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Design and analysis of non-pneumatic tyre

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Abstract: Non-Pneumatic Tyre (NPT) as the name suggests is a type of tyre that doesn't use air to support the load. Even though tyres made out of solid rubber exists, they don't have enough compliance and will not provide a supple ride if used in normal vehicles. The NPT discussed here consists of mainly three parts. A rigid hub, Deformable spokes that support vertical load, Reinforced shear band and tread made out of rubber which comes into contact with the surface. The properties of NPT like contact pressure, rolling resistance and load carrying capacity can be varied by altering the dimensions or materials used to manufacture NPT. Several researches are being carried out all over the globe to make NPT an alternative to the conventional pneumatic tyre. This paper consolidates an overview of the research works that were carried out to develop and improve NPT.

1. Introduction

As far as automobiles are concerned, the engine, transmission and all other powertrain parts are only good as good as the tyres are. Since its invention in 1888 by Dunlop, pneumatic tyre has been the primary choice for use in automobile subjected to different operating conditions due to the several advantages offered by it mainly: 1. Low energy loss while rolling 2. Low vertical stiffness which produces cushioning effect. 3. Low contact pressure and 4. Low mass [1]. Even though several advantages exist for a pneumatic tyre which resulted in its widespread acclaim, there exist a chance for it to go flat during operation which is its greatest drawback till date. In the case of vehicles that are subjected to extreme conditions like tractors, solid tyres are used to avoid this issue but this deteriorate ride quality. Researchers have been trying long back as 1920s to build a non-pneumatic tyre (NPT) that has sufficient resilience [2]. With advancement in material science and manufacturing technologies, researchers were able to create NPTs having sufficient compliance [3]. Modern NPT designs integrate wheel and tyre into a single component. The NPT consists of a rigid hub, flexible spokes, shear band and tread which is made up of rubber as shown in Figure 1.

The flexible spokes and shear band are the components that support the load acting on an NPT like air in the case of a pneumatic tyre. Several researches are going on to optimize the design of spokes and shear band of an NPT and some of them are discussed below. Akshay Narasimhan et al [4] studied the effect of material properties on static behaviour of an NPT having radial spokes and shear band made of polyurethane and concluded that increase in shear modulus increased the stiffness of the NPT. Hysteresis loss due to the viscoelastic nature of rubber accounts for 90 % of energy loss. The spokes and shear band of NPT are usually made of polyurethane which also exhibits viscoelasticity.



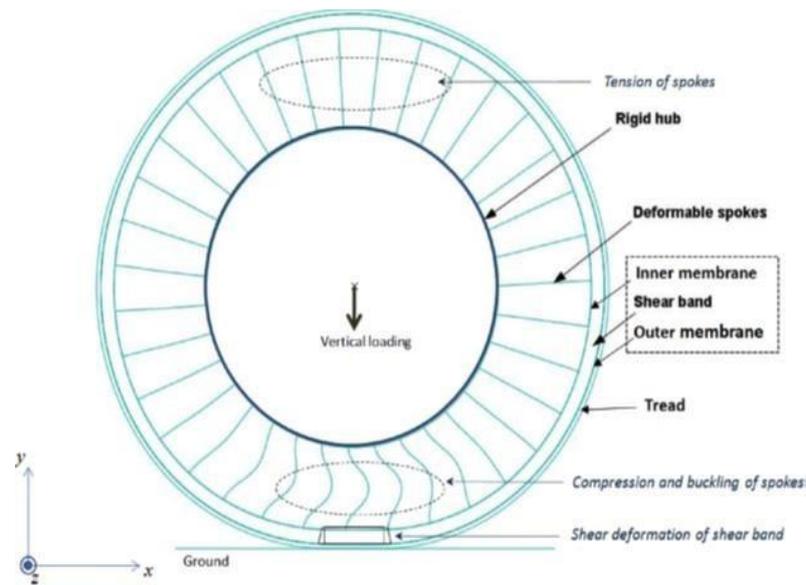


Figure 1. Schematic representation of a non-pneumatic tyre.

Porous shear band with reinforcements was one of the method proposed by researchers [5] to reduce the energy loss. In order to reduce losses, the possibility of cellular structures were explored. Mohammad Fazalpour and Joshua Summers [6] developed and studied the characteristics of NPT with shear band having cellular structure which is made of elastic material. Conventional materials don't exhibit high stiffness with good resilience. In order to achieve desired properties, the shear band was made into a cellular structure as cellular structures of desired properties can be made by optimizing the cell geometry. Cellular structures are also used for construction of spokes of an NPT. Cellular structures have low in plane stiffness and this can be used for applications requiring high deformation. Jaehyung Ju et al [7] studied the properties of NPTs having spokes made of both regular and auxetic honeycombs and mentioned that the behaviour of regular and auxetic honeycombs differ much as far as deflection under axial loading is concerned. Kwangwon Kim et al [8] studied the static behaviour of NPT with hexagonal spokes by comparing their designs with a pneumatic tyre of similar dimension and observed that NPT has less contact pressure than a pneumatic tyre. This project aims to study the static contact behavior of NPTs having regular hexagonal honeycomb spokes with different cell geometries having same thickness.

