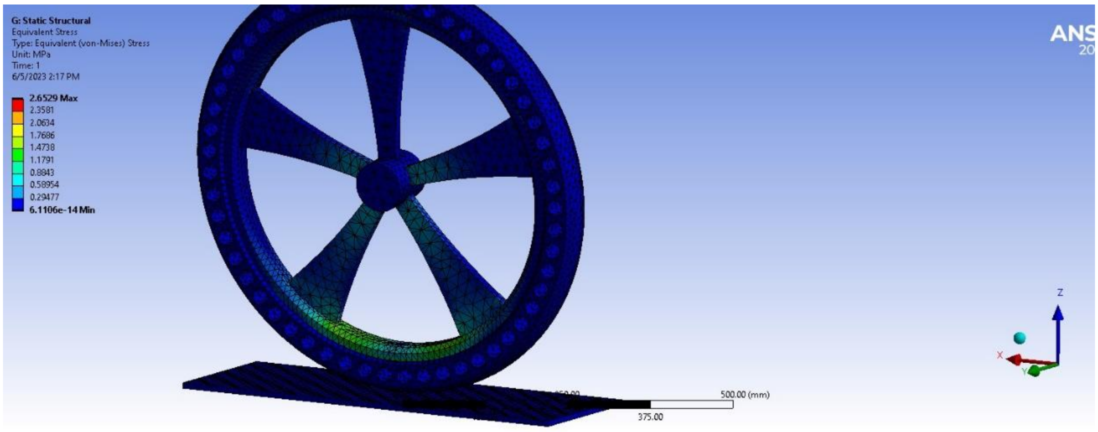


*Figure 44 Lateral Stress*

**Braking Force:**

For the braking force, the fixed support was set at the rim hub, a force of 600N was applied along the x-axis, and the simulation gave a result of a maximum deformation of 1.59mm and a maximum stress of 0.21MPa.

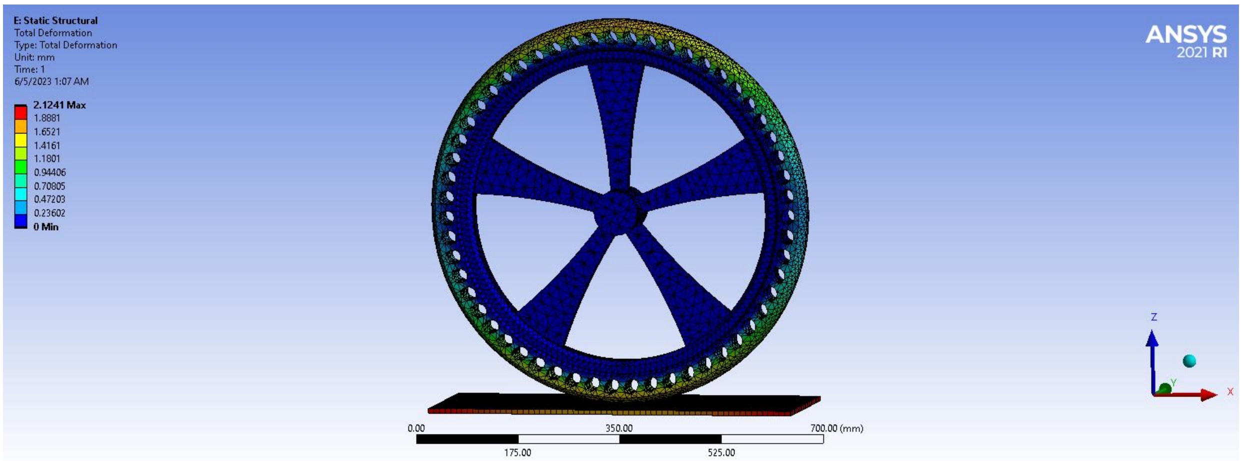


*Figure 45.9 Braking Total Deformation*

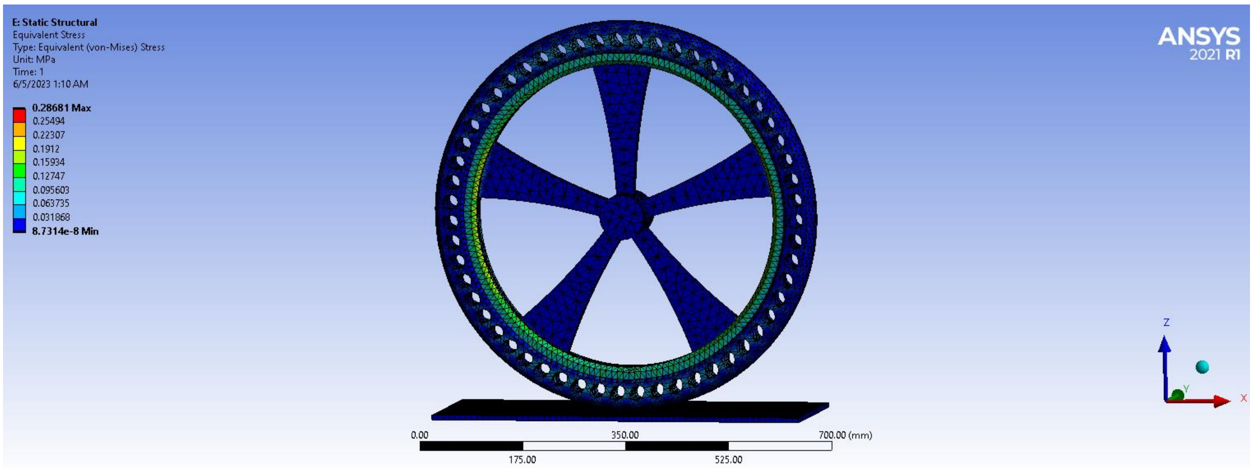


*Figure 46 Braking Stress*

| | Vertical | Lateral | Braking |
|---|---|---|---|
| **Element Size** | 10mm | 10mm | 10mm |
| **Element Type** | Tetrahedral | Tetrahedral | Tetrahedral |
| **No. of Nodes** | 132,730 | 132,730 | 132,730 |
| **Load and Location** | 800N (z axis) | 400N (yz plane at $45^0$) | 600N (x axis) |
| **Fixed Support** | Contact Patch | Contact Patch | Rim Hub |
| **Max Deformation** | 10.9mm | 84.7mm | 1.59mm |
| **Max Stress** | 17MPa | 2.65MPa | 0.21MPa |

*Table 5.1 Analysis Settings and Results*

### 5.3.1.2 PVC Rings Tyre Analysis:

This analysis shows the resulting deformation and stresses on the PVC rings tyre. The forces applied and fixed supports used have been elaborated via the given table. The deformation and the stresses generated at the contact patch are also shown.

In performing this Finite Element Analysis (FEA), the mesh size was kept at 15mm, the element types a tetrahedral shape, and the number of nodes cumulated to 94,589.

**Vertical Loading:**

For Vertical loading, the fixed support was set at the contact patch of the tyre, a force of 800N was applied along the z-axis, and the simulation gave a result of a maximum deformation of 2.26mm and a maximum stress of 24.97MPa.

