Design Optimisation and Static Analysis of Non-Pneumatic Tyres

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Abstract -*Transportation is regarded as one of the most important development factors for any country because it maximizes mobility for individuals and moves loads for the industry. Tires play an important role in ensuring end-to-end connectivity. Tires and their structures have evolved to meet the needs and applications of the time. Many changes have been made to solve problems that, if resolved, may improve the performance of tyres. We are attempting to solve the problem of tyre punctures in this paper. The solution is airless tyres, or non-pneumatic tyres (NPT), which do not support the concept of compressed air.*

This paper presents four distinct spoke structures of a Non-Pneumatic Tire model. The structure and material investigation of airless tyres is carried out by contrasting them with pneumatic tyres. A thorough structural analysis of several airless tyres spoke geometries has been done, and these spokes have then been further analyzed for important parameters like total deformation, stress, and strain. Solidworks was used for the 3D modeling of these various designs, while Ansys Software handled the in-depth analysis.

Key Words: **Non-pneumatic tyre, Honeycomb spokes, Triangular spokes, Curvy spokes, Diamond Spokes, Ansys.**

1. INTRODUCTION

An airless tyre's basic construction is similar to that of a pneumatic tyre. They all have an internal core that contains pressurized air, which is subsequently wrapped with a layer of rubber called a tread that comes in direct contact with the ground. The tread aids in maintaining road traction and guards against sliding and skidding. Because the tread tends to wear down over time, if the tyre has not gone flat, it is normally replaced at this point.

There are three sections to the NPT: a rigid hub, deformable spokes capable of withstanding vertical loads, a strengthened shear band, and a rubber tread that makes contact with the ground. Rolling resistance, Contact pressure, and carrying load capacity of NPT can be changed by modifying NPT materials and dimensions.

1.1REASONS TO PREFER NPT OVER CONVENTIONAL TYRES

The importance of NPT is now understood on a global scale. The most crucial features of

NPT that distinguish it from ordinary tyres are:

1. Because of its shear band, additional suspension, and lower rolling resistance, the NPT tyre aims at performance standards above those made achievable by conventional pneumatic technology.
2. It offers comfortable rides, and a load-carrying capability similar to pneumatics, and because it lacks a cavity for pressurized air, it cannot malfunction due to a loss of air pressure.
3. Its strong lateral rigidity for improved handling without compromising comfort can be achieved, and it may eventually be able to outperform conventional tyres.
4. The conventional tyre is replaced with an NPT tyre, which is lighter than a regular tyre and helps to improve engine economy by lowering the overall weight of the vehicle.
5. Right now, tyre manufacturers must discover a means to recycle the huge pile of bald tyres that is destroying the landscape or come up with a material that is both durable and recyclable. because composite materials are typically used in airless tyres. Because most models' tread lives are longer than that of pneumatic tyres, the rubber does not need to be changed all that frequently.

Table 1: Comparison of NPT with respect to Pneumatic tyres in tabular form.

S.No	Factors considered	Pneumatic tyres	Non Pneumatic tyres
1	Tyre's life	Short life	Comparatively longer life in the case of polymer-made NPT
2	Use of air	Yes	No use of air
3	Problem of Puncture	Yes.	No problem with punctures.

The above factors confirmed the need for validating the NPT tyre performance and the specifications that can lead to better results. Thus, different NPT spoke structures are chosen to determine which structure can withstand the structural ability of pneumatic tyres. As per the currently available literature on NPTs, the static validation of tyre structure is illustrated under a single type of loading scenario only, and the structural validation under different loading conditions is yet to be researched. In this paper, dynamic conditions are not taken into consideration, and the results and inferences are based on static loading analysis. Section II discusses the geometry or 3D modelling of different tyre structures using Solidworks 2020, which contains the CAD of the tyre and will form the physical domain for the static structural analysis. Section III consists of the various inferences and graphical representations obtained after analysis done using Ansys R18.1.

2. CAD MODELLING USING SOLIDWORKS

With the 3D modelling programme Solidworks, four different spoke designs —Honeycomb, Diamond, Triangular, and Curved Spoke Structures—have been developed. The wheel hub, spoke structure and shear band with treads make up the three main parts of these NPT tyre models. To facilitate analysis, a hub-centred axle has been added to the model. This axle serves as the centre from which the vehicle will receive load and power.

CAD Model

SOLIDWORKS 2020 is the design software used for developing the CAD model.