2. Honeycomb Structure

Honeycomb structures have been widely used in aircraft industry to construct light weight sandwich structures having high out of plane stiffness. As mentioned before, the magnitude of in plane stiffness of honeycomb cellular structures are less [9]. Triangular and kagome structures are known to be extension dominant structures whereas hexagonal and square structures have good flexibility. The hexagonal structures exhibit greater flexibility under both axial and shear loading conditions. The advantage of hexagonal structures is that desired in plane properties can be achieved by changing cell parameters like cell angle, cell length and wall thickness. Effective in plane moduli of hexagonal honeycombs were developed using beam theory and are collectively called as cellular material theory (CMT). The effective moduli according to this theory are given by the following equations,

$$E_r^* = E_s \left(\frac{t}{l} \right)^3 \frac{\cos \theta}{(h/l + \sin \theta) \cdot \sin^2 \theta}$$

$$E_\Omega^* = E_s \left(\frac{t}{l} \right)^3 \frac{(h/l + \sin \theta)}{\cos^3 \theta}$$

$$G_{r\Omega}^* = E_s \left(\frac{t}{l} \right)^3 \frac{(h/l + \sin \theta)}{(h/l)^2 (1 + 2h/l) \cos \theta}$$

Where E_r , E , and G are the effective moduli in radial, circumferential and shear directions.

3. Design of NPT's

3.1 Structure and Materials

An NPT integrates wheel and tyre into a single unit and different parts of an NPT are made of different materials. CAD models of 3 NPTs were made which is discussed in the next section. The materials properties assigned to the components of these designs were the same. The hubs of all three NPTs are made of 10mm thick aluminium alloy. The flexible honeycomb spokes which plays the role of air in NPT is made of polyurethane and is attached to the rigid hub. The shear band of NPT is also made of polyurethane and is reinforced by two shear rings of 5mm thickness which are made up of high strength steel. The shear band is provided to have a uniform contact patch and the shear rings help to keep the tyre in the shape when it is deformed. The tread similar to that of a pneumatic tyre is the outermost part of an NPT which comes into contact with road surface and the material used for construction tread is rubber. The material properties of different materials used in the construction of NPT are mentioned in Table 1.

Table 1. Material properties

Material Properties	Aluminium Alloy 7075- T6	High Strength Steel	Polyurethane	Rubber
Density (Kg/m ³)	2800	7800	1200	1043
Youngs Modulus (Gpa)	72	210	32	11.9
Yield stress (Mpa)	503	710	145	16
Poissons Ratio	0.33	0.29	0.49	0.49

3.2 CAD Models of NPT

The design of spokes influences the stiffness and resilience of an NPT. The dimensions of other components were kept as a constant and the dimensions of cells of the spokes were varied to generate different designs. The overall diameters of all the three designs are 654mm. The Cell angle θ , inclined cell length l , vertical cell length h and wall thickness t are the parameters that influence in plane properties of a honeycomb structure. The cells were designed to have uniform thickness of 4mm. Since the hexagonal cells are of not regular type, the dimensions of each cell vary slightly and the average dimensions of a cell of each type is mentioned in Table 2. The effective in plane moduli for

different spoke designs were calculated using CMT. Cell angle and the ratio of inclined length to cell height (l/h) are the critical factors that determine the flexibility of the structure [10].

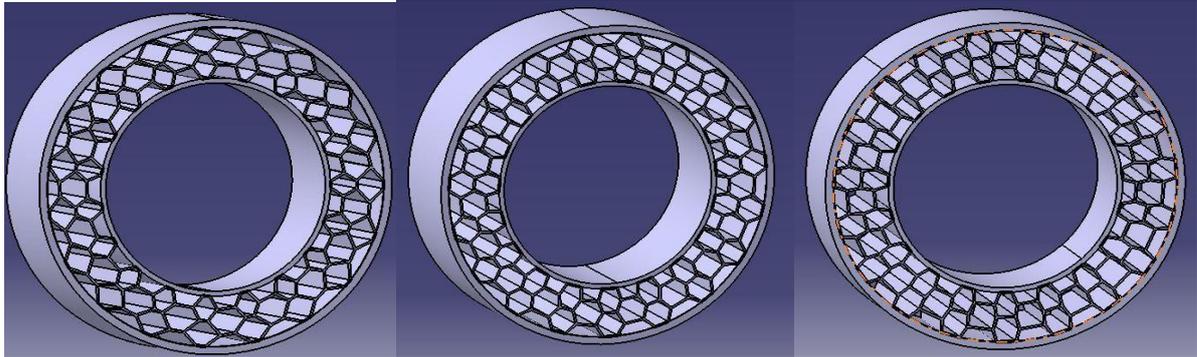


Figure 2. Various models of NPT used.