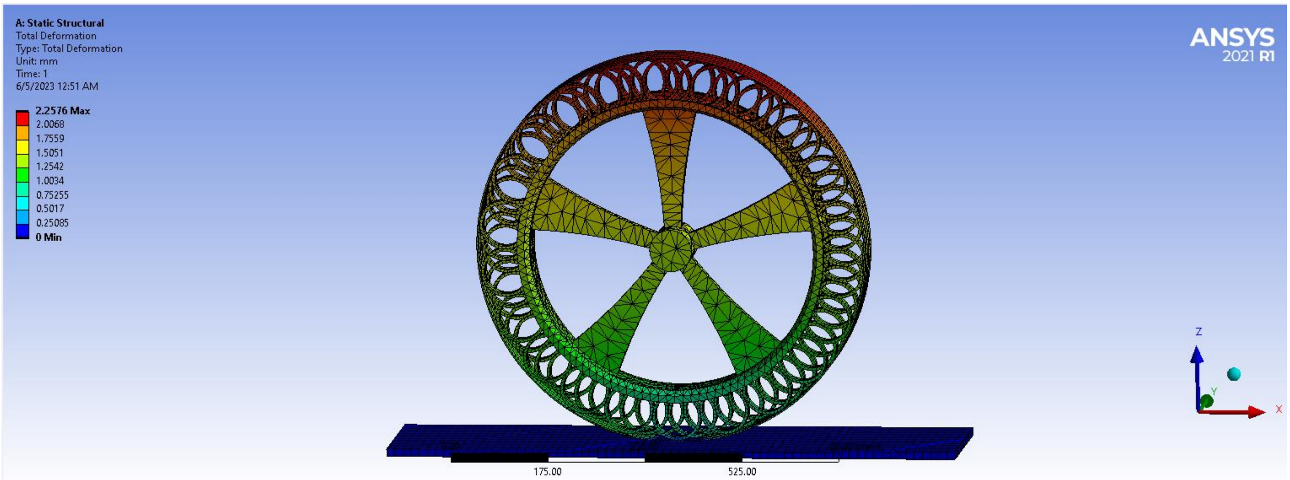


*Figure 47 Vertical Total Deformation*

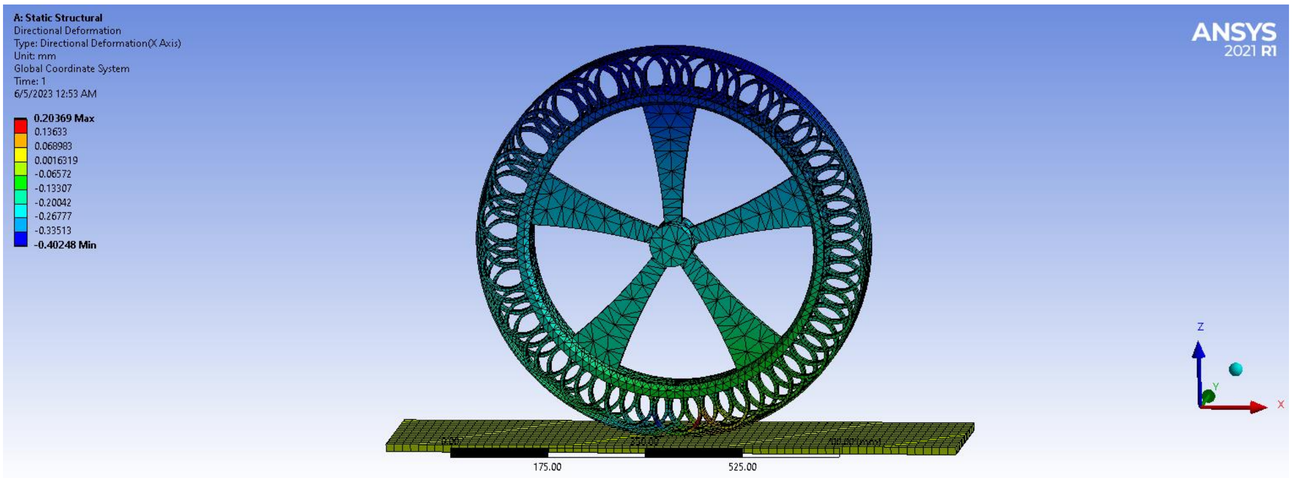


*Figure 48 Vertical Directional Z Deformation*

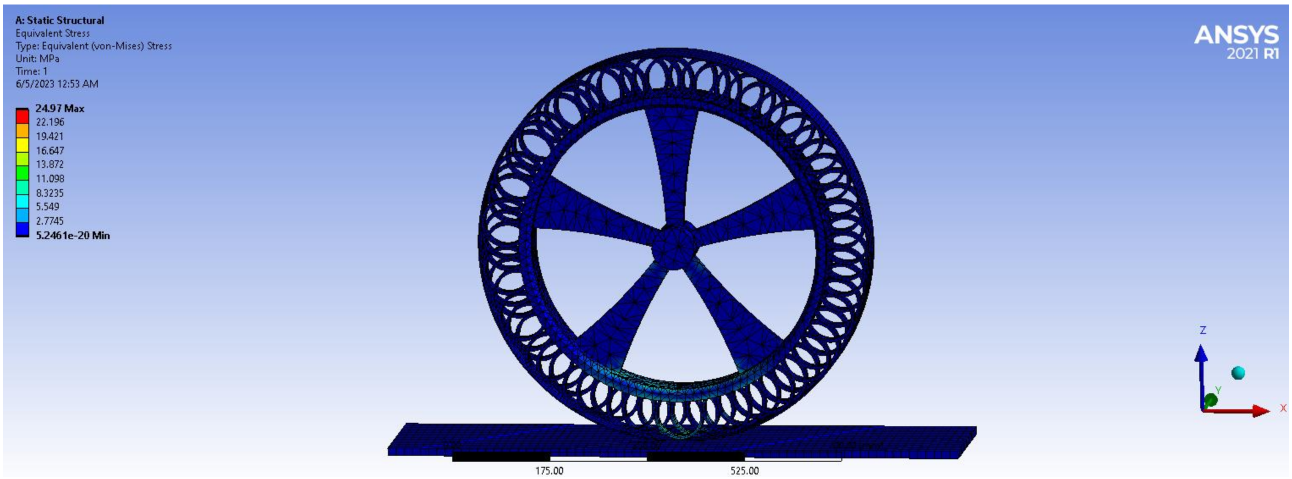


*Figure 49 Vertical Stress*

**Lateral Loading:**

For lateral loading, the fixed support was set at the contact patch of the tyre, a force of 400N was applied along the yz-plane at $45^0$, and the simulation gave a result of a maximum deformation of 24.26mm and a maximum stress of 12.10MPa.

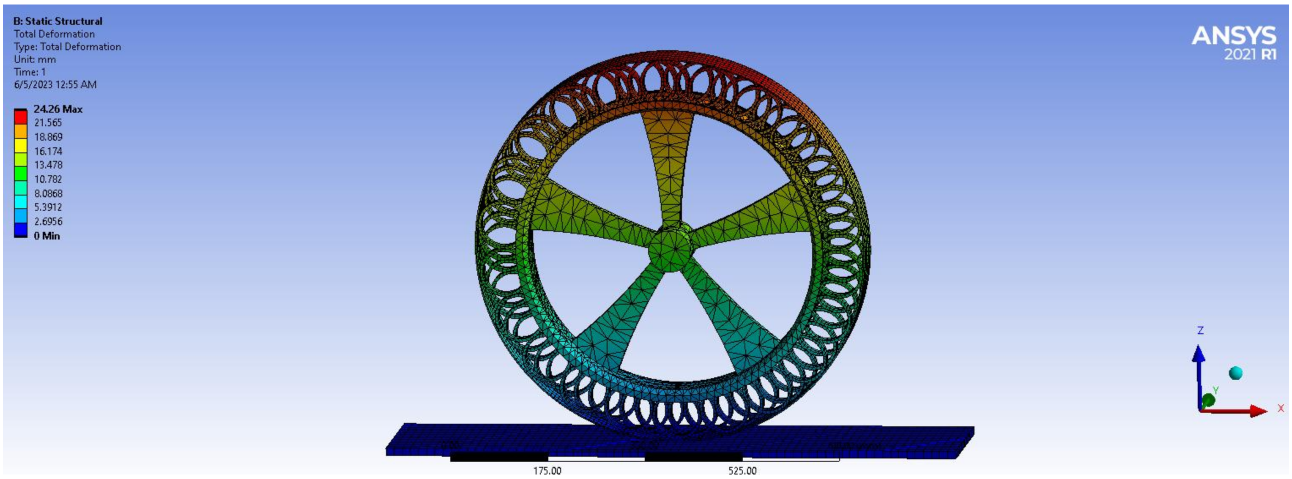


*Figure 50 Lateral Total Deformation*

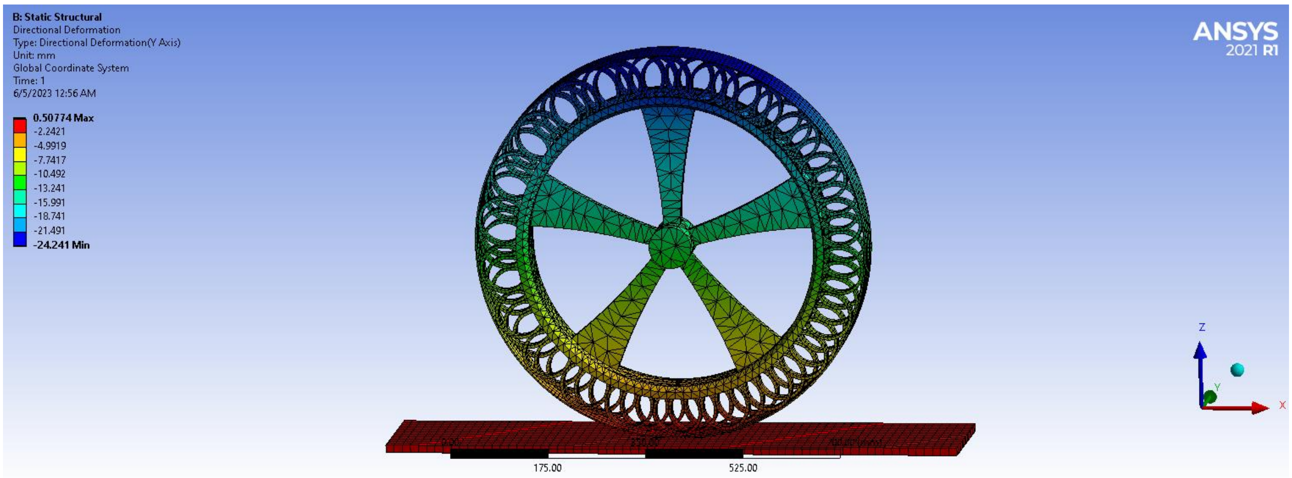


*Figure 515 Lateral Directional Y Deformation*

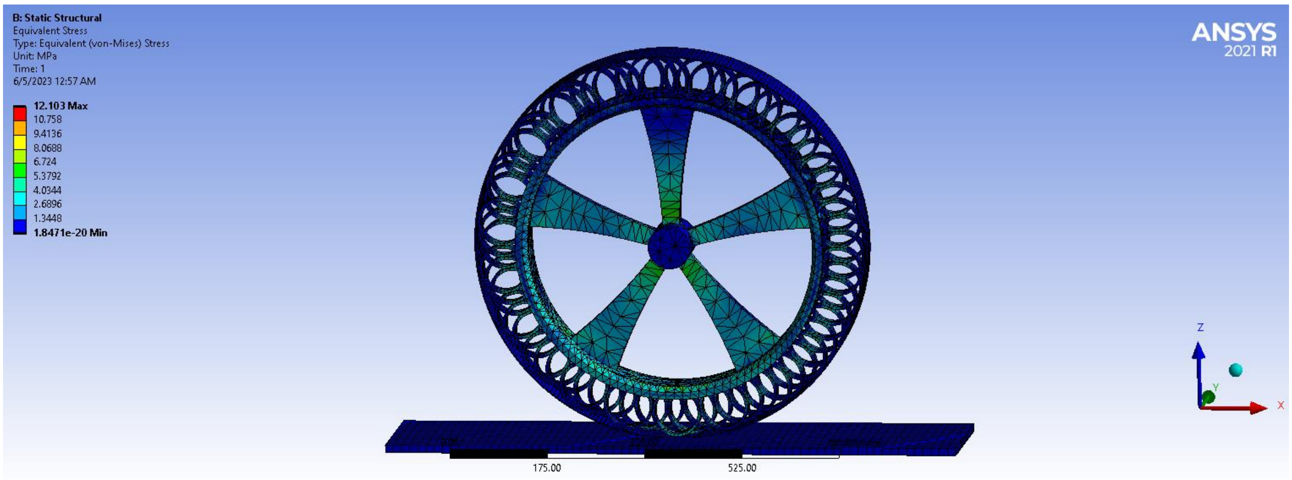


*Figure 52 Lateral Stress*

## Braking Force:

For the braking force, the fixed support was set at the rim hub, a force of 600N was applied along the x-axis, and the simulation gave a result of a maximum deformation of 18.05mm and a maximum stress of 0.9MPa.

