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Modeling and Analysis of Non-Pneumatic Tyres with Hexagonal Honeycomb Spokes

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Abstract

A pneumatic tyre is made of an airtight inner core filled with pressurized air. Pneumatic tyre have been dominant in the world market due to many advantages like low mass design, low vertical stiffness and low contact pressure. However, it have certain disadvantages like the possibility of a flat while driving, complex manufacturing procedure, the required maintenance for proper internal air pressure. Hence Non-Pneumatic tyres are introduced to overcome these disadvantages. Non-pneumatic tyres (NPT) are introduced with a compliant cellular solid spoke component which functions as air of a pneumatic tire. This project investigates hexagonal honeycomb spokes for NPT tire under macroscopic uni-axial loading. The spokes of an NPT undergoes tension-compression cycle while the tyre rolls. The spokes of an NPT is required to have both stiffness and resilience, which are conflicting requirements. Three types of honeycomb spokes are designed in AUTOCAD, namely A, B and C. Three dimensional models are created in CATIA. The mass of the designed tyres are found out. ANSYS finite element analysis is used to study about the deformation and stresses developed in different type of honeycomb spokes. Type C honeycomb spokes are found to be better considering both fatigue resistance and lower mass design.

Keywords: Tyres, Non-Pneumatic Tyre, Honeycomb, Ansys, Catia, Modeling, Analysis

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I. INTRODUCTION

A tyre is a ring shaped vehicle component that covers the wheel's rim to protect it and enable better vehicle performance. A pneumatic tyre is made of an airtight inner core filled with pressurized air. Most tyres, such as those for automobiles and bicycles, provide traction between the vehicle and the road while providing a flexible cushion that absorbs shock. The pneumatic tyre was first introduced in 1888 by Dunlop, since then has been dominant in the world tyre market for more than 100 years due to four major advantages it has over a rigid wheel: (i) low energy loss on rough surfaces, (ii) low vertical stiffness, (iii) low contact pressure, and (iv) low mass. However it has some disadvantages like: (i) The possibility of a blowout or a flat while driving, (ii) The required maintenance for proper internal air pressure, and (iii) the complicated manufacturing procedure. Thus non pneumatic tyres (NPT) were developed which overcome these disadvantages.

When the non-pneumatic tyre is put to the road, the spokes absorb road impacts the same way air pressure does in pneumatic tyres. The thread and shear bands deform temporarily as the spokes bend, then quickly spring back into shape. Airless tyres can be made with different spoke tensions, allowing for different handling characteristics. More compliant spokes result in a more comfortable ride with improved handling. The lateral stiffness of the tyre is also adjustable. However, you can't adjust such a tyre once it has been manufactured.

The objective of the present investigation is to study about the constituent materials of an NPT and to conduct static structural analysis on designed models.

Masters IG and et al. (1996), presented a model about the elastic deformations in honey combs [1]. A theoretical model has been developed for predicting the elastic constraints of honeycombs based on the deformation of the honey comb cells by flexure, stretching ad hinging. The model has been used to derive expressions for the tensile moduli, shear moduli and Poisson's ratios. Examples are given of Structures with a negative Poisson's ratio.

Tonuk E. and et al. (2001), constructed a detailed finite element model of a radial automobile tyre and its characteristics are studied [2]. The stress strain relationship of rubber is modeled. Validity of various simplifications is checked.

Balawi S and et al. (2008), investigated different properties of honeycomb structure [3]. The modeling of the effective properties of these honeycomb cores is of key importance to predict the overall mechanical response of the sandwich structures. In particular, the in-plane elastic moduli were studied by analytical and numerical means and correlated with experimental results for aluminum hexagonal or regular honeycombs. It is found that the flexibility of the honeycomb increases with cell angle.

Stefano Gonella and et al. (2008), conducted a study about the equivalent in-plane properties for hexagonal and auxetic lattices, through the analysis of partial differential equations associated with their homogenized continuum models [4]. The adopted homogenization technique interprets the discrete lattice equations according to finite differences formalism, and it is applied in conjunction with the finite element description of the lattice unit cell.

II. PROBLEM DEFINITION

Non-pneumatic tyres generally have higher rolling resistance and provide much less suspension than similarly shaped and sized pneumatic tyres. Other problems for airless tyres include dissipating the heat buildup that occurs when they are driven. NPT's are often filled with compressed polymers (plastic), rather than air.