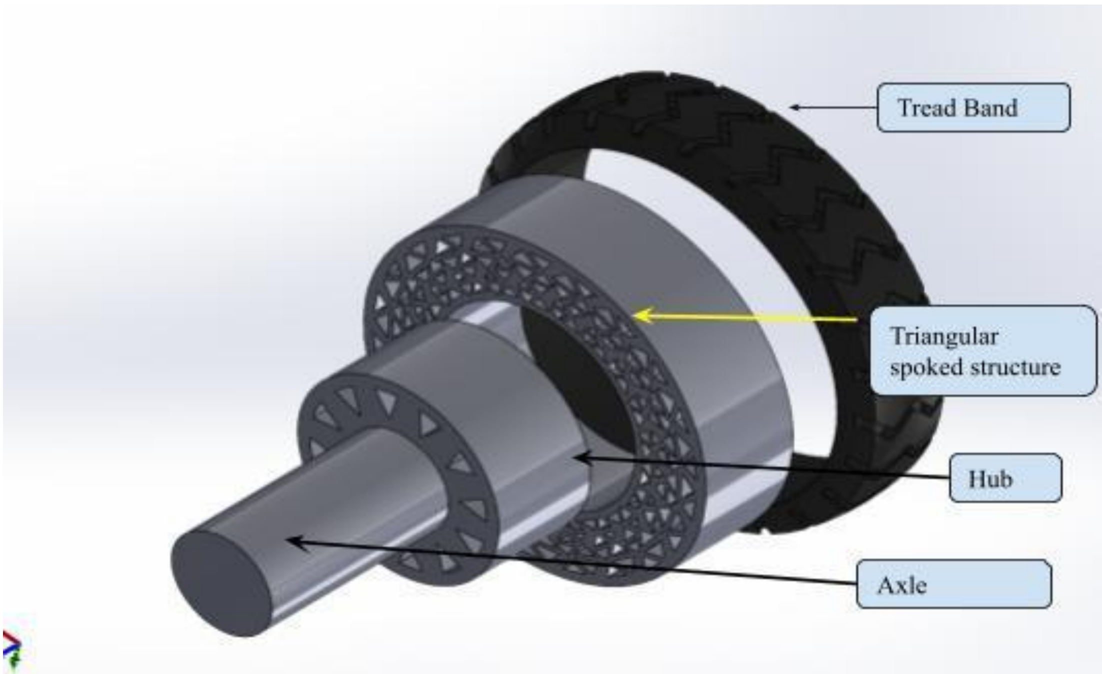


Figure 1: The CAD model of triangular spoked tyre structure representing the division of the structure.

The spoke structures were selected due to their theoretically stable designs.

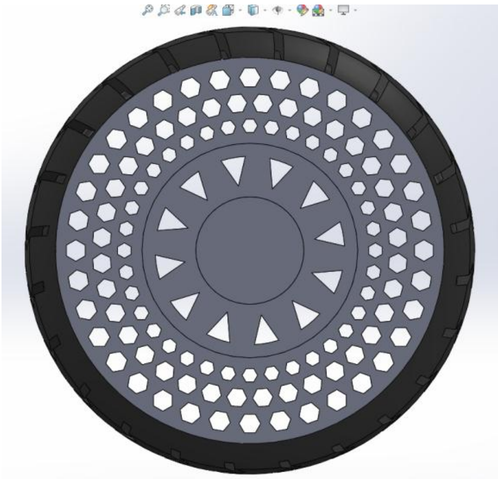
1. Honeycomb **-** Due to its evenly balanced angle of 60 degrees in the regular hexagons, this structure is one of the most geometrically stable ones. The fundamental advantage of these structures is their lightweight, which allows them to be utilized for structural protection, thermal isolation, and energy absorption.

2. Diamond **-** When compared to the preceding constructions, this structure can tolerate heavier loads being applied to the tyre; additionally, because of its sturdy construction and structural design, this structure only experiences a minimal total deformation.

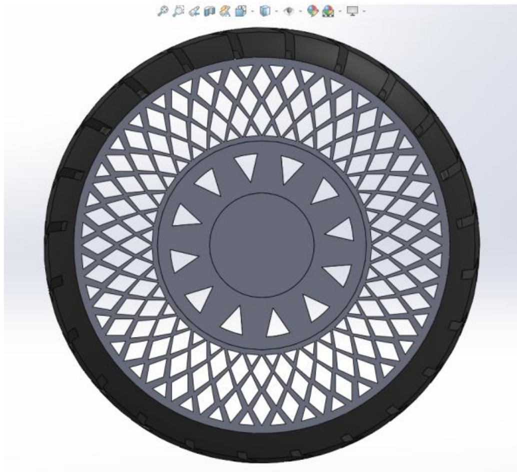
3. Triangular (Equilateral) **-** Due to the fact that just one force is acting on each of the triangle's sides at once, the triangle as a geometric shape does not bend. The spoke construction is strengthened by this feature, which helps with optimal force and weight distribution.

4. Curved Spokes**-** The curved spokes can take some of the force of variable torque (rapid speed variations) without breaking. Also, because of the angle of the curve, the wheels have an aerodynamic advantage because less air resistance is created when passing through them.

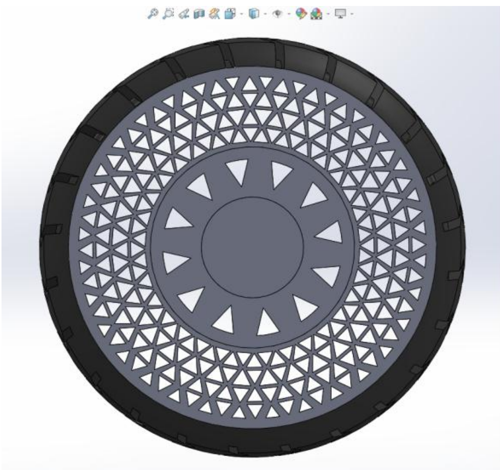
Following are the figures representing CAD assembly model of : (a) Honeycomb spoke structure (b) Diamond spokes structure (c) Triangular spokes and (d) curvy spokes structures.



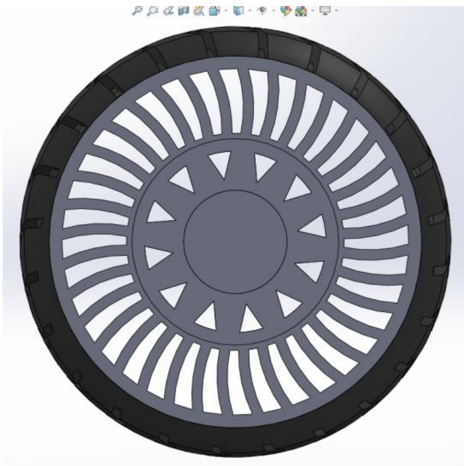
(i) Honeycomb spokes



(ii) Diamond spokes



(iii) Triangular spokes



(iv) Curvy spokes

Figure 2: CAD model of different spokes geometry on NPT

MATERIAL PROPERTIES

Aluminium alloy, polyurethane, alloy steel, and nitrile rubber are the materials employed in this analysis for the four distinct tyres with various spoke structures. These materials were chosen primarily due to their vast range of mechanical qualities, including high flexibility, high-temperature resistance, high stiffness and resilience, hyperelasticity, etc. The table below includes the chosen material's properties.