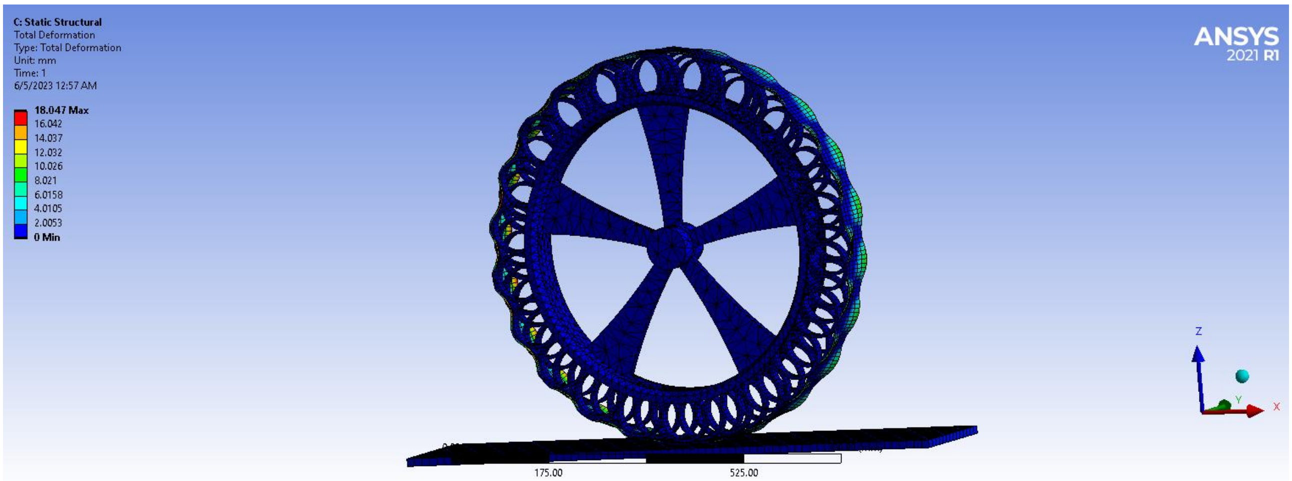


*Figure 53 Braking Total Deformation*

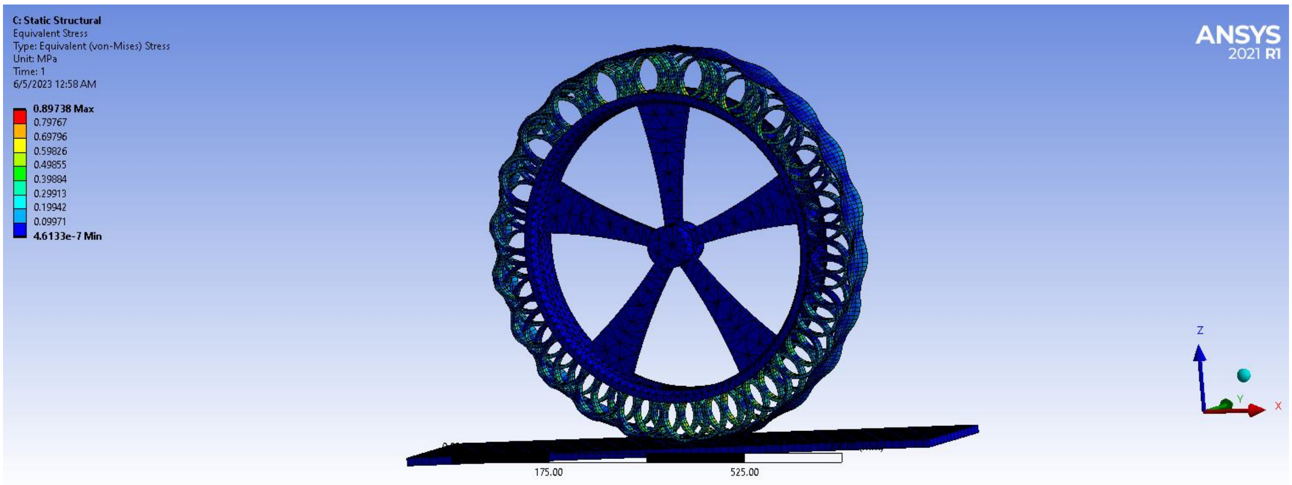


*Figure 54 Braking Stress*

| | Vertical | Lateral | Braking |
|---|---|---|---|
| **Element Size** | 15mm | 15mm | 15mm |
| **Element Type** | Tetrahedral | Tetrahedral | Tetrahedral |
| **No. of Nodes** | 94,589 | 94,589 | 94,589 |
| **Load and Location** | 800N (z axis) | 400N (yz plane at $45^0$) | 600N (x axis) |
| **Fixed Support** | Contact Patch | Contact Patch | Rim Hub |
| **Max Deformation** | 2.26mm | 24.26mm | 18.05mm |
| **Max Stress** | 24.97MPa | 12.10MPa | 0.9MPa |

*Table 5.2 Analysis Settings and Results*

### 5.3.1.3 Metallic Loops Tyre Analysis:

This analysis shows the resulting deformation and stresses on the metallic loops tyre. The forces applied and fixed supports used have been elaborated via the given table. The deformation and the stresses generated at the contact patch are also shown.

In performing this Finite Element Analysis (FEA), the mesh size was kept at 15mm, the element types a tetrahedral shape, and the number of nodes cumulated to 94,589.

**Vertical Loading:**

For Vertical loading, the fixed support was set at the contact patch of the tyre, a force of 800N was applied along the z-axis, and the simulation gave a result of a maximum deformation of 2.65mm and a maximum stress of 277.46MPa.

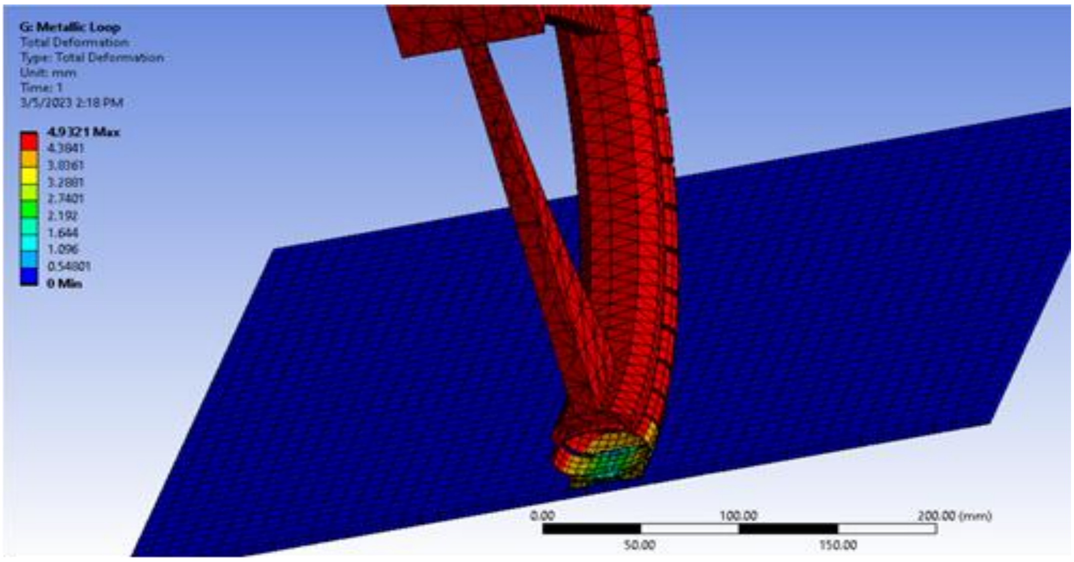


*Figure 55 Vertical Total Deformation*

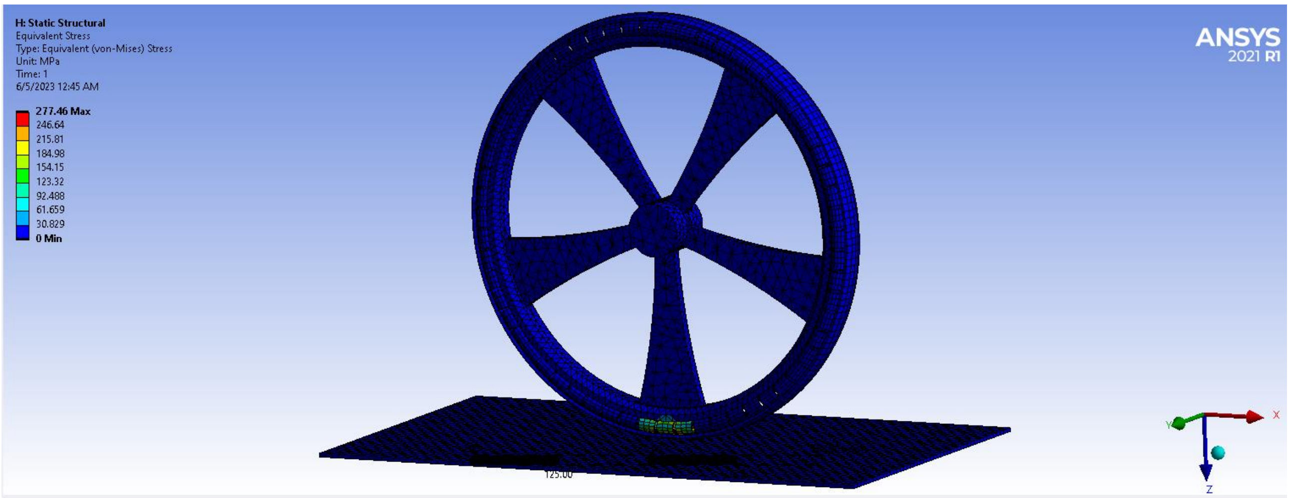


*Figure 56 Vertical Stress*

**Lateral Loading:**

For lateral loading, the fixed support was set at the contact patch of the tyre, a force of 400N was applied along the yz-plane at $45^0$, and the simulation gave a result of a maximum deformation of 21.42mm and a maximum stress of 736.94MPa.

