Design and Analysis of Hexagonal Cellular Spoked Non – Pneumatic Tires for Automobiles

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Abstract

In the following paper design of Non-Pneumatic tires has been analyzed for automobile application. In the inner airtight core compressed air has been filled. It has various advantages like low vertical stiffness, low mass design, and low contact pressure, pneumatic tires have dominated the global market. Yet, it has several drawbacks, such as complex manufacturing, the risk of a flat tire while driving, and the ongoing maintenance required to maintain adequate internal air pressure. Therefore, to alleviate these drawbacks, non-pneumatic tires were introduced. Non-pneumatic tires (NPT) have a complex cellular solid state spoke component that acts as a stiffness member similar to air in a pneumatic tire. The qualities of NPT are determined by the rolling resistance, contact pressure, contact surface provided by the material in relation to the surface, and load carrying capacity. These properties can be altered by modifying the structural design or the materials used to make NPTs.

In macroscopic uniaxial loading, a comparison was done between two distinct types of spokes for NPT. Although the tire is rolling, the spokes of an NPT go through a tension-compression cycle. Both resilience and stiffness and are required of the spokes of an NPT, which are opposing needs. In Creo, two different types of spokes are designed, namely various Hexagonal spokes with differing structures. In Creo, 3D models have been built and its mass have been determined. Ansys is used to investigate the deformation and stresses that emerge in various types of non-pneumatic tire spokes.

Keywords: Non-pneumatic tires (NPT); Tires; Honeycomb; Ansys; Creo; Modelling; Analysis.

1. Introduction to Non Pneumatic Tires

The NPT tire is a one-piece airless wheel and having a rubber tread and polyurethane spokes attached to the wheel hub. As well as the increased suspension system, treaded shear band design and reduced rolling resistance, the NPT tire objectives on the performance levels beyond the capabilities of traditional pneumatic technology. NPT delivers pneumatic stiffness similar to a pneumatic tire with load-bearing capacity, driving comfort with no pressurized air cavity which reduces the rate fail because loss of air pressure. Eventually NPT will outperform the conventional tires since NPT's are designed to provide high lateral stiffness for better driving comfort with high surface contact. However, it is non-confirmative – new environmental issues might happen because of these radical changes in design. There are currently environmental hazards occurring as a result of tire lifespan. Traditional tire has been substituted with the NPT, which is lighter, reducing the wear and failure of pneumatic tires on the road even while enhancing engine efficiency. NPTs are also predicted to have a good influence on the environment. Most tire firms are currently working to establish a mechanism to recycle or develop something that lasts longer and can be recycled in order to solve the growing pile of bald tires defiling the landscape. As most models have a longer tread life than pneumatic tires, the rubber does not need to be replaced frequently.

The study has been made to optimize the design functions of NPT to reduce the weight of the tire by providing all the functionalities similar to a pneumatic tire. This will contribute to the performance optimization with better design that ensure factor of safety of the NPT.

The application of NPT has moreover increased from road transport systems to aerospace and space applications because the NPT's are able improve the NASA human exploration system's fuel economy by replacing the elastomer materials in shear bands with materials with linear elastic materials that can withstand high temperatures and shear loads and or replaced with linear elastic materials with low hysteretic loss, for such reasons topologies such as honeycomb structures were developed. The shear band of a non-pneumatic tire with meso-structure was carried out using shear flexure, shear strain, and contact pressure [1]. The stress, contact pressure and vertical tire stiffness are affected by the spoke structures and shear band of an NPT. The spoke shape and size affect the tire behavior, and the shear layer mitigates the effects of deformed spoke shape on contact pressure distribution [2]. The environmental impact of the Tweel tire throughout its lifecycle, from manufacturing through usage and disposal. Because the Tweel tire has wide applications and is unlikely to be manufactured and used on a large scale, there are inconsistencies in terms of end-of-life scenarios and rolling resistance evaluations that will affect the LCA (Life Cycle Architecture) [3].The modelling effects i.e., number of spokes, spoke angle, outer radius of tire, inner radius of tire, thickness of tread, thickness of web, shift in mold, maximum width of tire configure the tire strength and performance [4]. NPT's deform in both static and dynamic conditions and the deformations are controlled by proper design of hexagonal cell design [5]. Polyurethanes are used in development of complex honeycomb structures of the NPT. Speeding agents, interfacial tension, blowing agents, and other additives are included in the poly stream and the mixture proportions will result in various mechanical properties [6]. The application of a uniformly distributed weight to the center of the rim, which acts at the rim tire contact region, causes vertical loading on the wheel [7]. And the honeycomb structures made of polyurethane distributes the load uniformly on to the center of the rim. By minimizing air-related problems in the tire, the driver's mind-stress can be reduced in the vehicle field. Meantime, air-less tires provide as uniform traction and wear as possible [8]. Non-pneumatic and pneumatic tires both bear a substantial load with deformation; the exception would be that non-pneumatic tires do not have any contact pressure [9]. The comparison of static contact pressures of NPT with standard pneumatic tires indicates the static validation of the structure under only one type loading condition subjected to an automobile tire [10].