Table 2: Material Properties

PART	HUB	SPOKES	OUTER RING	SHEAR BAND
MATERIAL	UNS A97075	POLYURETHANE FOAM	AISI 4140	NITRILE RUBBER
Yield Strength (MPa)	503	145	480	1.23
Elastic Modulus (MPa)	75000	35	210000	11.9
Poisson's Ratio	0.33	0.48	0.3	0.48
Density(kg/)	2180	1210	7810	1043
Shear Modulus (MPa)	32000	11.18	80000	4.0203

GEOMETRICAL ASPECTS OF TIRE

1. Wheel size = ϕ 794mm
2. The outer hub diameter is = ϕ 400 mm
3. Inner hub diameter = ϕ 100mm
4. Hub thickness is = 200mm
5. The outer diameter of the wheel is = ϕ 794mm
6. The width of the wheel is = 180mm

3. STATIC STRUCTURAL ANALYSIS

A) Load and Boundary Conditions

Inner and outer band layers combine to form the composite structure of an airless tyre. In airless tyres, steel rings are also employed as reinforcing components. The most common cause of tyre failure is heat accumulation. It's important to determine the mechanical stability of an airless tyre under the applied load in order to improve its design. It is also important to look into the simultaneous development of stress and strain energy distribution. The prediction of metallic elements was validated using the pneumatic tyre data.

Connections

- Contact: Between Axle and Hub - Bonded

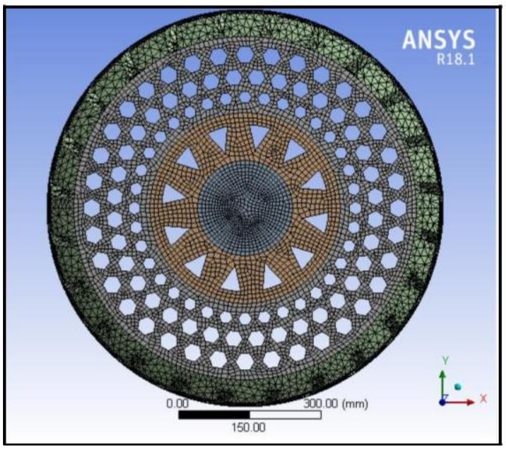
  Between the Hub and Spoke structure - Bonded Between the Spoke structure and Shear Band - Bonded

- Vertical Load on a bottommost patch of each wheel = (1800*10)/4 = 4500N
- Fixed Contact = Axle
- Mesh Element Shape - Tetrahedron
- Element Size: 10mm (Fine)

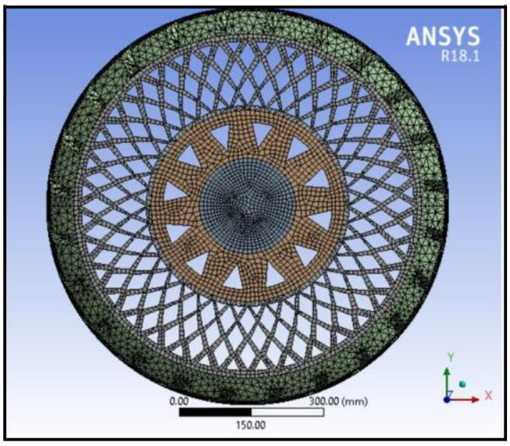
B) Mesh Results

The result obtained after meshing in different spoke structures of the tyre is shown below.

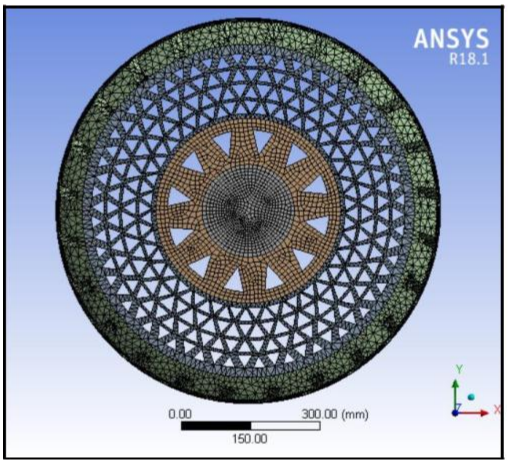
Ansys R18.1 is used for meshing. Here, we used a **Tetrahedron element** for meshing.