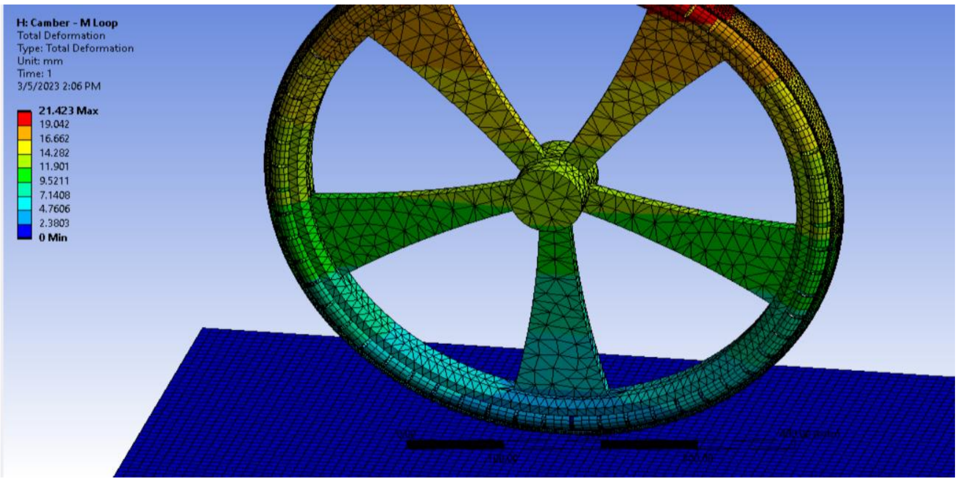


*Figure 57 Lateral Total Deformation*

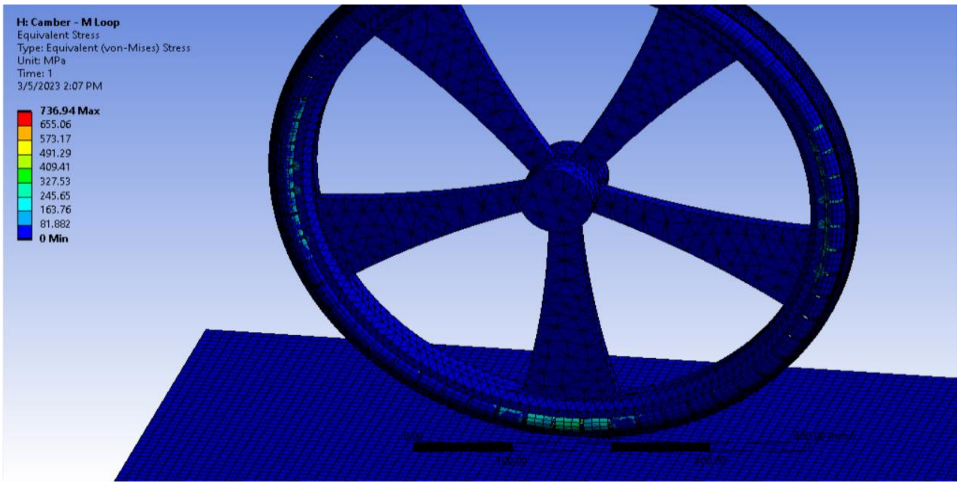


*Figure 58 Lateral Stress*

**Braking Force:**

For the braking force, the fixed support was set at the rim hub, a force of 600N was applied along the x-axis, and the simulation gave a result of a maximum deformation of 0.116mm and a maximum stress of 16.38MPa.

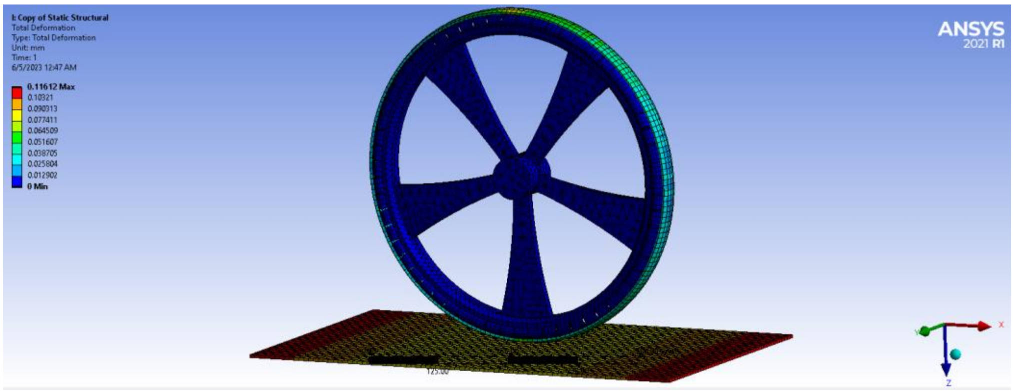


*Figure 59 Braking Total Deformation*

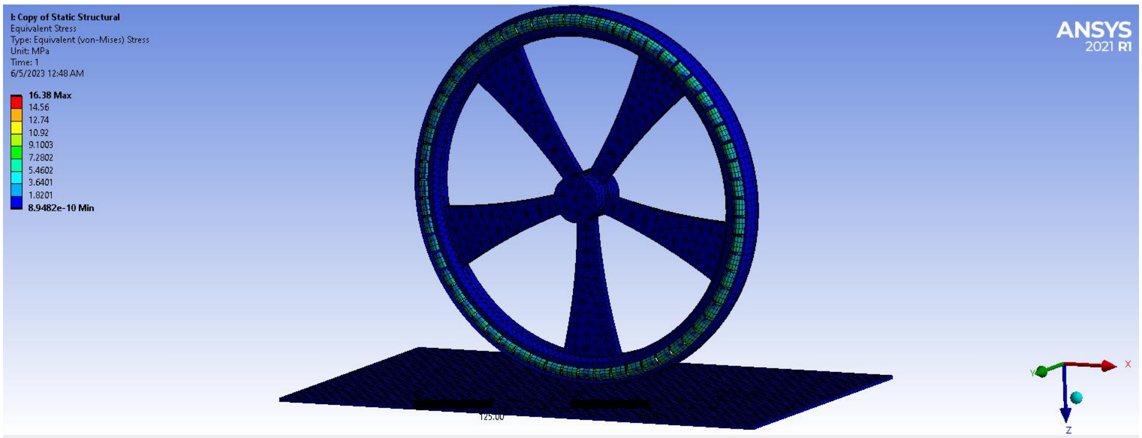


*Figure 60 Braking Stress*

| | **Vertical** | **Lateral** | **Braking** |
|---|---|---|---|
| **Element Size** | 10mm | 10mm | 10mm |
| **Element Type** | Tetrahedral | Tetrahedral | Tetrahedral |
| **No. of Nodes** | 95,609 | 95,609 | 95,609 |
| **Load and Location** | 800N (z axis) | 400N (yz plane at $45^0$) | 600N (x axis) |
| **Fixed Support** | Contact Patch | Contact Patch | Rim Hub |
| **Max Deformation** | 2.65mm | 21.42mm | 0.116mm |
| **Max Stress** | 277.46MPa | 736.94MPa | 16.38MPa |

*Table 5.3 Analysis Settings and Results*

### 5.3.2 Analysis Result:

In light of the above analyses, we can draw some basic results regarding the capabilities of each design.

First of all, we have the solid rubber design. This design is good at vertical load-bearing, but exhibits notable deformation on lateral loading, and can have the problem of deformed holes due to braking force, which could lead to rubber shearing.

Next, we have the PVC rings design. Now this design is good at both vertical and lateral load-bearing, but its tread deformation due to space in rings, and no other connection than tread being tension bound to rim.

Finally, we have the metallic loops design. This design exhibits low deformation but high stresses for both vertical and lateral load-bearing. For vertical force, the stress is at contact patch. For lateral force, the stress can cause permanent deformation. Even under braking force, the elements are under high stress.

# Chapter 6

# DESIGN DECISION MATRIX

As for the decision in finalizing the design before we proceed to prototyping, we used the design decision matrix methodology. The matrix is shown below:

| | SOLID | METALLIC | PVC |
|---|---|---|---|
| **Cost (40)** | 10 | 35 | 30 |
| **Material Availability (20)** | 15 | 20 | 20 |
| **Fabrication Feasibility (10)** | 6 | 8 | 10 |
| **FEA (30)** | 25 | 15 | 25 |
| **TOTAL** | 56 | 78 | 85 |

*Table 6.1 Design Decision Matrix*

## 6.1 Justification:

After evaluating the three design options for a non-pneumatic bicycle tyre, the decision matrix was utilized to assess the suitability of each option based on four factors: cost, material availability, fabrication feasibility and FEA. The provided data allows us to analyze these factors and justify the selection of the PVC rings design, which received the highest total score.

### 6.1.1 Cost:

The cost factor is crucial in any design decision. The scores assigned to each design option reflect the cost considerations associated with material procurement, mold making, and manufacturing processes. In terms of cost, the PVC rings design received a score of 30, which is the second highest among the three options.