In the current study, the NPT's models are modelled in a 3-Dimensional environment each with different hexagonal cellular spoke design & rubber tread, their performance is studied under both the static and modal analysis conditions. The results are compared with each other configuring the best NPT out of the mentioned models. The performances are evaluated with low stress, high strain with low deformation and the conditions of being static structural and modal conditions helps to evaluate the NPT performances during rest and motion under load.

2. Methodology

2.1. Parts

Outer ring, hub, honeycomb spokes and thread are the essential pieces of a NPT. The hub offers a solid foundation to the honeycomb spokes. The honeycomb spokes are an important part of the NPT, it substitutes pneumatic tires with air. Under cyclic compression loading, the spokes of an NPT should be rigid and resilient. The outer ring's purpose is to keep the thread rubber from being deformed by shear. In between road and the car, the thread provides the essential traction.

2.2. Materials

- An NPT's hub should provide a robust structure. The hub is made of AL 7075-T6 aluminum alloy. AL7075-T6's major alloying element is zinc. It's tough, with tensile strength similar to many steels, as well as good fatigue resistance and machinability. Nonetheless, because of its high cost, it can only be used in applications where cheaper alloys aren't suited. The composition of the 7075 aluminum alloy is around 1.2–1.6% copper, 5.6–6.1% zinc, 2.125% magnesium, and less than 0.5% of iron, titanium, silicon, chromium, manganese, titanium, and other metals. The T6 alloy has been heat treated and tempered artificially. Gears and shafts, aircraft fittings, fuse parts, gears and shafts meter shafts and gears, regulating valve parts, keys, aircraft, worm gears, aerospace and defense applications, bike frames and missile components are just a few of the applications.
- The honeycomb spokes are made of polyurethane as a constituent material. Polyurethane is a one-of-a-kind material that combines rubber's elasticity with metal's toughness and endurance. Polyurethane has a high level of rigidity and resilience.
- The outer ring is constituting of AISI 4340 high-strength steel. This causes the thread rubber to distort when shear is applied. The edges of the spokes over the contact zone with the ground would buckle without the outer ring, causing an undesired nonlinear effect in the honeycombs.
- Synthetic rubber is used for the thread component. Thread's offers traction between the road and the tire. On diverse terrains, the thread should have a decent grip. Any sort of artificial elastomer primarily manufactured from petroleum byproducts is known as synthetic rubber, which is invariably a polymer. An elastomer has the mechanical (or material) attribute of being able to bend far more elastically under stress than most materials while still returning to its original size without permanent distortion.

2.3. Properties of the Constituent Parts of NPT

Table 1. The following table demonstrates the properties of the constituent parts of NPT [11]

Part	Hub	Spokes	Outer Ring (Shear Band)	Tread Band
Material	AL 7075-T6	Polyurethane	AISI 4340	Synthetic Rubber
Young's Modulus E (GPa)	72	32	210	11.9
Yield Strength (GPa)	503	145	710	16
Poisons Ratio, υ	0.33	0.49	0.29	0.49
Density ρ (kg/m^3)	2800	1200	7800	1043

2.4. Modelling of Different Types of NPT

Different cell angles, cell heights, and cell lengths are investigated in two types of non-pneumatic tires. Creo is used to construct the NPT models. The size of the honeycomb spokes varies between the two types, which is what distinguishes them. The material's other qualities and dimensions remain unchanged. The geometrical aspects and design considerations of type 1 are tabulated below

[12].And the type 2 tyre geometrical aspects and design considerations are designed according to general considerations as listed in the Table 2 & Table 3.

2.5. Geometrical Aspects

Table 2. The following table demonstrates the Geometrical aspects of NPT

Parameter	Type 1	Type 2
Wheel size	25" ×6.5" ×15"	19.2" ×6.5" ×12.5"
Diameter of hub or rim (mm)	380.1	318
Thickness Hub (mm)	25	10.2
Outer ring diameter (mm)	605	467.5
Outer diameter of wheel (mm)	625	492
Thickness of shear band (mm)	5	10.2
Width of the wheel (mm)	165.1	165.1
Thickness of spoke (mm)	5	5

2.6. Dimensions of Honeycomb Spokes

Table 3. The following table demonstrates the Dimensions of Honeycomb spokes for Type 1 & Type 2

NPT Type	*l(mm)*				*h(mm)*		*θ (˚)*			*t(mm)*
	l_1	l_2	l_3	l_4	h_1	h_2	θ_1	θ_2	θ_3	t
Type 1	22.5	20.8	20.5	21.5	20	25	22	32	35	4
Type 2	30.8	22.3	22.0	28.0	25	25	15	33	30	3.46

The dimensions of the Honeycomb spokes for type 1 are tabulated above in Table 3 [2]. The dimensions of the modelled NPT have been shown in the table above. Only regular honeycombs, i.e. those with a positive poison's ratio, are considered. The ratio of inclined cell length to cell height, *l/h1*, is a significant consideration in constructing in-plane flexible structures for simple tensile–compression stress. As a result, when designing in plane flexible structures, the cell angle may be unimportant. In all other respects, auxetic honeycombs' in-plane flexure behavior may be identical to that of normal honeycombs. Auxetic honeycombs have a negative poison-to-poison ratio. While compared to regular spokes, it has more lateral stiffness under loading. Cell angle (θ) is a crucial factor while designing a fatigue-resistant honeycomb structure. The flexibility of hexagonal honeycomb increases as the cell angle (θ) increases.