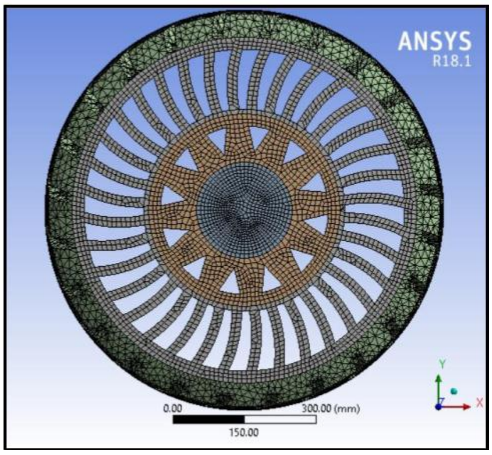
(i)Honeycomb spoke mesh



(ii)Diamond spoke mesh



(iii) Triangular spoke mesh

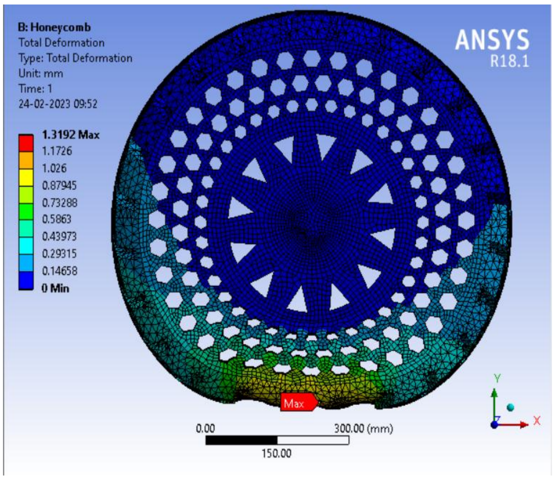


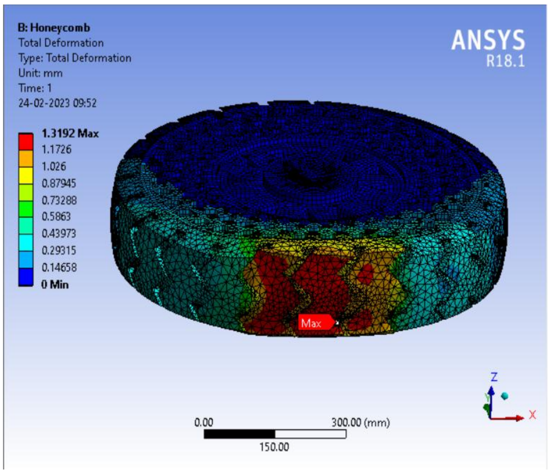
(iv) Curvy spoke mesh

Figure 3: Meshed model of different spokes geometry of NPT

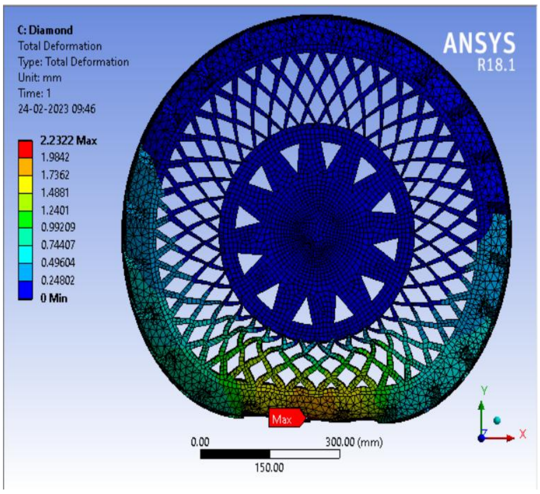
Analysis Results

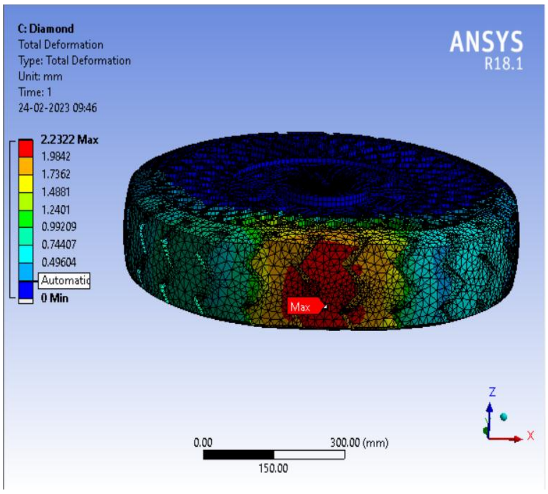
- The pictorial presentation in the method of contour plots of **Total Deformation**