The solid rubber tyre option was assigned a score of 10 due to the high cost of mold making (250,000 Rs) and the additional expense for casting (5,000 Rs. per tyre) leads to a total cost of 260,000 Rs. This makes it a less viable choice for prototyping.

The metallic loop tyre option received a score of 35, indicating the lowest cost among the three designs. Since it involves the process of cutting and joining galvanized steel pipes, the only cost comes from procuring the required material. Moreover, all the necessary tools and machinery are already available at the institution. So, the cost is only around 30000Rs, which is basically just the cost of the bicycle and steel pipes. However, it requires a considerable amount of time and labor, making it difficult while also leading to increased production expenses.

The PVC rings design, with a score of 30, generally offers a cost advantage over the solid rubber and metallic loop options. The cost of PVC material at around 6000Rs, nuts, bolts and washers at around 2000 – 3000Rs per tyre for every iteration, and additional components, is relatively lower (41,000 Rs) compared to the other two options. Additionally, the ease of machining and assembly further contributes to cost savings during the fabrication process.

### 6.1.2 Material Availability:

The availability of materials is another important aspect when making a design decision. The assigned scores reflect the accessibility and feasibility of obtaining the required materials for each design option.

The solid rubber tyre, despite being a conventional material, received a score of 15 for material availability. This lower score is due to the specific material requirement of butyl rubber and the associated challenges in procuring it.

The metallic loop tyre, with galvanized steel pipes as the material, received a score of 20. This is because these steel pipes are commonly available. The only limitation may come from the need for specific dimensions, and the possibility of undetected material deterioration in the available steel pipes. However, they are widely accessible, and thus these limitations should not pose too much of a problem.

The PVC rings design, assigned a score of 20, demonstrates comparable material availability to the metallic loop tyre. PVC schedule 80 is a widely accessible material, and the required dimensions can be easily obtained from various suppliers.

### 6.1.3 Fabrication Feasibility:

Fabrication feasibility is a critical factor that determines the practicality and ease of manufacturing the chosen design option. The assigned scores reflect the level of complexity and feasibility associated with fabrication.

The solid rubber tyre, with a fabrication feasibility score of 6, faces challenges in achieving precise mold making due to its material properties. Additionally, the high cost of mold creation makes it less favorable for prototyping and initial production phases.

The metallic loop tyre received a score of 8 for fabrication feasibility. While metalworking processes can be more intricate compared to rubber molding, the cutting and joining of galvanized steel pipes can be achieved with reasonable accuracy.

The PVC rings design received the highest score of 10 for fabrication feasibility. PVC material can be easily machined, allowing for precise shaping and assembly. The simplicity of the manufacturing process further supports its feasibility.

### 6.1.4 FEA:

FEA (or finite element analysis) allows us to run an analysis and hence, simulate the deformations and stresses that each tyre design would experience under different types of loading conditions. The assigned scores reflect the level of deformations and stresses generated which, in turn affect the rider comfort. A higher score indicates better results.

The PVC rings tyre is allotted a score of 25 out of 30, because its tread tends to deform undesirably on braking force. The solid rubber tyre with through holes is also given a score of 25 out of 30. This is because while it does not generate high stresses, it does deform undesirably upon braking, and it exhibits a very high deformation upon lateral loading. Finally, the metallic tyre is given the lowest score, 15 out of 30, as it experiences exorbitantly high stresses both on lateral and vertical loading. It also still exhibits an uncomfortable amount of deformation from lateral loading.

Thus, the PVC rings design seems the most feasible from these FEA results, as it showcases the results closest to ideal requirements from the three available options, and does not have any severe problems from any single aspect.

## 6.2 Conclusion:

After careful evaluation of the three design options based on cost, material availability, fabrication feasibility and FEA, the PVC rings design emerges as the most suitable choice. The justification lies in its relatively lower cost compared to the solid rubber and metallic loop options, coupled with comparable material availability. Moreover, the PVC rings design demonstrates high fabrication feasibility, enabling efficient manufacturing processes.

While each design option has its own merits, the PVC rings design aligns with the criteria outlined in the design decision matrix, resulting in the highest overall score.

# Chapter 7

# FABRICATION

The fabrication procedures of this project depended on the approach undertaken to fabricate a working model/prototype.

## 7.1 Possibilities:

### 7.1.1 Large-Scale Production:

If the tyre is to be manufactured on a large scale (industrial level), then making mold design for the tyre is the recommended approach. In the mold design, the structural design remains the same as illustrated in the models with the same dimensions. This is because the analytical model has not changed and structural loading on the tyres can be assumed to remain the same, as calculated before in section → **Methodology**.

### 7.1.2 Prototype Production:

But, if large-scale manufacture is not the case, especially as in this case, it is the fabrication of a pair of NPTs for testing purposes, then it would be uneconomical, and hence, unfeasible to rely on injection molding process. Rather, it is recommended to rely on obtaining the raw materials, and rely on simple mechanical procedures such as machining, drilling, and using bolts and nuts to hold together an assembled chain of PVC rings around the periphery of the rim. Washers may also be used as desired to prevent unwanted scraping damage.

## 7.2 Limitations:

### 7.2.1 Approach adopted:

Now, since we are only prototyping and testing, we went with the economical option of using the PVC assembly approach with nuts and bolts. Taking the available budget into account, it is also unfeasible for us to manufacture a mold for our design.

### 7.2.2 Raw Materials:

The raw materials procured were the following:

1. PVC Pipe: A PVC schedule 80 pipe, 4 m (13 feet) long. This pipe was to be cut into PVC rings, each piece with a width of 20mm (0.8 in). Thus, a total of 200 PVC rings could be made via lathe machine in this way.
2. Bolts: A total of 300 M5 bolts. The purpose of these bolts was to connect the PVC rings to form a chain, each of 22 PVC rings. Their purpose was also to connect this chain to the tyre rim.
3. Nuts: A total of 300 M5 nuts. These nuts were to be used with the bolts in connecting the PVC rings with each other as well as the tyre rim.
4. Washers: A total of 900 washers. These washers were to be used between the bolt head and PVC ring surface, nut and PVC ring surface or tyre rim surface, and between two PVC rings in a chain.

### 7.2.3 Tools used:

The following tools were used for the manufacturing:

1. Band Saw: PVC Pipes were cut down to size using the band saw so that the cut pieces could be mounted onto the lathe machine.
2. Lathe Machine: The PVC pipe pieces from the band saw were mounted on the chuck of the lathe machine, and each piece was cut down to rings on the lathe machine.
3. Drilling Machine: It was used to make holes in all the PVC rings, for the nuts, bolts and washers.
4. Box Cutter: A box cutter was used to smoothen the sides of each PVC ring manually.
5. Screw-drivers: Screw-drivers were used for proper fitting of the nuts and bolts.

### 7.2.4 Resource Planning:

With the available resources in mind, the allocation was planned so that even if the design may exhibit some problems prone to failure, there should be sufficient resources left to try to improve the existing

design or try manufacturing possible alternatives. An example of this would be that the total amount of PVC rings required to fabricate both the front and rear wheels was 132, whereas we had 200 rings readily available, in case the design required some adjustments, changes or improvements.
Although, these spare resources are in an insufficient amount, in case it is desired to use them to manufacture alternative designs alongside the main one, and compare their performance via fabricated testing.

### 7.2.5 Fabricated Model:

3 PVC chains were used as the compliant material in each tyre. Each PVC chain comprised of 22 PVC rings.
The rings in these chain were interconnected using nuts, bolts and washers. 1 nut, 1 bolt and 3 washers were used to connect each ring with another. Thus, 22 nuts, 22 bolts and 66 washers were used for the connections in an entyre chain. This means a total 66 nuts; 66 bolts and 198 washers were used for PVC chains per tyre.

Now, coming to the connection of the PVC chains with the rim, each PVC ring was connected to the rim via 1 nut, 1 bolt and 2 washers. Since we have 66 PVC rings per tyre (22 per chain), a total of 66 nuts, 66 bolts and 132 washers were used for the connection of the rim to the PVC rings.
Since we had to fabricate Non-Pneumatic Tyres for both the rear and the front of the bicycle, this means a total 132 nuts, 132 bolts and 330 washers were used in the fabrication process.
Thus, only the PVC rings tyres were fabricated first. When their testing exhibited successful and satisfactory results, further testing and improvements were incorporated in them. Therefore, the available time and resources were focused on the successful model to improve its success and impact even further. However, all these directed resources meant there were none available for the other designs, and thus, only the PVC rings design would be fabricated.

Fabricated Prototype

## 7.3 Material Properties:

This brings forth the question of how much the material properties would allow the structure to hold up if we use an assembly of PVC rings via nuts and bolts, and how would these properties alter if a different method and material is used. It can be addressed by the table of material properties provided within the sub-heading, as well as the bar graphs.

### 7.3.1 PVC in assembly:

| PVC (assembled) | |
|---|---|
| **Property** | **Value** |
| Tensile Strength | 7,000-9,000 psi (48-62 MPa) |
| Flexural Strength | 10,000-12,000 psi (69-83 MPa) |
| Compressive Strength | 8,000-10,000 psi (55-69 MPa) |
| Impact Strength | 1.5-2.5 ft-lb/in (80-134 J/m) |
| Modulus of Elasticity | 400,000-500,000 psi (2,758-3,448 MPa) |

*Table 7.1 Table of PVC Schedule 80 Properties [16]*

For each of these mechanical properties of PVC Schedule 80, in terms of load bearing:

- Tensile Strength: Tensile strength is the maximum stress a material can withstand before breaking under tension. This property is required to be high so that none of the PVC rings break. Because if even one breaks, it will disrupt the effectiveness of the entyre chain.
- Flexural Strength: Flexural strength represents the ability of the material to resist bending and deformation when subjected to a load. Rather than an absolutely high or low value, this property is required to have an optimal value to ensure rider comfort without any compromise on structural integrity.
- Compressive Strength: Compressive strength refers to the ability of a material to withstand loads that tend to reduce its volume. This property carries significant importance, because as soon as the rider sits on the bicycle, the rings right by the contact patch will undergo some compression. This property will determine how much compression occurs.
- Impact Strength: Impact strength measures a material's ability to absorb energy when subjected to a sudden shock or impact. This property carries weightage when taking into

account bumpy roads and rough surfaces, often encountered when off-roading on a bicycle. It determines how well the bicycle can handle these sudden shocks.