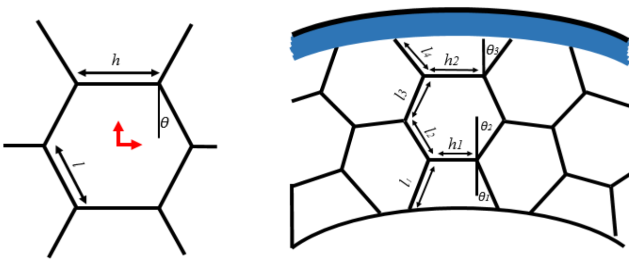

Figure 1. Geometrical dimensions of Hexagonal Honeycomb structure

In Creo, the suggested types of NPT design have been shown in the figure 1. Sketching, developing, padding, and other aspects are included in 3D modelling. In order to calculate the mass of designed tires, the properties of the material are defined in Creo. Afterwards, 3D models have been designed with the help of ANSYS Workbench software for static and modal analysis.

2.7. Analysis

ANSYS, permits the simulation of tests or working circumstances, allows testing in a virtual environment prior to the fabrication of product prototypes. Furthermore, 3D simulations in a virtual environment can be used to identify and improve weak points, increase computing life, and predict potential problems. The geometry has been imported from Creo 3.0 and the material is selected.

- Material Selection

Go to Geometry, select MSBR and Select the material and then go to material properties, material model and add values to the respective parts of the NPT.

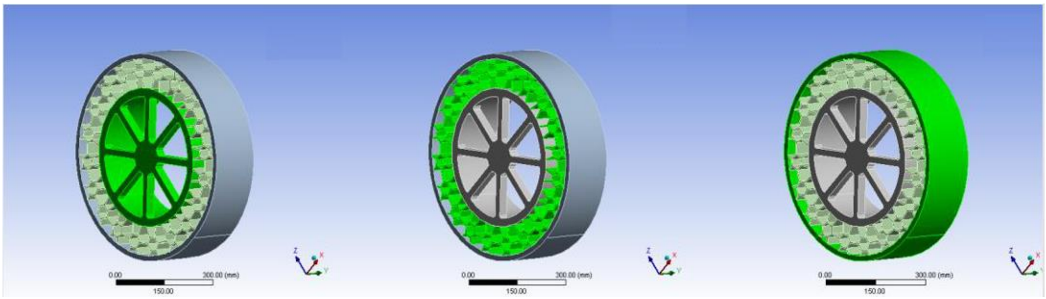

Figure 2: Selected material of the model

- Meshing

The NPT's basic elements are appropriately intertwined. All the components are symmetrical; therefore, a cubical meshing has been chosen. The mesh size has been set to fine. The three models each include about 15000 components.

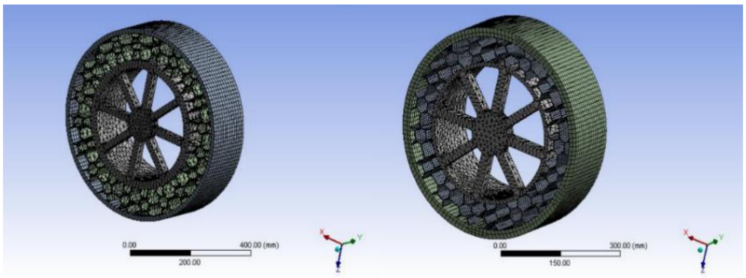

Figure 3. Meshed Models of Type1 and Type2

- Boundary Conditions

2943 N of load has been applied to the top surface of each tire structure, with the center of the wheel fixed (hub). Applied rotational velocity to the wheel's outer surface (Shear Band).