Considering the NPT structure, the spokes undergo tension–compression cyclic loading while the tyre rolls. Therefore, it is important to minimize the local stresses of spokes that is, the spokes should be fatigue resistant. In this project we designed NPT based on hexagonal honeycomb spokes. Honeycombs have been primarily used in lightweight sandwich structures for which a high out-of-plane stiffness is desired. A honeycomb structure is an array of hollow cells formed between thin vertical walls. Two dimensional prismatic cellular materials of periodic microstructures are called honeycombs. Different types of honeycomb structures are: square, hexagonal, kagome, triangle, mixed squares and triangles, and diamond shape. Triangular, Kagome, and diamond cell honeycombs are good for high modulus structural designs. Square and hexagonal cell honeycombs are known to be good for flexible structural designs. Hexagonal cell structures are known to be flexible in both axial and shear loadings. Also, hexagonal honeycombs can easily be tailored to have targeted in-plane properties by changing the cell angle, the cell wall thickness, and the cell length.

The spokes of an NPT are required to have both stiffness and resilience under cyclic tension–compression loading. In general, stiffness and resilience are conflicting requirements if a material has a high modulus, it shows a low elastic strain limit, and vice versa. The challenge, then, is to design materials that have both high stiffness and high resilience.

Finite element analysis (FEA) has been utilized extensively in the simulation of tyre models due to its capability to solve complicated structural behaviors combining the nonlinearity of a material and geometry. FEA is often used to verify design integrity and identify critical locations on components without having to build the part or assembly. The different types of NPT geometry are created using CATIA and AUTOCAD. The analysis is done by modeling the structure into thousands of small pieces (finite elements).In this study, ANSYS WORKBENCH is used for a numerical experiment with NPTs having hexagonal honeycomb spokes.

III. STUDY ABOUT CONSTITUENT MATERIALS OF NPT

The Non-pneumatic tyre is designed using following constituent parts, which are hub, honeycomb spokes, outer ring and thread. The function of hub is to provide a rigid support to the honeycomb spokes. The honeycomb spokes are the key component of the NPT, which replaces the air-filled pneumatic tyres. The spokes of an NPT should have both stiffness and resilience under cyclic compression loading. The function of outer ring is to enforce the thread rubber to be deformed by shear. The thread provides the necessary traction between the road and the vehicle.

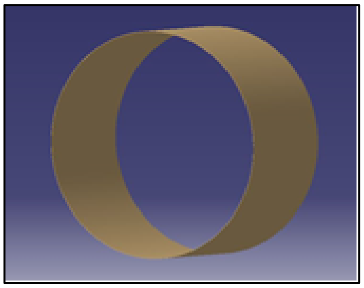

Fig. 1: Hub

The hub of an NPT should provide a rigid frame. Aluminium alloy, AL 7075-T6 is selected as the hub. Zinc is the primary alloying element in AL7075-T6. It is strong, with strength comparable to many steels, and has good fatigue strength and average machinability. However, its relatively high cost limits its use to applications where cheaper alloys are not suitable. 7075 aluminium alloy's composition roughly includes 5.6–6.1% zinc, 2.1-2.5% magnesium, 1.2–1.6% copper, and less than half a percent of silicon, iron, manganese, titanium, chromium, and other metals. The T6 alloy is heat treated and artificially tempered.

Its applications are; Aircraft fittings, gears and shafts, fuse parts, meter shafts and gears, missile parts, regulating valve parts, worm gears, keys, aircraft, aerospace and defence applications, bike frames. T6 temper 7075 has the following properties: density, ρ = 2800 kg/m3, Modulus, E = 72 GPa, and Poisson's ratio, υ = 0.33, Yield strength = 500 MPa. A 1 mm thick aluminum alloy is used for the inner hub. The outer radius of the hub is taken as 217mm, as shown in Figure 1.

Fig. 2: Honeycomb Spokes

Polyurethane is used as the constituent material of the honeycomb spokes. Polyurethane is a unique material that offers the elasticity of rubber combined with the toughness and durability of metal. Polyurethane has good resilience and stiffness. The properties of Polyurethane are: density, ρ = 1200 kg/m3, modulus, E = 32 MPa, shear modulus, G = 10.81 MPa, and poisons ratio, υ = 0.49 and Yield strength = 140 MPa. In the Figure 2, the spokes of TYPE A is shown, whose dimensions is specified later. The radius of the spokes is taken as 317mm.