- Modulus of Elasticity: The modulus of elasticity, also known as Young's modulus, represents the stiffness of a material and its resistance to deformation under an applied load. A higher Young's Modulus means more force required per unit of deformation. So, we want this property to be at an optimal level too for tyre design, and preferably within the elastic limit.

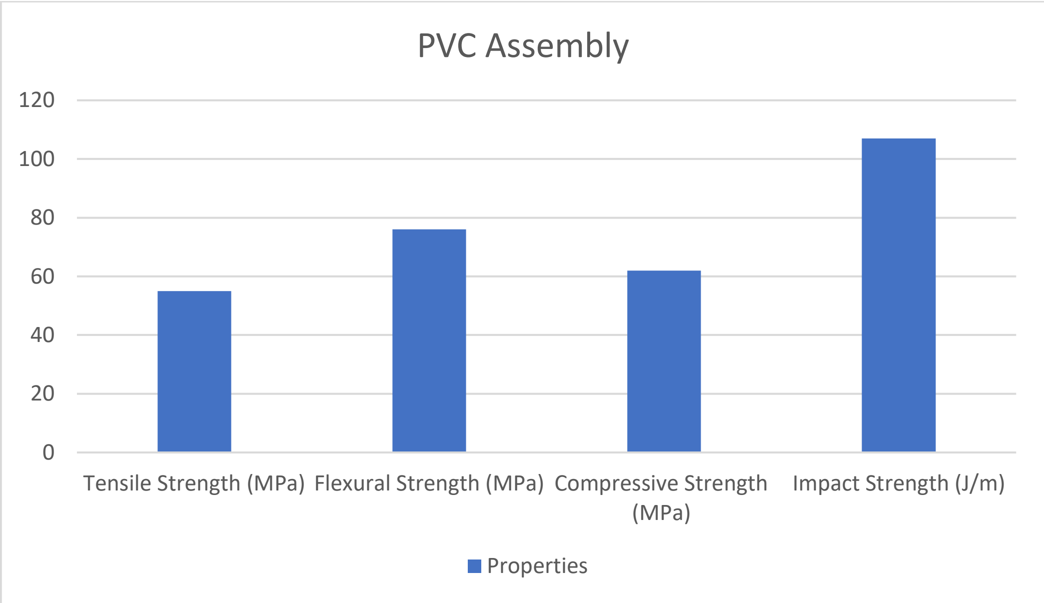


*Figure 61 Graph of Mechanical Properties of PVC*

In our case, we used rings made from a U-PVC schedule 80 pipe of 89mm (3.5 in) outer diameter, and 5.5mm wall thickness. This pipe and thus, its pieces had the following properties:

- An ultimate tensile strength of 27.6 MPa
- A yield strength of 20.7 MPa
- A modulus of elasticity of 2.6 GPa
- A Poisson's ratio of 0.4
- A specific gravity of 1.4
- A coefficient of thermal expansion of $8.6 \times 10^{-5}$ m/m·K
- A density of 1430 kg/m$^3$

These properties are based on the standard ASTM D1785.

### 7.3.2 Other options for Fabrication:

In other options, we move towards taking a look at those materials in which fabrication can be done such that mass manufacturing is possible. These fabrication options may include methods like injection molding [17], and for materials, we can move towards better options in terms of load carrying and cyclic load bearing.

These materials include polyurethane [2], which is quite famous for non-pneumatic tyre research, as well as other composites, such as graphene, Molybdenum disulfide etc. [18]

Basically, we aim to use such materials which are capable of load bearing, can dampen vibrations, and do not fail under cyclic stress. There are multiple works ongoing for designing a composite material with the ideal properties demanded by non-pneumatic tyres. [19]

## 7.4 Fatigue Failure:

### 7.4.1 Aspect of Fatigue in PVC:

As far as fatigue failure is concerned, there are certain factors to be considered when it comes to PVC:

1. Fatigue Strength: PVC pipes' fatigue strength is quite low when compared to their static strength. The maximum stress amplitude that a material can tolerate for a predetermined number of cycles before failing is known as the fatigue strength. It typically falls below the material's ultimate tensile strength.
2. Stress Concentration: PVC pipes can experience stress concentrations at notches, splits, or other geometrical changes. The pipe's fatigue life may be considerably shortened by these stress concentrations.
3. Load Magnitude and Frequency: Critical elements in fatigue failure are the magnitude and frequency of cyclic loads. Shorter fatigue life can result from faster crack initiation and spread caused by higher stress amplitudes and more frequent loading cycles.
4. Environmental Factors: The fatigue properties of PVC pipes can be impacted by environmental factors such as temperature, chemical exposure, UV light, and moisture. Exposure to certain chemicals or harsh environments may hasten the material's decomposition and shorten its fatigue life.

5. Design considerations: For reducing stress concentrations and enhancing fatigue resistance, proper pipe design is crucial, taking into account elements like wall thickness, pipe diameter, and reinforcement (if necessary).

**Testing and Standards:** A number of testing techniques, including dynamic mechanical analysis and cyclic pressure testing, can be utilized to assess the fatigue properties of PVC pipes. For testing and evaluating the long-term performance of PVC pipes under cyclic stress, standards and guidelines like ASTM D1598 and ISO 9080 offer suggestions.

## 7.4.2 Fatigue Analysis for PVC Schedule 80:

Considering the different aspects of fatigue discussed above, it is necessary to run an analysis to acquire an estimate of the fatigue life of the PVC rings tyre design.

In each tyre, there are three PVC ring chains for the load bearing. Each element comes into contact for the load-bearing once per revolution, and consists of three PVC rings. Thus, each of the PVC rings comes under cyclic load once every revolution. Each of the PVC rings is constrained from three sides, one side from the rim connection, and two sides from the PVC rings it is connected to in the chain.

So, when a force is applied, it is equally distributed on top of each PVC ring. Applying a force of a 1000N per tyre (which is extremely high, especially considering the calculations done in Chapter → Methodology), we can see from the results produced by ANSYS that the fatigue life of a tyre comes out to be 300,000 cycles. This means each element, comprising of three PVC rings, can hypothetically last up to 300,000 revolutions.

The ANSYS analysis is displayed as follows:

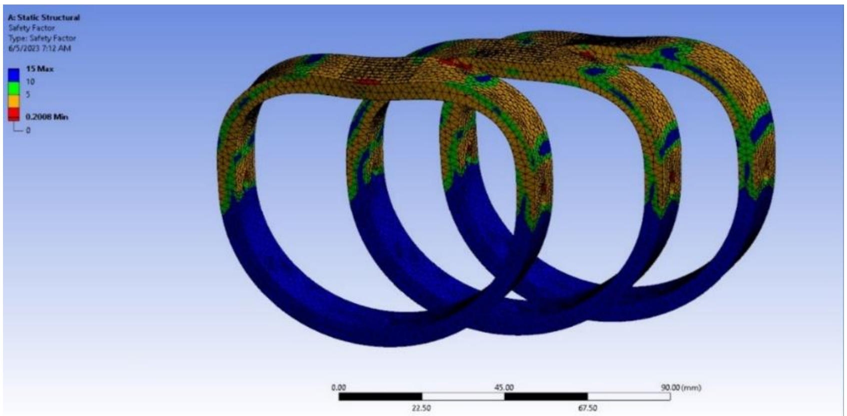


*Figure 62 Safety Factor*

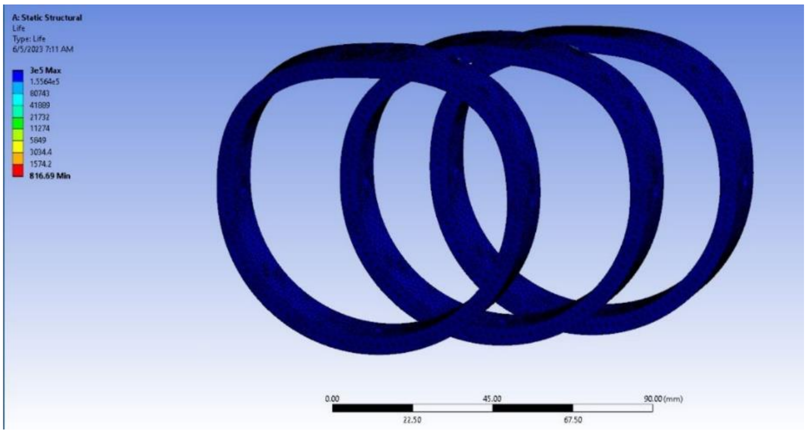


*Figure 63 Fatigue Lifecycle*

## 7.5 Future Prospects:

The designed and fabricated pair of Non-Pneumatic Tyres with PVC schedule 80 as the compliant material were applied on a bicycle in this project. However, the work covered in this project is not limited to bicycles only.

The solution is aimed at all two-wheeler dynamic systems, after necessary adjustments have been made to the design and material used, as required by the two-wheeler dynamic system it is being applied on.

### 7.5.1 Implementation of Non-Pneumatic Tyres on a Bicycle:

For example, in the case of a bicycle, the implementation of Non-Pneumatic Tyres involves using 2-3 layers of PVC rings-chain per tyre. Due to the generally lower speeds of bicycles, no problems are encountered by the tyres when in motion, considering the radial stiffness as well as camber stiffness. This is applicable for the PVC rings-chain assembled through nuts and bolts too. The thickness and width of the PVC rings can be about 5 mm and 18 mm respectively. The fatigue of PVC rings chain is calculated via ANSYS to be about 300,000 cycles.