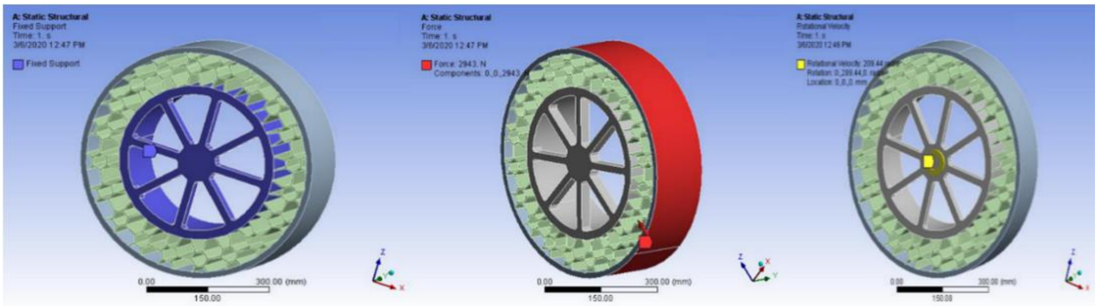

Figure 4. Boundary Conditions of Type 1 Tire

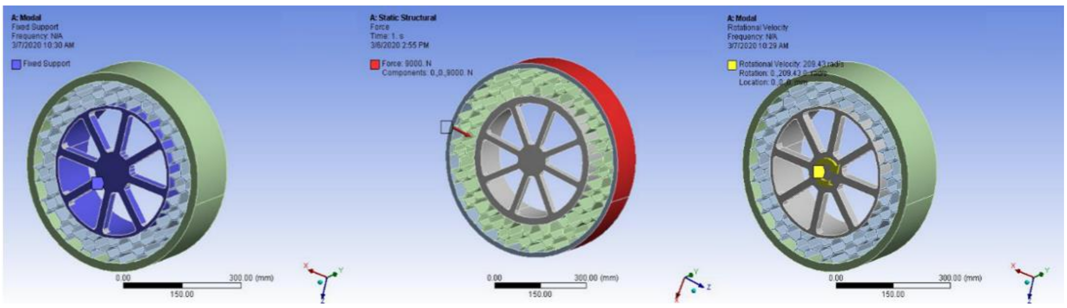

Figure 5. Boundary Conditions of Type 2 Tire

2.7.1. Static Structural Analysis

Ansys has been used to static structurally evaluate the manufactured wheels of distinct tire structures in Creo, which are Type 1 structure and Type 2 structure. On the other hand, the results are based on the application of boundary conditions, such as a 2943N force on the top surface and a 209.4 rad/sec (2000 RPM) of rotational velocity. Stresses, strains, shear stresses, and total deformations are the outcomes obtained here, as illustrated in the figures below.

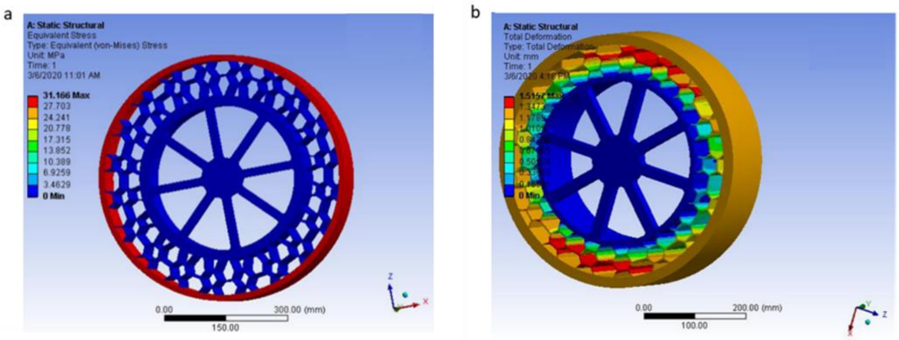

Figure 6. Total deformation (a) type 1; (b) type 2.

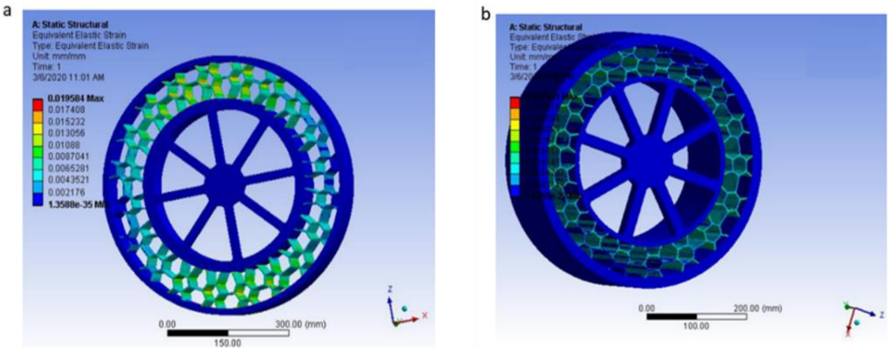

Figure 7. Equivalent (Von-Mises) Strain (a) type 1; (b) type 2.

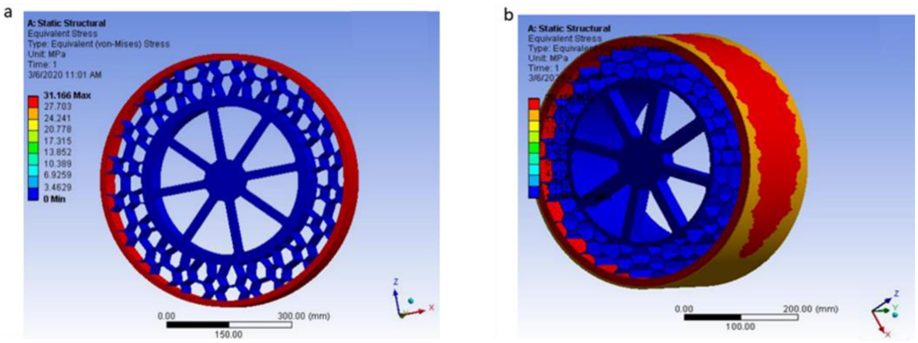

Figure 8. Equivalent (Von-Mises) Stress (a) type 1; (b) type 2.