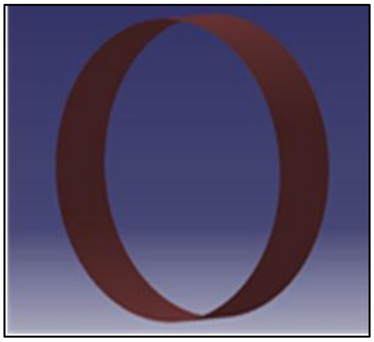

Fig. 3: Outer Ring

The outer ring is made of high strength steel, AISI 4340. This enforces the thread rubber to be deformed by shear. Without the outer ring, the edges of the spokes over the contact zone with the ground would buckle and cause an undesirable nonlinear effect of the honeycombs.

The properties of AISI 4340 are density, ρ = 7800 kg/m3, modulus, E = 210 GPa, poisons ratio, υ = 0.29 and yield strength = 470 MPa. The thickness of outer ring is taken as 0.5 mm. The outer radius of the outer ring is 317.5 mm, as shown in Figure 3.

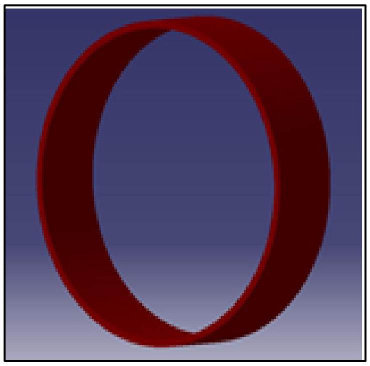

Fig. 4: Thread

The thread component is made of a synthetic rubber. The function of thread is to provide necessary traction between road and tyre. The thread should have a good grip on various terrains. Synthetic rubber, invariably a polymer, is any type of artificial elastomer mainly synthesised from petroleum by products. An elastomer is a material with the mechanical (or material) property that it can undergo much more elastic deformation under stress than most materials and still return to its previous size without permanent deformation. The properties of rubber are: density, ρ = 1043 kg/m3, modulus, E = 11.9 MPa, sheer modulus G = 4 MPa, poisons ratio, υ = 0.49 and yield strength = 16Mpa. The thickness of thread is taken as 15mm. The outer radius of thread is 332.5 mm, as shown in Figure 4. The properties of the constituent parts of an NPT is summarised in the Table 1.

Table -1:
Properties of the Constituent Parts of NPT

Part	*Hub*	*Spokes*	*Outer Ring*	*Thread*
Material	*AL 7075-T6*	*Polyurethane*	*AISI 4340*	*Rubber*
Density P,kg/m3	*2800*	*1200*	*7800*	*1043*
Youngs Modulus E (MPa)	*72000*	*32*	*210000*	*11.9*
Poisons Ratio,υ	*0.33*	*0.49*	*0.29*	*0.49*
Yield Strength (MPa)	*500*	*140*	*470*	*16*

IV. MODELLING OF DIFFERENT TYPES OF NPT

Three types of non-pneumatic tyres are studied, namely Type A, B and C. The models of the NPT's are created in AUTOCAD and CATIA. The difference between the Type A, B and C are in the variation of dimensions of the honeycomb spokes. The other material properties and dimensions remains the same.

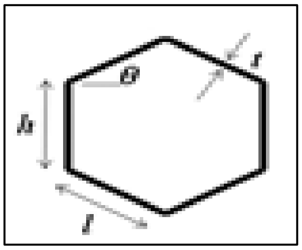

Fig. 5: Hexagonal Notations

Hexagonal honeycombs are modeled with the cell wall thickness, t, vertical cell length, h, the inclined cell length, l, and the cell angle, θ, as illustrated in Figure 5. When designing honeycombs, numerous configurations are available with cell angle, θ, cell height, h, and cell length, l. The dimensions of the honeycomb spokes are chosen arbitrarily. Here we are considering three different types of hexagonal spoke.