The case of a PVC rings chain fatigue is only calculated through simulation due to limitation of the available testing machinery. Thus, the fatigue life cycle, as discussed before in section 7.4, for a bicycle with such non-pneumatic tyres is about 300,000 cycles. However, the introduction of a different composite material for mass manufacturing via procedures such as injection molding could significantly improve this fatigue life. This estimate is based upon the fact that the collected data from internationally recognized authentic sources [19] indicates a significant increase in the fatigue life cycle of non-pneumatic tyres should an appropriate composite be used for their fabrication.

### 7.5.2 Expanding the application to Higher Speed Two-Wheel Dynamic Systems:

Another example would be using Non-Pneumatic Tyres in higher speed two-wheel dynamic systems, such as a motorbike. Now, in this case, due to the higher speeds and larger heat produced, these exact same design and materials may not be applicable, and would definitely need to be further worked on to be applied on fast vehicles like motorcycles.

Improvements may include approaches such as reinforcing the interior hollow structure of the tyre, adding further layers with appropriate separation, and since large heat build-up is an issue, changing the material used to a more heat resistant variant with similar or better load-varying and cushioning capabilities.

Obviously, there may be other methods of improvement not listed here, but this solution essentially paves the way for future work to bring forth a feasible concept for such high speed, large heat generating applications.

The current concept can be brought forth to implementation on the large scale by manufacturing via injection molding, as mentioned before.

# Chapter 8

# NON-PNEUMATIC TYRES VS PNEUMATIC TYRES

## 8.1 Vertical Stiffness:

The vertical stiffness is the deformation of the tyre per vertically applied load, such as when a rider sits on the bicycle. It was determined by applying weights on a tyre and measuring deformation per each applied weight. For NPT, it was measured to be approximately 35 N/mm within a range of extension from 0 – 7 mm, whereas for a pneumatic tyre, it was measured to be approximately 163 N/mm within a range of extension from 0 – 1.5 mm.

| **Force (N)** | **NPT Displacement (mm)** | **Pneumatic Tyre Displacement (mm)** |
|---|---|---|
| 0 | 0 | 0 |
| 49 | 0.5 | 0 |
| 98 | 2.5 | 0.2 |
| 147 | 4 | 0.5 |
| 196 | 4.4 | 1 |
| 245 | 7 | 1.5 |

*Table 8.1 Comparison of Vertical Stiffness (Pneumatic vs NPT)*

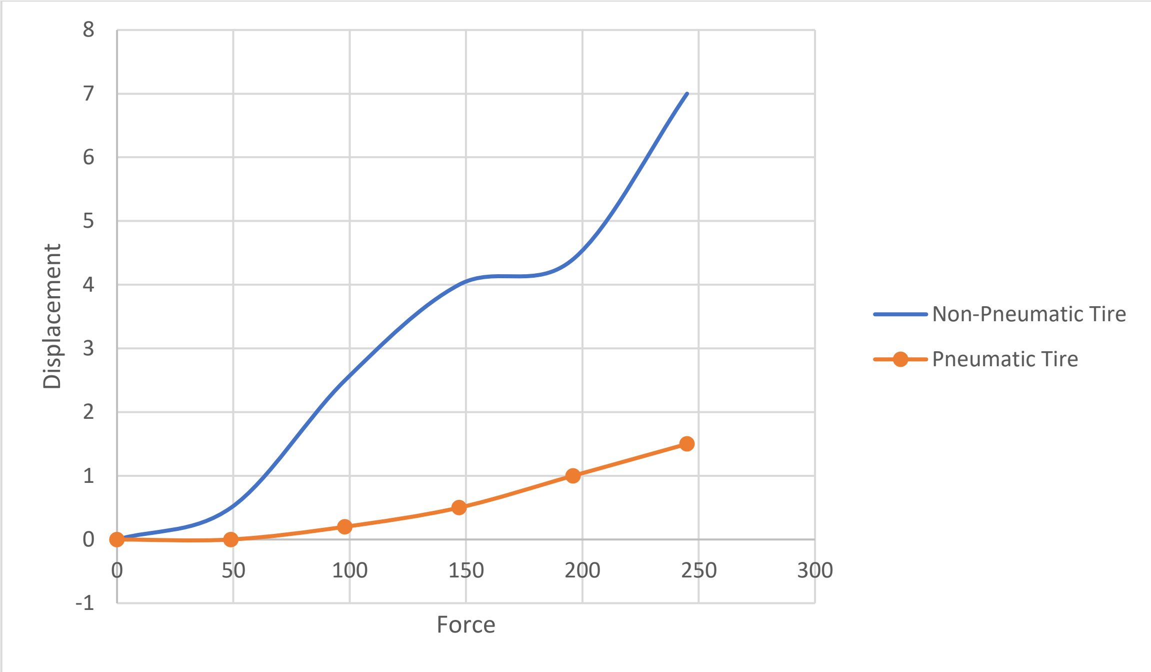


*Figure 64 Vertical Stiffness Graph*

## 8.2 Rolling Resistance:

Pneumatic tyres generally have lower rolling resistance compared to non-pneumatic tyres. The air-filled structure of pneumatic tyres allows them to deform and roll more efficiently, reducing friction between the tyre and the ground. This results in better energy efficiency and smoother rolling, allowing for easier pedaling and improved overall performance. [8]

Non-pneumatic tyres, on the other hand, tend to have a higher rolling resistance due to their solid construction, which doesn't allow for as much flexibility and deformation. This makes it slightly more challenging to pedal and may require more effort from the rider. [13]

## 8.3 Traction:

The following three parameters determine traction of tyres:

1. Surface Area: The contact patch between the tyre and the ground determines the traction. Generally, a wider tyre (common in pneumatic tyres) provides a larger contact area, resulting in increased traction compared to a narrower tyre (typical in non-pneumatic tyres).
2. Tyre Pressure: Pneumatic tyres can be inflated to different pressures, which affects their traction. Higher tyre pressure tends to reduce the contact area, leading to decreased traction

but increased rolling efficiency. Lower tyre pressure increases the contact area, enhancing traction but potentially decreasing efficiency due to higher rolling resistance.

3. Tyre Composition: The material and tread pattern of the tyre impact its grip on the road. Pneumatic tyres often have a rubber outer layer with a tread pattern designed for specific surfaces (e.g., road, off-road). Non-pneumatic tyres can use various materials, including solid rubber or foam, which may have different traction characteristics.

Keeping the above parameters in view, pneumatic tyres generally offer better traction compared to non-pneumatic tyres. The air-filled design of pneumatic tyres allows them to conform to the surface irregularities and provide a larger contact patch with the ground. This increased contact area improves grip and traction, particularly on uneven or slippery surfaces. [15]

Non-pneumatic tyres, due to their solid construction, may have limited ability to conform to the terrain, resulting in reduced traction. While non-pneumatic tyres can still provide sufficient traction in certain conditions, pneumatic tyres are generally preferred in situations where optimal grip and traction are crucial, such as in wet or off-road environments.

## 8.4 Durability:

Non-pneumatic tyres tend to have an advantage in terms of durability compared to pneumatic tyres. Pneumatic tyres are susceptible to punctures and flats, which can affect their lifespan and require regular maintenance and repairs. In contrast, non-pneumatic tyres, often made of solid rubber or resilient materials, are more resistant to punctures and are designed to withstand tough conditions. This increased durability allows non-pneumatic tyres to have a longer lifespan and require less frequent replacement, making them a preferred choice in applications where durability and reliability are essential, such as heavy-duty industrial or off-road use.

## 8.5 Comfort:

Pneumatic tyres generally offer better comfort compared to non-pneumatic tyres. The air-filled structure of pneumatic tyres provides cushioning and shock absorption, allowing them to effectively dampen vibrations and impacts from the road or trail surface. This results in a smoother and more comfortable ride for the rider, reducing fatigue and enhancing overall comfort.

Non-pneumatic tyres, due to their solid construction, lack the ability to provide as much cushioning and vibration dampening. As a result, they may transmit more vibrations and impacts to the rider, potentially leading to a less comfortable riding experience, particularly on rough or uneven terrain.

## 8.6 Tyre Weight:

Coming to a comparison of both the tyres in terms of weight, non-pneumatic tyres generally have a higher weight as compared to pneumatic tyres due to the presence of a solid structure between the tyre-tread and rim instead of air. Illustrated below are the weights of both the Pneumatic and Non-Pneumatic Tyres, including the tyre rim:

| | **Front tyre weight** | **Rear Tyre weight** |
|---|---|---|
| **NPT** | 6.3 kg | 6.9 kg |
| **Pneumatic** | 5 kg | 5.6 kg |
| **RIM** | 2.4 kg | 3 kg |

*Table 8.2 Tyre Weights*

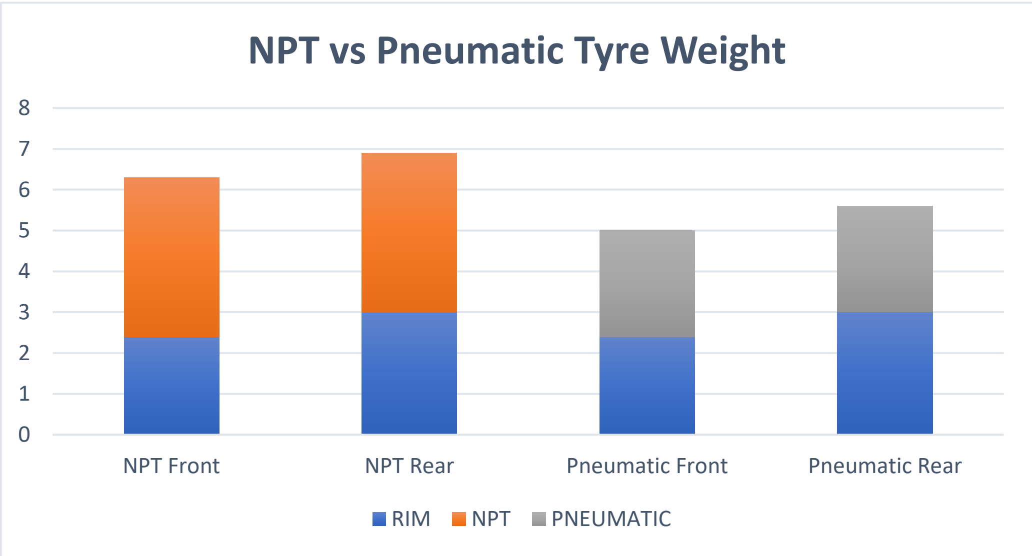


*Figure 65 Pneumatic Tyre vs NPT Weight*

## 8.7 Cost:

Pneumatic tyres are filled with air, which is free. The only thing they have which could contribute to a cost is the tyre tube, which is also extremely cheap.