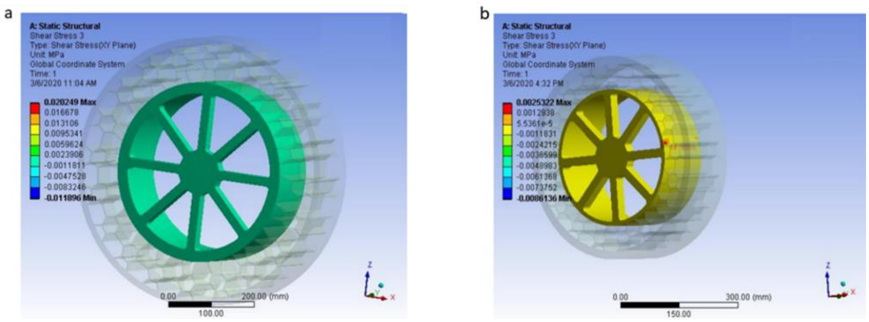

Figure 9. Shear Stress of a Hub (a) type 1; (b) type 2.

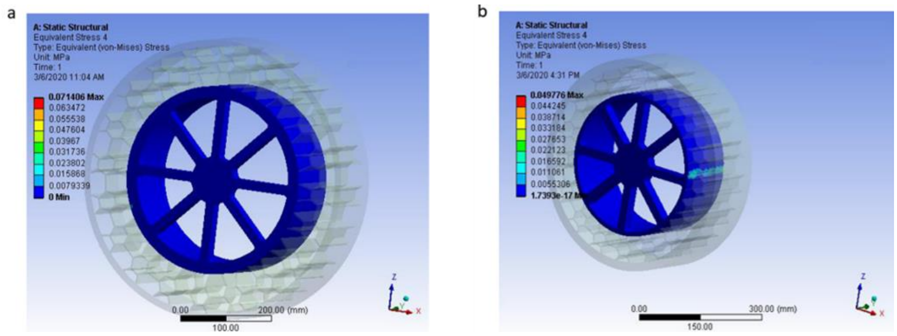

Figure 10. Equivalent (Von-Mises) Stress of a Hub (a) type 1; (b) type 2.

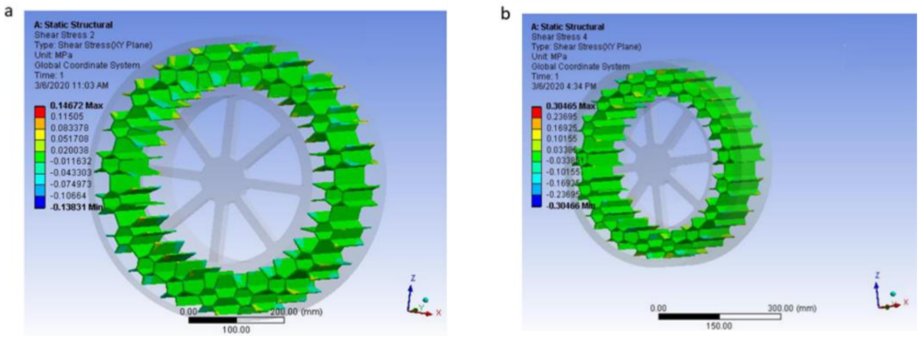

Figure 11. Shear Stress of a Spokes (a) type 1; (b) type 2.

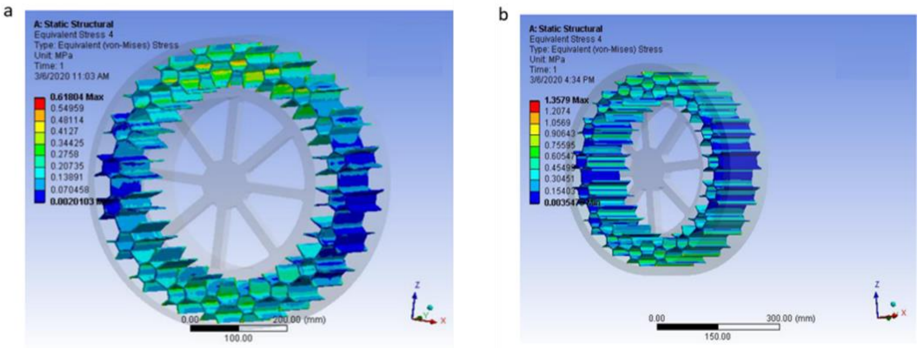

Figure 12. Equivalent (Von-Mises) Stress of a Spokes (a) type 1; (b) type 2.