Table -2:
Dimensions of Honeycomb Spokes

NPT Type	*l (mm)*	*h(mm)*	*θ (degree)*	*t (mm)*
Type A	*26.25*	*36.66*	*15.76*	*3.2*
Type B	*29.65*	*28.52*	*31.50*	*3.8*
Type C	*37.21*	*16.74*	*47.14*	*4.2*

The Table 2 shows the dimensions of the three types of NPT, which are modelled. Only regular honeycombs are considered, i.e. those with a positive poisons ratio. The ratio of the inclined cell length to the cell height, l/X_1 is the critical factor to design in-plane flexible structures for simple tension–compression loading. Therefore, the cell angle may not be important when designing the in plane flexible structures. In other words, the in-plane flexure behavior of auxetic honeycombs may not be greatly different from that of regular honeycombs. Auxetic honeycombs are those with a negative poisons ratio. It has more stiffness in lateral direction under loading, compared to regular spokes. Cell angle, θ is the important dimension in designing a fatigue resistant honeycomb. As the cell angle, θ increases the flexibility of hexagonal honeycomb increases.

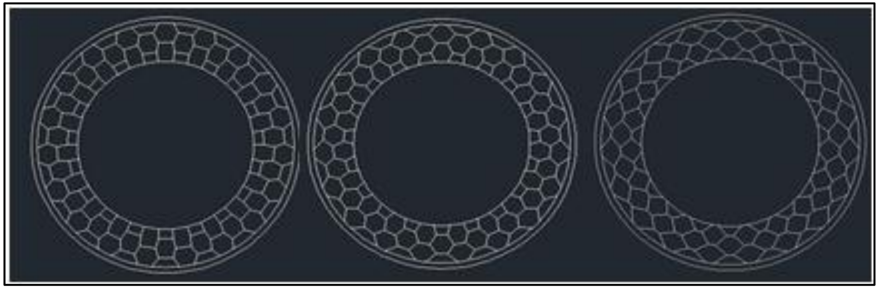
Type A Type B Type C

Fig -6: Suggested honeycomb design in AUTOCAD

The Figure 6 shows the suggested types of NPT design in AUTOCAD. Two dimensional models are created in AUTOCAD. The 2D modeling involves steps like sketching, rotating, explode etc. The explode function in AUTOCAD is very helpful in structural analysis. Explode command allows to break a compound object into its components separately, so the properties could be individually modified. Objects that can be exploded include blocks, circles etc. The 2D model is then imported into CATIA.

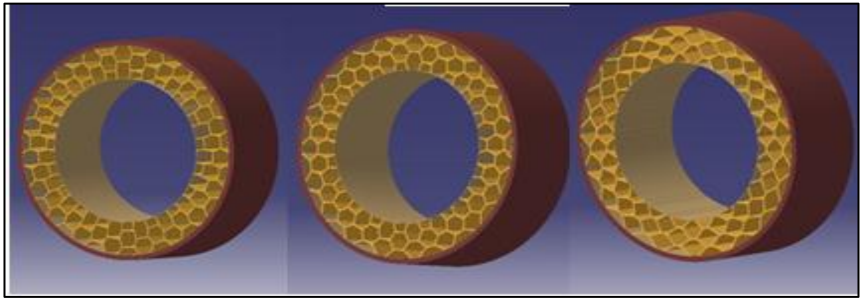
Type A Type B Type C

Fig. 7: Suggested honeycomb design in CATIA

The Figure 7 shows the suggested types of NPT design in CATIA. Three dimensional models are created in CATIA. The 3D modeling involves various steps like sketching, padding etc. The material properties of the constituent parts are defined in CATIA inorder to find out the mass of designed tyres. The designed 3D models are then imported into ANSYS WORKBENCH for static structural analysis.

V. RESULTS AND ANALYSIS

The models that are created in AUTOCAD are imported into ANSYS WORKBENCH. It is finite element analysis software, which is used for static structural analysis. The three types of NPT's are imported into the WORKBENCH, and the corresponding material data are defined. The bonding operation in WORKBENCH is used to produce a bonding between all the components. The element type of hub, outer ring and spokes are defined.

The constituent parts of the NPT are properly meshed. Cubical mesh is used for meshing since all the components are symmetrical. The mesh size is set as medium.