On the contrary, non-pneumatic tyres have a compliant material which adds to the cost. This means non-pneumatic tyres cost more than a pneumatic tyre depending on the compliant material used. The cost can be mitigated relying on cheaper materials, such as the PVC rings we used.

## 8.8 Performance:

### 8.8.1 Evaluation Method:

The performance was evaluated by giving the bicycle equipped with a pair of NPTs a test run on a paved road with bumps and cracks, as well as off-road areas with rough areas having sharp bumps, riding it at nominal speed for about 30 mins. The total distance driven was 5 km (~3 miles) with an average speed of 9.8 km/h. The max speed was 27.4 km/h on a sloped road with bumps and a speed breaker the end.

### 8.8.2 Ride Comfort:

Rider comfort was observed to be slightly lower than the Pneumatic Tyre the bicycle originally came with, due to the rigidity and hence lower bounce of the fabricated prototype. However, rider comfort could be significantly improved by using suspension forks on the bicycle.

### 8.8.3 Effort for Acceleration:

Furthermore, higher speeds for this bicycle require a larger effort from the rider as compared to a regular bicycle. The tyre being a mountain bike already has a broad tread, and hence a larger traction with road, so it already required a high amount of effort for higher speeds even with the Pneumatic Tyre.

### 8.8.4 Additional Weight:

The other factor can be attributed to the additional weight due to the material weight of the Non-Pneumatic Tyre. But this additional weight can also be further reduced by removing the weight of nuts and bolts. As discussed before, we have currently fabricated only a concept prototype, by a reasonable method without expending too much budget. The product in mass-manufacturing would be fabricated via injection molding, thus removing the need for nuts and bolts for inter-ring connections. Hence the weight would be reduced by as much as 2 kg. This would reduce the amount of effort required to accelerate the bicycle.

# Chapter 9

# DELIVERABLES AND TARGETED SDGs

The main deliverable of the project is to fabricate a properly designed pair of NPT (airless tyres) feasible to be manufactured and serve the purpose for a bicycle. The key points of this major deliverable are mentioned below:

- These tyres will be flat-free, and hollow structured.

- Solid spokes of a flexible material such as polyurethane (this does not mean we will use polyurethane, but we will use a similarly flexible material) will be used in these airless non-pneumatic tyres, which shall serve as the substitute to air in conventional tyres.

- These solid spokes in the non-pneumatic tyres will perform the functions that were previously performed by air in conventional tyres such as shock absorption, offer low rolling resistance so that the bike can move smoothly along the road via rolling tyres and support the load of the rider while still allowing the tyres to roll.

- Additionally, since these tyres do not depend on air in a tube, they can survive penetration via sharp objects and still roll smoothly. This effectively counters the problem of **puncture** faced by many bicyclists. This shall lower repair requirements

- Conventional tyres face problems caused by fluctuations in pressure due to changes in temperature or humidity. However, NPTs are free from such limitations as they are airless, without compromising key deliverables of standard tyres such as traction and user comfort.

- The designed pair of airless tyres shall be analysed via FEA to confirm whether they achieve the above-mentioned objectives. This will require multiple iterations using different materials until we can finalize which spoke material is best to fulfil the desired goals.

- The hollow structure for the NPTs can range from honeycomb to diamond shaped, each having its own advantages and disadvantages. Therefore, FEA shall also be necessary for each structure to understand which structure will be the most feasible one for our application

- Basically, Finite Element Analysis shall play a key-role in finalizing the material to be used for spokes as well the structure

- Furthermore, the pair of non-pneumatic tyres shall also be fabricated and tested in real-time by driving it on a carpeted road with normal turns and curves.

Sustainability and development should be the prime goal of any research and project. The governing framework for sustainability and development is laid down by United Nations Sustainable Development Goals (SDGs). This project is essentially targeted to be in-line with the SDGs of the UN for adding a positive value in the sustainable development. The targeted SDGs by this project from the seventeen SDGs of UN are briefly explained as under:

1. **Responsible Consumption and Production**:

   In conventional tyres, the air tube is made of a non-biodegradable material. Given how often its punctures have to be treated, it soon reaches a stage where it has to be discarded. This leads to excessive material wastage.

   However, in the case of non-pneumatic tyres, the spokes will be replacing the air tube, making them flat-free and greatly lowering the repair requirement. These NPTs will last much longer than the tubes of conventional air tyres, greatly lowering material wastage.

2. **Climate Action:**

   The discarded tubes of conventional tyres are made of rubber, and it causes significant environmental damage when disposed of on land or into the sea. For example, leaching, pests, combustibility (discard harmful chemicals into the environment when burnt) and much more.

Since the NPTs will have to be replaced much less often than the tubes of conventional tyres, they will reduce environmental damage caused by discarded tyres.

# References


[1] S. M. C. T. B. Rhyne, "Development of a Non-Pneumatic Wheel," *Tyre Science and Technology*, vol. 34, no. 3, p. 150–169, September 2006.

[2] B. K. D. C. Manibaalan, "STATIC ANALYSIS OF AIRLESS TYRES," *International Journal of Scientific and Research Publications*, vol. 3, no. 8, pp. 2250-3153, August 2013.

[3] D.-M. K. K. K. Jaehyung Ju, "Flexible cellular solid spokes of a non-pneumatic tyre," *Composite Structures*, vol. 94, no. 12, p. 2285–2295, January 2012.

[4] Y. S. R. S. V. D. G. Jayanthi Srivatsa Sharma, "Study on The Feasibility of using Non-Pneumatic Tyres with Re-Entrant Type Auxetic Structured Spokes in Cessna 172 Aircraft Tyres," *International Journal of Engineering Research & Technology (IJERT)*, vol. 10, no. 5, pp. 2278-2287, May 2021.

[5] D. K. S. E. Nibin JacobMathew, "DESIGN AND STATIC ANALYSIS OF AIRLESS TYRE TO REDUCE DEFORMATION," in *IOP Conf. Series: Materials Science and Engineering*, Chennai, 2017.

[6] M. K. KAZUYUKI KABE, "Tyre Cornering Simulation Using Finite Element Analysis," *Journal of Applied Polymer Science*, vol. 78, no. 2, pp. 1566-1572, 2000.

[7] M. T. G. C. V. B. A. C. B. K. Alberto Doria, "Identification of the mechanical properties of bicycle tyres for modelling of bicycle dynamics," *Vehicle System Dynamics: International Journal of Vehicle Mechanics and Mobility*, vol. 51, no. 3, pp. 405-420, 2013.

[8] R. C. B. B. M. D. H. A. B. J.-D. R. F. GRAPPE, "Influence of tyre pressure and vertical load on coefficient of rolling resistance and simulated cycling performance," *ERGONOMICS*, vol. 10, no. 4, pp. 1361-1371, 1999.

[9] R. S. SHARP, "The Lateral Dynamics of Motorcycles and Bicycles," *International Journal of Vehicle Mechanics and Mobility*, Vols. 4-6, no. 14, pp. 265-283, 1985.

[10] F. B. ,. G. M. ,. M. G. G. Dell'Orto, "Bicycle tyres – Development of a new test-rig to measure mechanical characteristics," *Measurement*, vol. 3, no. 12, pp. 118-136, 2022.

[11] A. D. D. v. d. B. B. K. Vera E Bulsink, "The effect of tyre and rider properties on the stability of a bicycle," *Advances in Mechanical Engineering*, vol. 7, no. 12, pp. 1-19, 2015.

[12] H. Y. R. M. M. K. a. J. M. W. Liang, "Vehicle Pure Yaw Moment control using differential tyre slip," in *2009 American Control Conference*, St. Louis, MO, USA, 2009.

[13] U. Nackenhorst, "Finite element analysis of tyres in rolling contact," *WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim*, vol. 37, no. 1, pp. 27-65, 2014.

[14] W. K. Shingo Ozaki, "Finite element analysis of tyre traveling performance using anisotropic frictional interaction model," *Journal of Terramechanics*, vol. 6, no. 4, pp. 1-9, 2016.

[15] M. Z. H. Z. X. G. Peng Yang, "The interactions between an off-road tyre and granular terrain: GPU-based DEM-FEM simulation and experimental validation," *International Journal of Mechanical Sciences*, vol. 5, no. 1, pp. 179-185, 2020.

[16] L. Workman, "Characteristics of PVC pipe," *Grounds Maintenance*, 1988.

[17] M. Parsons and P. Toyoda, "Co-injection molding of PVC with other thermoplastics: Processing, properties, and applications," *J Vinyl Addit Technol*, vol. 8, no. 8, pp. 202-208, 2002.

[18] Y. Deng, Z. Wang, H. Shen, J. Gong and Z. Xiao, " A comprehensive review on non-pneumatic tyre research," *Materials & Design*, vol. 227, p. 111742, 2023.

[19] C. Liang, Z. Gao, S. Hong, G. Wang and B. Kwaku Asafo-Duho, "A fatigue evaluation method for radial tyre based on strain energy density gradient," *Advances in Materials Science and Engineering*, pp. 1-12, 2021.