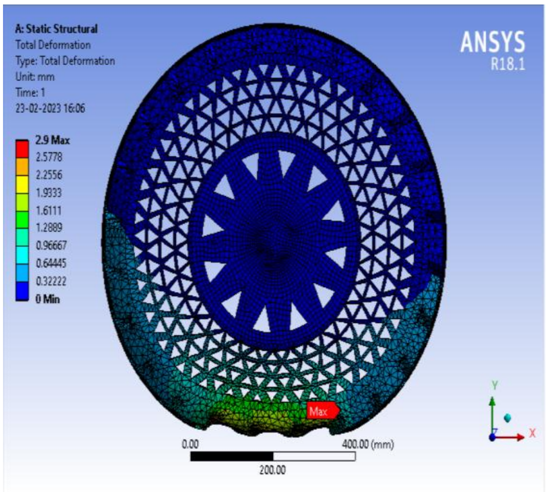


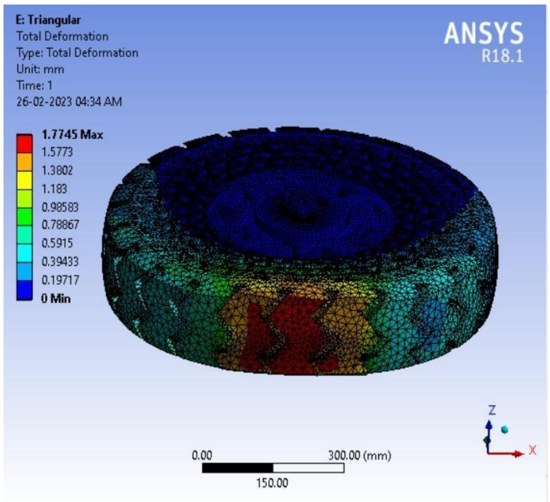
Honeycomb



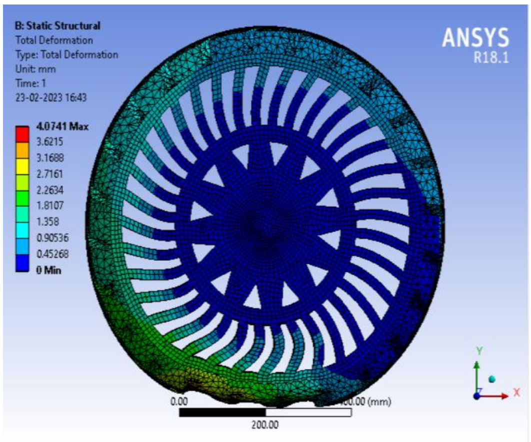


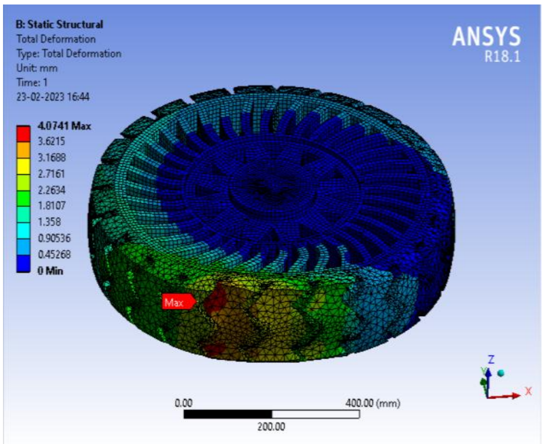
Diamond





Triangular

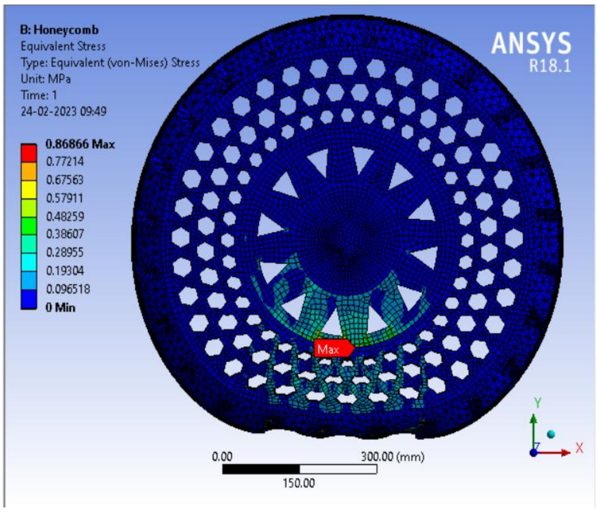




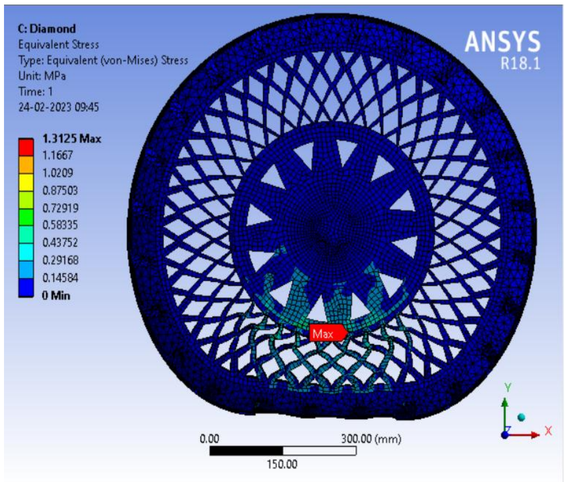
Curvy

Figure 4: Result contour of Total deformation.

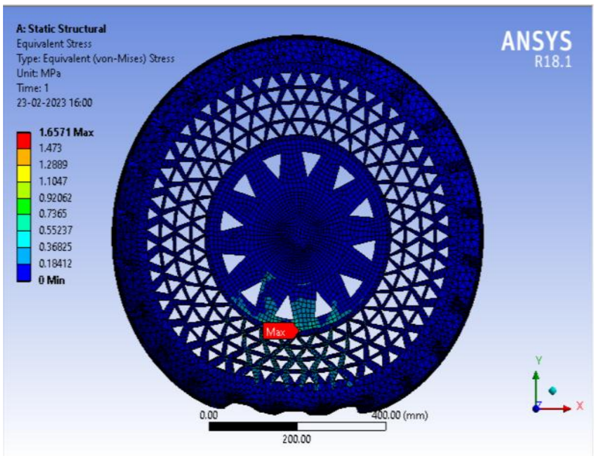
- The pictorial presentation in the method of contour plots of Equivalent(Von-Mises) Stress