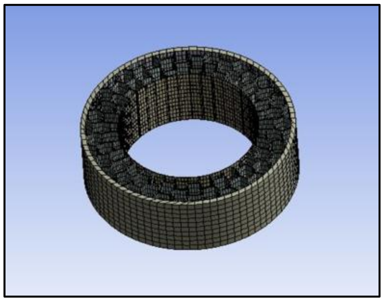

Fig. 8: Meshed Model

The number of elements in the three models is around 15000. The meshed model is shown in Figure 8.

While the vertical displacement loading is applied at the hub center, the horizontal displacement of the bottom center on the thread is set to zero so that a deformed geometry can be maintained to be symmetric with respect to the plane perpendicular to the road surface. The load is applied at the hub of the NPT. All degrees of freedom of a line of contact at the bottom of the thread is set as zero. The load applied at the hub is 750N, 1500N, 3000N and 9000N. The corresponding deformed shapes and Von-Mises stress is found out.

The deformed shapes and stress distribution of Type A, B and C under a load of 3000N is shown. The summarized results are shown in the Table 3.

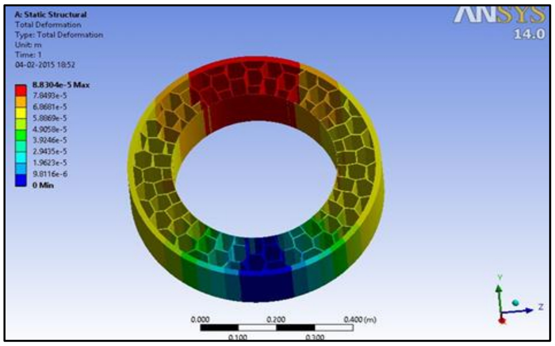

Fig. 9: Total Deformation of Type A under 3000 N

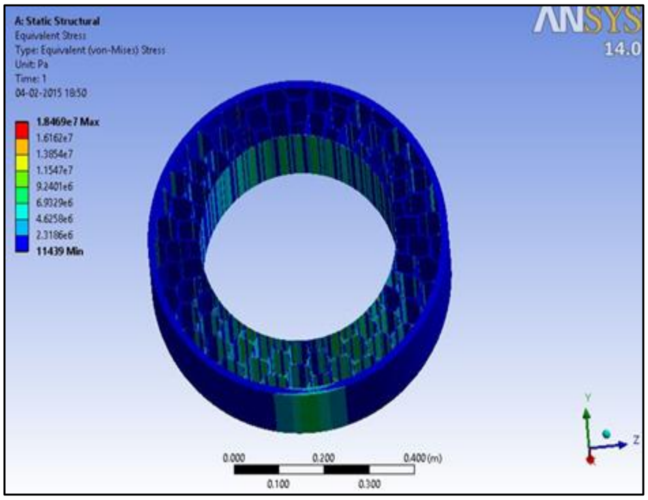

Fig. 10: Von-Mises Stress of Type A under 3000 N

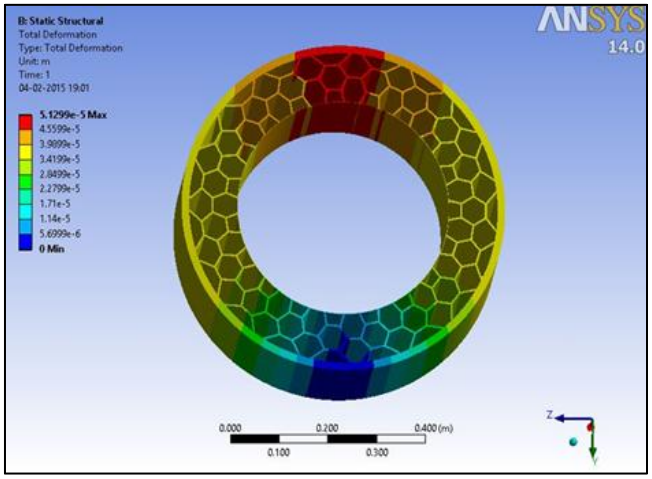

Fig. 11: Total Deformation of Type B under 3000 N

The Von-Mises stress in Type B is found to be lesser than that of Type A. So Type B spokes are more fatigue resistant than Type A spokes. For example, consider the Type A and B under 3000 N load at hub, Figures 10 and 12. The maximum Von-Mises stress in Type A is found to be 18.469 MPa, while in Type B is only 14.92 MPa.