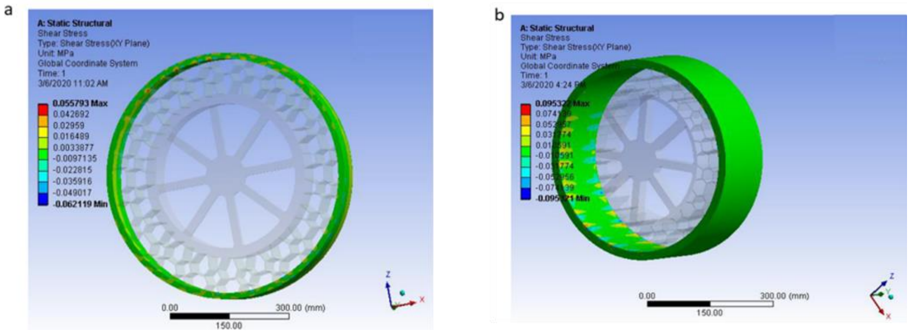

Figure 13. Shear Stress of a Shear Band (a) type 1; (b) type 2.

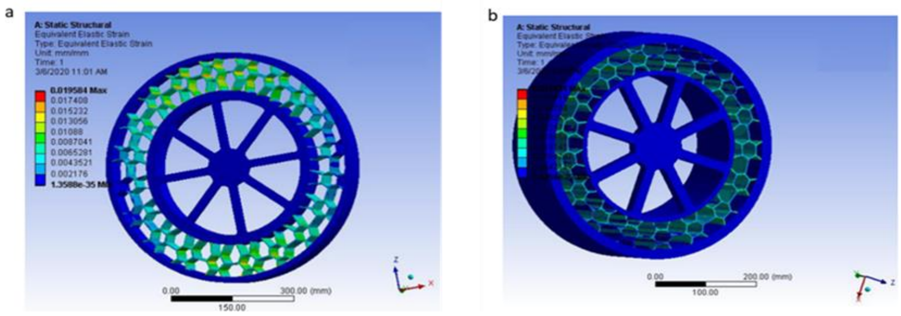

Figure 14. Equivalent (Von-Mises) Stress of a Shear Band (a) type 1; (b) type 2.

2.7.2. Modal Analysis

Modal Analysis has been used to determine the NPT'S natural frequency and mode shape. To avoid structure failure due to resonance, the natural frequencies of the NPT should not fall between the operating frequency ranges. The Model analysis is made to investigate different mode shapes and natural frequency. This happens when a static load of 2943 N is applied and a 209.4 rad/sec of rotational velocity is performed in the y-axis. Volume and density are used to compute the tire's mass. Since the volume of the tire is known, the density is calculated using material parameters, which will help in computing the component's natural frequency if mass and load are known.

In the Modal analysis, the frequency indicates the energy state and the effect of deformation on the wheel structure. Which provides the comparative results to both the type 1 and type 2 tire. The comparative study between modes of frequency and total deformation for both the tires helps in justifying the adaptable one.

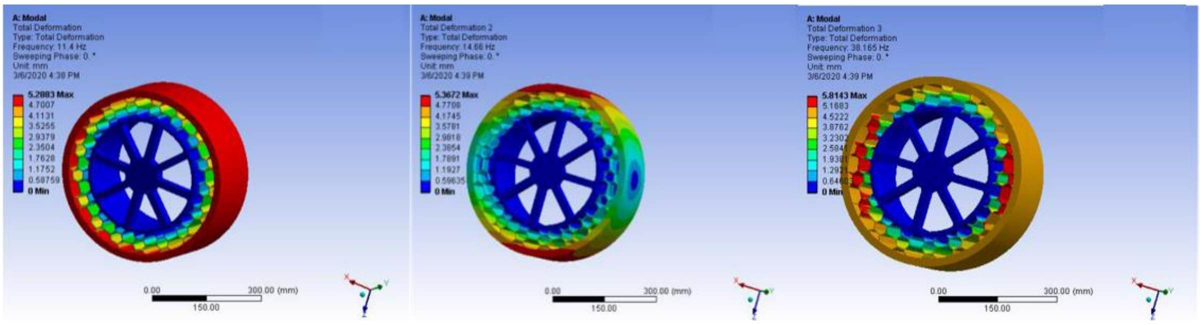

Figure 15. First, Second and Third mode of deformation of type 1.