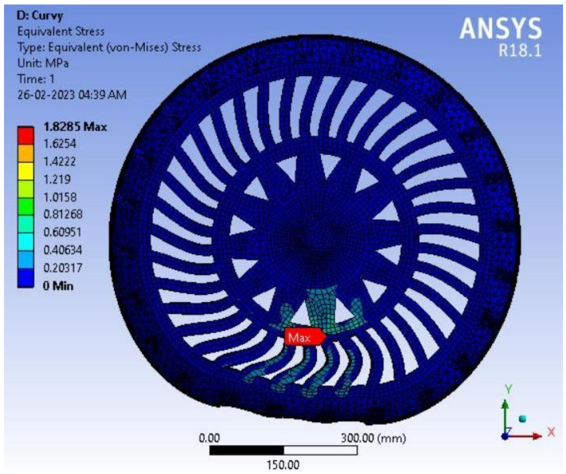
Honeycomb



Diamond



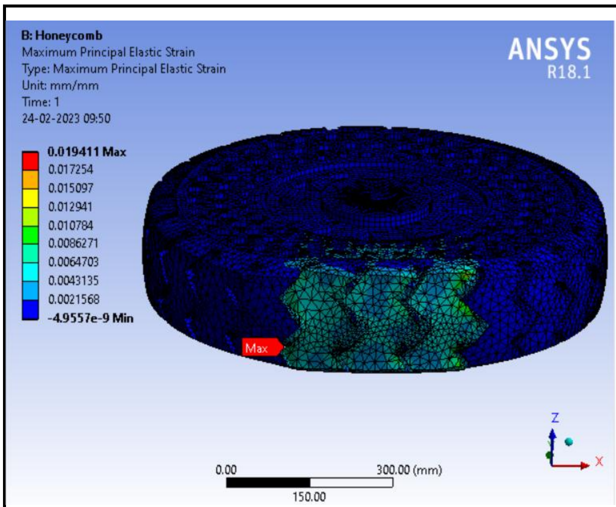
Triangular



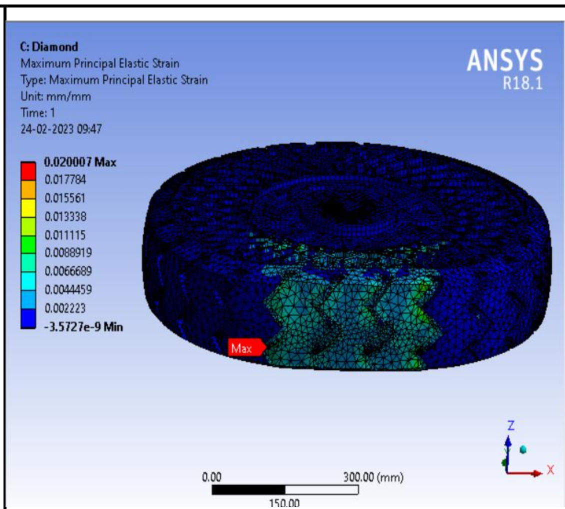
Curved spokes

Figure 5: Result contour of Equivalent(Von-Mises) Stress

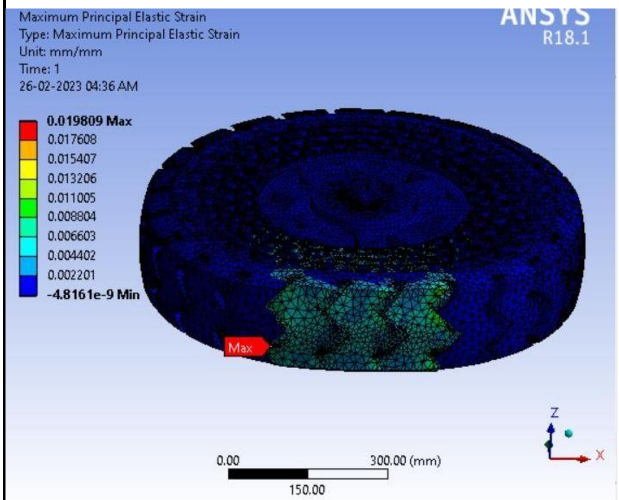
- The pictorial presentation in the method of contour plots of Maximum Principal Elastic Strain



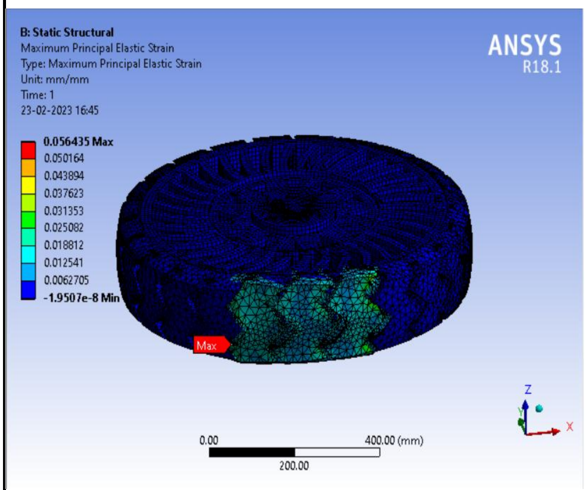
Honeycomb



Diamond



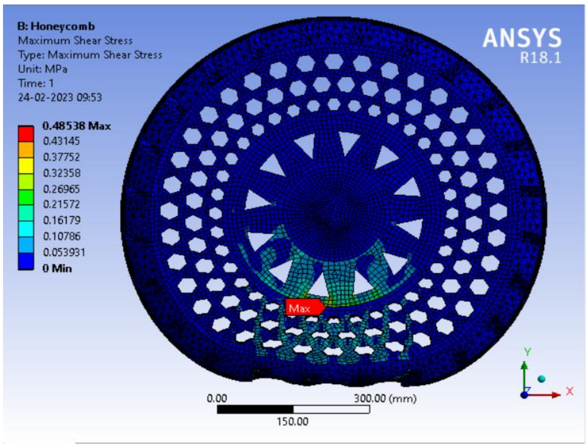
Triangular



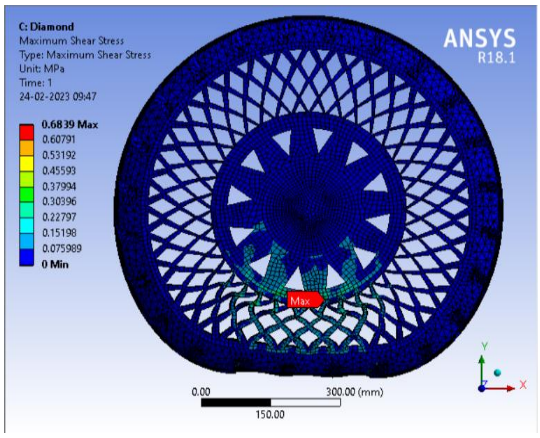
Curved spokes

Figure 6: Result contour of Maximum Principal Elastic Strain

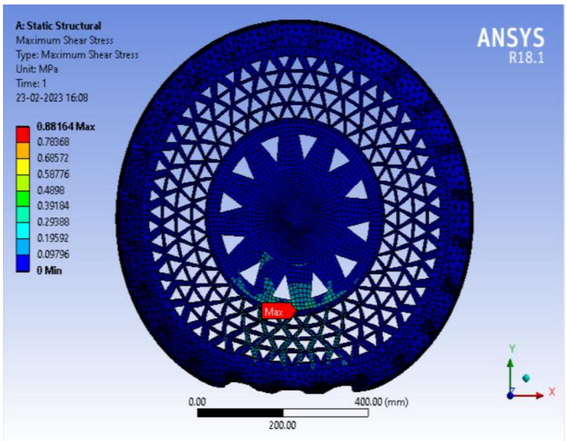
- The pictorial presentation in the method of contour plots of Maximum Shear Stress