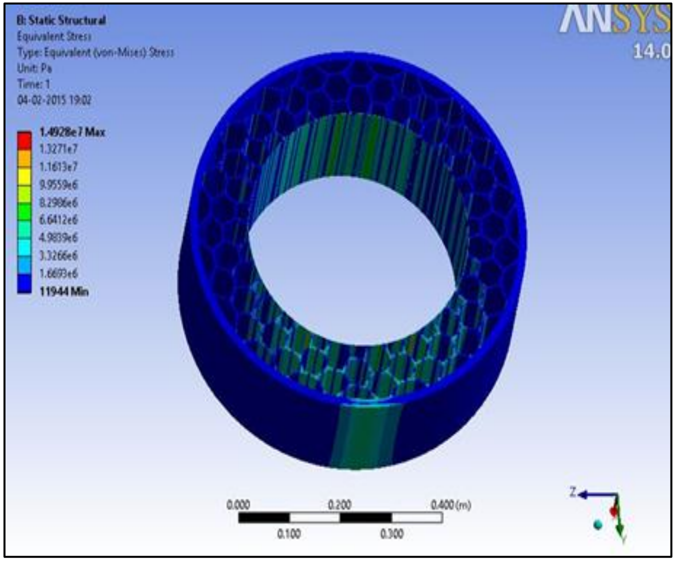

Fig. 12: Von-Mises Stress of Type B under 3000 N

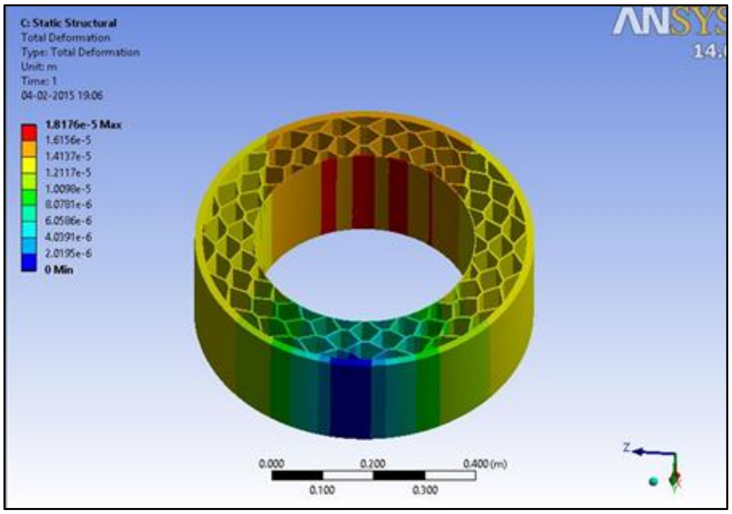

Fig. 13: Total Deformation of Type C under 3000 N

The Von-Mises stress in Type C is found to be much lower than that of Type A and B, which turns out to be better for the fatigue resistant design of honeycomb spokes. For example, for 3000 N at the hub, Figure 14, the maximum Von-Mises stress in Type C is found to be 7.26 MPa which is lower than that of an NPT with Type A and B spokes.

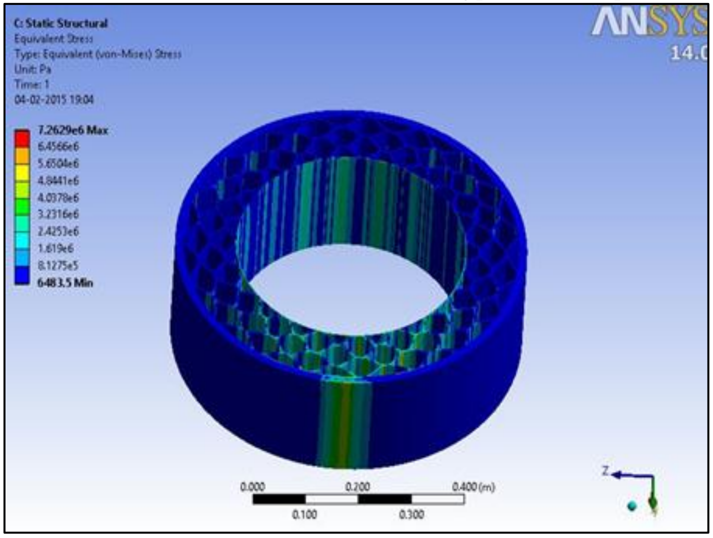

Fig. 14: Von-Mises Stress of Type C under 3000 N

From the deformation of the NPT under load, Figures 9, 11 and 13, we can infer that the maximum deformation is at the top portion of the tyre. The deformation is very small under small loading. The Von-Mises stress is found to be maximum at the edges of the spokes which are in contact with the outer ring.