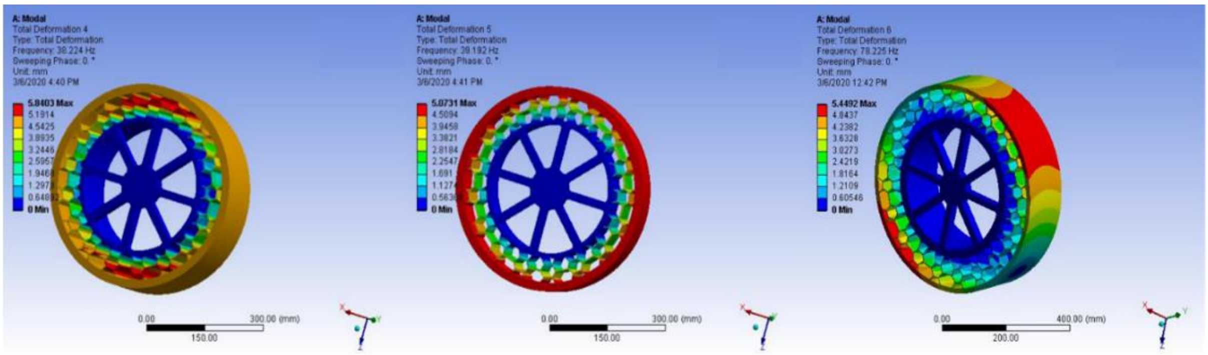

Figure 16. Fourth, Fifth and Sixth mode of deformation of type 1.

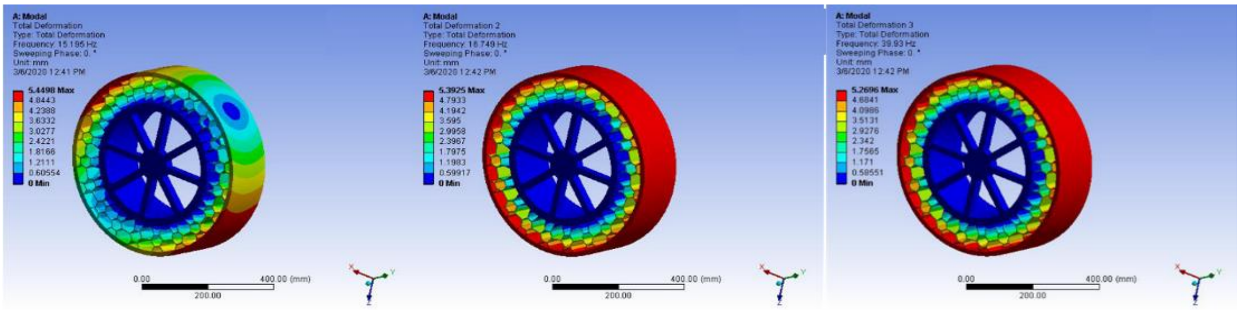

Figure 17. First, Second and Third mode of deformation of type 2.

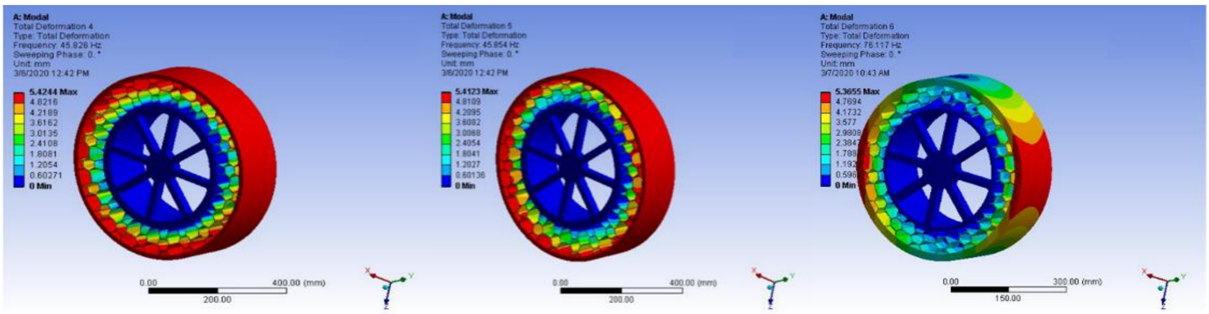

Figure 18. Fourth, Fifth and Sixth mode of deformation of type 2.

3. Results and Discussion

3.1. Results Comparison

All the results are collected and tabulated from the reference figure.6 to figure.18.

Table 4. Comparison of Static analysis results in between Type 1 & Type 2 Tire Assembly

Condition	Type 1	Type 2
Total Deformation(mm)	0.046238	1.5157
Equivalent Elastic Strain	0.019584	0.144031
Equivalent Von-Misses Stress(MPa)	31.166	28.456

The data from Table.4 explicit the total deformation of type 1 tire is 0.046238 mm and while the type 2 is 1.5157 mm, which provides better stiffness properties to the tire 2. The Equivalent Von-Mises Strain for type 1 tire is 0.019584, while the type 2 tire delivers the strain as 0.144031, which states the maximum ratio of deformation happens in type 2 tire design. The Equivalent Von-Mises Stress for type 1 tire is 31.166 MPa while the type 2 tire design provides the value of 28.456 MPa, which states the Type 2 design has better design feasibility that reduces the stress by increasing the stiffness properties.