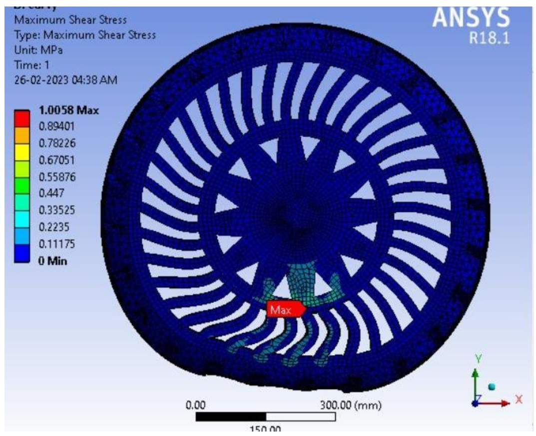
Honeycomb



Diamond



Triangular



Curved spokes

Figure 7: Result contour of Shear Stress

4. RESULTS

The results obtained by comparing the different spoke structures using a mix of materials that were examined are compiled below.

- **Total Deformation**

Table 3: Maximum total deformation values in different spokes structures.

S.No.	Structure	Force Applied (N)	Max Total Deformation (mm)
1.	Honeycomb	4500	1.3192
2.	Diamond	4500	2.2322
3.	Triangular	4500	2.9000
4.	Curved Spokes	4500	4.0741

Graphical Representation: Total deformation (mm) Vs. Tyre Geometry

Inference-

From the above data it's pretty evident that the Honeycomb structure has the least deformation whereas the Curvy structure has the largest deformation. Thus it can be concluded that the Honeycomb structure will give the Highest load-carrying capacity amongst the 4 spoke structures compared and would be suitable for heavier vehicles in contrast to which the Curvy structure would be suitable for lighter vehicles with less load and could provide more cushioning effect.

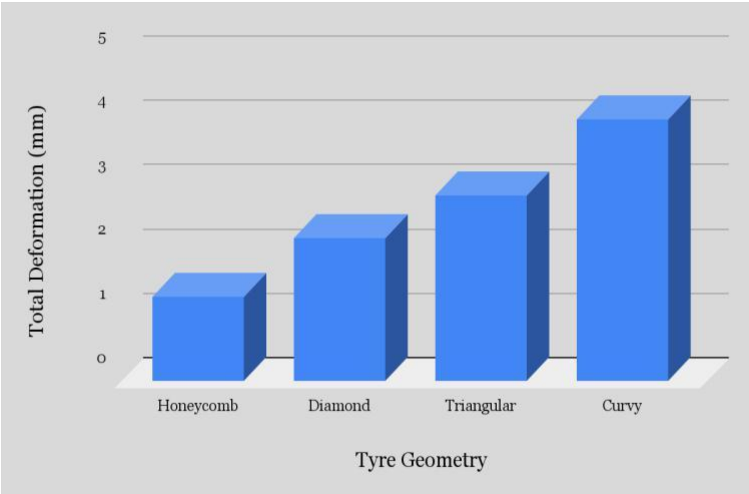


Chart 1: Total deformation (mm) Vs. Tyre Geometry

- **Equivalent(Von- Mises) Stress**

Table 4: Maximum Von-Mises Stress (MPa) values in different spokes structure.

S.No.	Structure	Force Applied(N)	Max Von-Mises Stress (MPa)
1.	Honeycomb	4500	0.86866
2.	Diamond	4500	1.3125
3.	Triangular	4500	1.6571
4.	Curved Spokes	4500	1.7811

Graphical Representation: Von Mises Stress(MPa) Vs. Tyre Geometry

Inference-

From the data collected using the table above , Honeycomb spoke structure came with the least Von mises stress compared to other spokes structure. Thus, this can be said that Honeycomb spoke structure will have the highest Compressive strength. NPT with honeycomb spokes offered minimum stress concentration which is important for Fatigue resistant designs.

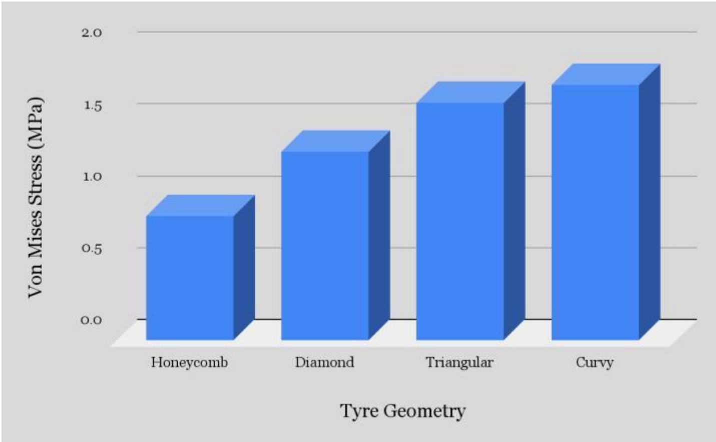


Chart 2: Von Mises Stress (MPa) Vs. Tyre Geometry

- **Maximum Principal Elastic Strain**

Table 5: Maximum Principal elastic Strain values in different spokes structure.

S.No.	Structure	Force Applied(N)	Max Principal Elastic Strain
1.	Honeycomb	4500	0.019411
2.	Diamond	4500	0.020007
3.	Triangular	4500	0.056325
4.	Curved Spokes	4500	0.056435

Graphical Representation: Maximum Principal Elastic strain Vs. Tyre Geometry

Inference-

Here, Honeycomb spokes structure shows the least value of maximum principal elastic strain value while triangular and curvy spokes structure design has similar results. Thus, we can say that Honeycomb structure design in tyres will lead to longer life by reducing the rate of wear and tear.