Table -3:
Summarized Results

NPT type	*Condition*	*750 N at Hub*	*1500 N at Hub*	*3000 N at Hub*	*9000 N at Hub*
TYPE A	*Max. Von-Mises stress (MPa)*	*4.61*	*9.234*	*18.469*	*55.40*
	Max Deformation (mm)	*0.022*	*0.044*	*0.088*	*0.264*
TYPE B	*Max. Von-Mises stress (MPa)*	*3.732*	*7.463*	*14.92*	*44.78*
	Max Deformation (mm)	*0.012*	*0.025*	*0.0512*	*0.153*
TYPE C	*Max. Von-Mises stress (MPa)*	*1.815*	*3.631*	*7.262*	*21.78*
	Max Deformation (mm)	*0.004*	*0.009*	*0.018*	*0.054*

From the results obtained, we can infer that the Von mises stress is lesser for Type C than A and B. which means that Type C is better design in terms of fatigue resistance. It can carry more load without much deformation. The lower local stresses of the Type C spokes are favorable in designing fatigue resistant spokes due to the lower cyclic stresses. The lower Von-Mises stress in Type C is due to the higher cell angle. Because as cell angle increases, flexibility increases leading to lesser local stresses.

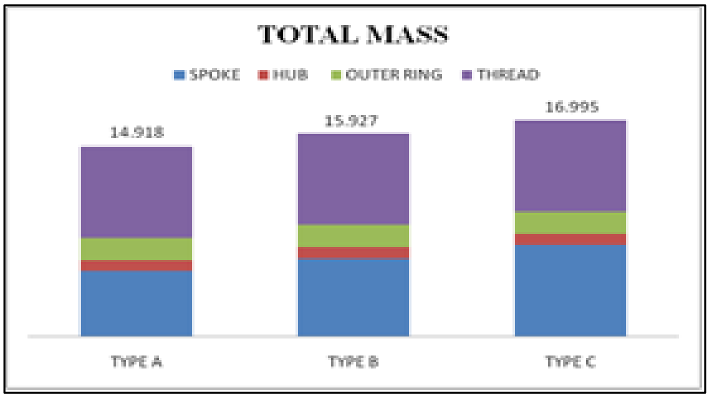

Fig. 15: The total mass of Npt's when the lateral width is set to be 225 mm

The total mass of NPTs with the honeycomb spokes when the lateral width is set to be 225 mm is found from CATIA, Figure 15. The mass can be found out after assigning all the material properties to the constituent parts of NPT. The mass of the hub, outer ring and the thread is same, only the mass of the spokes is a variable. The mass of the tyre increases as the cell wall thickness of spokes increase. The Type C is found to be of higher mass. The mass of Type C is about 14% higher than that of Type A. Inorder to design a tyre for both, low mass and high fatigue resistant honeycomb spokes, a higher modulus elastomer as a base material with the Type C spokes is preferable.

VI. CONCLUSIONS

In this project, the cellular spoke geometries for a Non pneumatic tyre were studied with regular honeycomb spokes. Non pneumatic tyres are the tyres that are not supported by air pressure. The Non pneumatic tyres overcome many disadvantages over conventional tyre like possibility of a catastrophic damage, required maintenance of proper internal air pressure and complex manufacturing procedure.

The constituent materials of a hexagonal honeycomb spokes were studied. Different types of hexagonal honeycomb spokes are modelled and their static structural analysis was conducted. The total mass of the designed models were found out from CATIA. It is seen that Type C have 14% higher mass than that of Type A. This increase in mass is due to increase in cell wall thickness.

The major conclusion is that the honeycomb spokes with a higher cell angle magnitude show lower local stresses, which is good for a fatigue resistant spoke design. Here Type C has lowest local stresses than A and B. The maximum Von-Mises stress is found to be at the edges of the spokes i.e. at the contact between spokes and the outer ring. The NPT based on hexagonal honeycomb spokes can be used to replace a conventional pneumatic tyre.

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