Table 5. Comparison of Static analysis results of Wheel Hub in between Type 1 & Type 2

Condition for Hub	Type 1	Type 2
Shear Stress (MPa) -along XY plane	0.020249	0.002532
Equivalent Von-Misses Stress(MPa)	0.071406	0.049776

The data from Table.5 explicit the static analysis performed on the hub, the type 1 hub shear stress along XY Plane is 0.020249MPa and while the type 2 hub shear stress along XY Plane is 0.002532MPa, which states the type 2 is functional with limited stress at the same load conditions. The Equivalent Von-Mises Stress for type 1 hub is 0.071406 MPa while the type 2 tire design provides the value of 0.049776 MPa, which states the Type 2 design has better design feasibility that reduces the stress by increasing the stiffness properties.

Table 6. Comparison of Static analysis results of Hexagonal Spokes in between Type 1 & Type 2

Condition for Spokes	Type 1	Type 2
Shear Stress (MPa) -along XY plane	0.14672	0.30465
Equivalent Von-Misses Stress(MPa)	0.61804	1.3579

The data from Table.6 explicit the static analysis performed on the Hexagonal wheel spokes, the type 1 hexagonal spokes - shear stress along XY Plane is 0.14672 MPa and while the type 2 hexagonal spokes - shear stress along XY Plane is 0.30465MPa, which states the type 1 is functional with limited shear stress at the same load conditions. The Equivalent Von-Mises Stress for type 1 hexagonal spokes is 0.61804 MPa while the type 2 hexagonal spoke design provides the value of 1.3579 MPa, which states the Type 1 design has better design feasibility that reduces the stress by increasing the stiffness properties.

Table 7. Comparison of Static analysis results of Shear Band in between Type 1 & Type 2

Condition for Shear Band	Type 1	Type 2
Shear Stress (MPa) -along XY plane	0.055793	0.095322
Equivalent Von-Misses Stress(MPa)	31.166	20.156

The data from Table.7 explicit the static analysis performed on the Shear band, the type 1 shear band - shear stress along XY Plane is 0.055793 MPa and while the type 2 shear band - shear stress along XY Plane is 0.095322 MPa, which states the type 1 is functional with limited shear stress at the same load conditions. The Equivalent Von-Mises Stress for type 1 shear band is 31.166 MPa while the type 2 shear band design provides the value of 20.156 MPa, which states the Type 2 design has better design feasibility that reduces the stress by increasing the stiffness properties.

Table 8. Modal Analysis Results of Type 1 Tire Assembly

Modes	Frequency (Hz)	Deformation(mm)
1	11.4	5.2883
2	14.66	5.3672
3	38.165	5.8143
4	38.224	5.8403
5	39.192	5.0731
6	78.225	5.4492

Table 9. Modal Analysis Results of Type 2 Tire Assembly

Modes	Frequency (Hz)	Deformation(mm)
1	15.195	5.4498
2	16.749	5.3925
3	39.93	5.2696
4	45.826	5.4244
5	45.854	5.4123
6	76.117	5.3655

From the data constructed in the Table 8 and Table 9, type 2 tire assembly works with less frequency and less deformation compared to type 1 tire assembly.

3.2. Summary of Results and Discussion

A structural analysis of NPT's has been carried out, spokes have been designed in hexagonal honeycomb structures with the same cell wall thickness was performed and the following conclusions were drawn as a result of the findings.

- NPT with Honeycomb Spoke and Larger Cell Angle demonstrated the least amount of stress, which is significant for fatigue-resistant designs [13].
- The Inclined Cell Angle to Cell Height Ratio is a key component that controls the Honeycomb Structure's Flexibility under Axial Loading. More structural flexibility is achieved with a higher ratio [14].
- NPT's with hexagonal spokes have lower contact pressures due to decreasing vertical stiffness with load [15].

Type 2 Design has the largest cell angle of the two designs and exhibits the lowest contact pressure, maximum deflection, least stress, and, as well as the best static performance.

- From all the test conductions, the type 2 design functionality with high stiffness and low stress brings out better outcome improving the surface contact with the shear band, stiffness improvements reduces damping in real time environment.

4. Conclusion

By the static and dynamic analysis conducted on the NPT designs of type 1 and type 2, the effect of geometric design of NPT honeycomb structure and their behavioral properties was investigated from the results illustrated in Table 8, 9, 10. The results presented in the mentioned tables indicate that

- Honeycomb spokes design constitutes low strain, deformation and stress values than other design, the honeycomb structure offers more space for the same material and closed cellular structural (hexagonal) withstand higher stress, resulting in increased compressive and shear strength.
- Since this honeycomb spoke's structure has lower localized stresses and deformation values, which is excellent for a fatigue resistant spoke design, the proposed work can sustain a greater amount of force while exhibiting relatively less overall deformation.

- The hexagonal honeycomb spoke NPT can be used to replace a normal pneumatic tire since it provides homogeneous wear and traction, as well as decent strength, reliability fatigue, light in weight and cost.
- The mechanical behavior of the NPT is modified by transferring the forces to honey comb core from the outer ring.
- Due to low vertical stiffness the NPT's honey comb structures deform and maintain high contact surface in between the wheels shear band and traction surface with low contact pressure.
- According to the design analysis, the Honeycomb spokes tire of type 2 were found to be solid, and it also bears a greater load than the type 1 design.

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