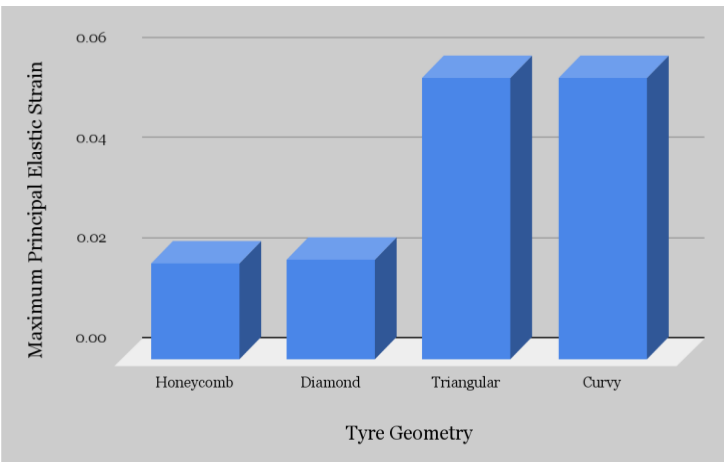


Chart 3: Maximum Principal Elastic strain Vs. Tyre Geometry

- **Maximum Shear Stress**

Table 6: Maximum Shear Stress values in different spokes structure

S.No.	Structure	Force Applied(N)	Max Shear Stress(MPa)
1.	Honeycomb	4500	0.48538
2.	Diamond	4500	0.6839
3.	Triangular	4500	0.88164
4.	Curved Spokes	4500	0.97808

Graphical representation: **Maximum Shear Stress (MPa) Vs. Tyre Geometry**

Inference-

The maximum shear stress that the tyre can withstand under a load of 4500 N is shown in the above table. For easier comparison and data visualisation, the shear stress of the various spokes in the tyre design are displayed graphically in the right corner.

In this instance as well, the honeycomb spoke structure had the lowest maximum shear stress value when compared to other spoke structures.

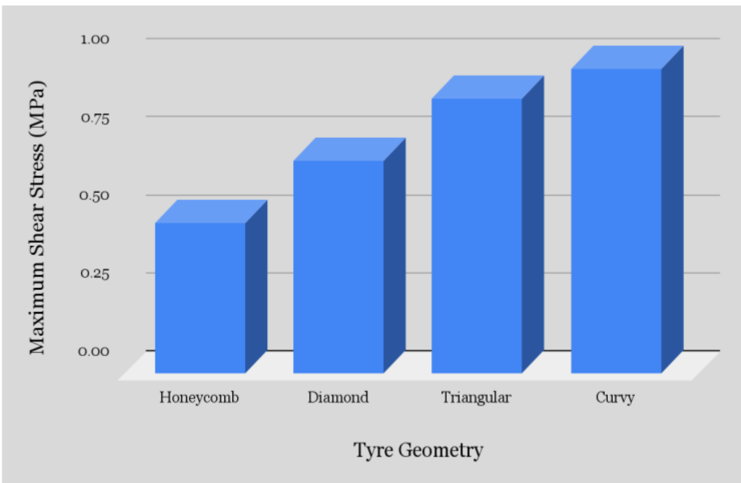


Chart 4: Maximum Shear Stress (MPa) Vs. Tyre Geometry

Consolidated Results

Table below illustrates the compiled results of total deformation, equivalent von-mises stress maximum principal elastic strain, and maximum shear stress for different spoke structures in a non-pneumatic tyre. It also gives a comparative analysis of four different spokes structures used for the same.

Table 7: Consolidated results of static structural analysis.

S.No	Types of analysis	Tyre Structure			
		Honeycomb	Diamond	Triangular	Curvy
1.	Total Deformation (mm)	1.3192	2.2322	2.9000	4.0741
2.	Maximum Elastic Strain	0.019411	0.020007	0.056325	0.056435
3.	Equivalent (Von-mises) Stress (MPa)	0.86866	1.3125	1.6571	1.7811
4.	Shear Stress (MPa)	0.48538	0.6839	0.88164	0.97808

From the result shown in the consolidated table above, we found that the Honeycomb spoke structure model gives better results than the other spoke structures of the tyre model. Similarly in different spokes structure constraints, with mentioned analysis parameters, the Honeycomb spoke structure yields better results. So for the given boundary conditions and applied load, the Honeycomb spoke structure airless tyre is more rigid and durable.

4. CONCLUSION

There are many advantages that Non Pneumatic tyres have in general over Pneumatic tyres. Some of the factors that can be counted includes : Elimination of air Leakage or tyre blow outs, Consistent economy and handling as there is no issue with gas pressure , Its flexibility provides a rise in extent of contact, No maintenance requirement, Elongated tread life,Facilitate utilisation, making a vehicle lot more economical with high lateral strength for higher handling without any loss in comfort, Vehicle remains in restraint even in parking brake, Remains mobile even with a number of the spokes broken or missing , has high Sturdiness & Long Life and Less environmental impact.

- The results obtained from static structural analysis confirms major of the factors stated above and It can be concluded that Honeycomb spokes structure of tyre are more stable structure as they have comparatively higher capability to withstand more load.
- It is found that Honeycomb spokes design constitutes least stress, strains and deformations values in comparison to other designs because the honeycomb structure is more geometrically stable for the same material and symmetrical which can sustain and uniformly distribute large amount of force thereby exhibiting more compressive and shear strength.

As per the analysis done on different spoke structure designs, the honeycomb spokes structure design that has given the results with least deflection is advisable and is concluded to be most suitable for heavier load application purposes.

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