Table 2. Dimensions of various types of NPT used.

Types	l	h	Theta	T
Type A	37	16	137	4
Type B	29	28	121	4
Type C	26	36	105	4

3.3 Finite Element Analysis

Figure 2 shows the meshed model of an NPT. Meshing was done in Ansys Workbench and tetrahedral elements were used for meshing. Tetrahedral elements have 3 degree of freedom at each node and can completely capture the behavior of component by creating appropriate mathematical model while analyzing.

3.3.1 Boundary Conditions and Loading

In order to perform static analysis on NPTs designed, the CAD model is imported into Ansys Workbench and material properties for each element of NPT were assigned. The tread and shear band with rings, the shear band and spokes, the spokes and aluminium hub were tied together using bonded constraint. Frictional type contact was used to define the nature of contact between road surface and the tread. The movement of NPT was arrested in all directions except the vertical and load varying from 1000N to a maximum of 4000N was applied at the center of the hub and corresponding total deflection in vertical direction and equivalent stresses developed in spokes were noted. Contact tool is used to get the value of contact pressure generated between the tread and road surface when the load is applied.

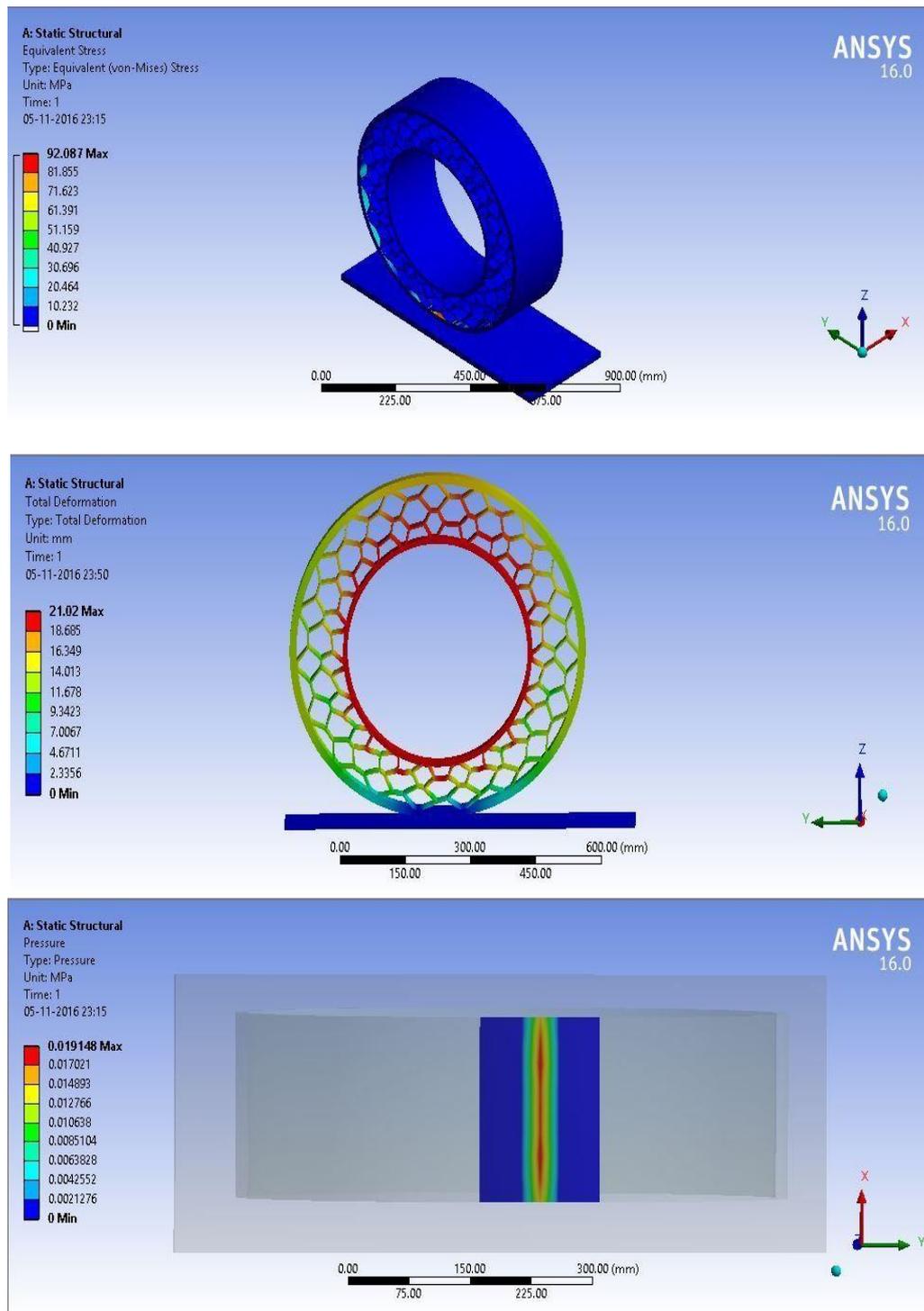


Figure 3. Ansys test results for Type A at maximum load showing Von-Mises Equivalent stress, Deformation, and Contact pressure in order.

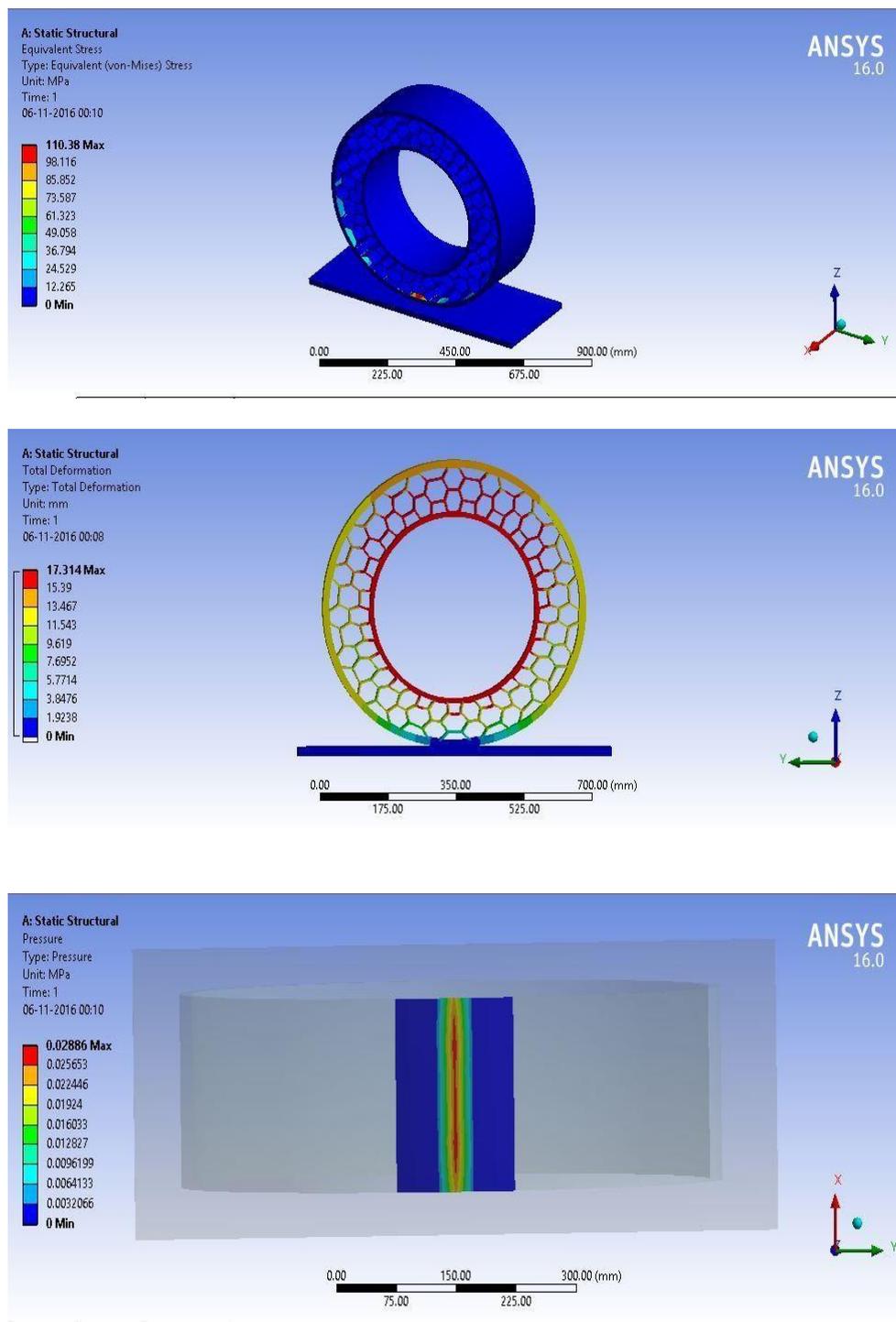


Figure 4. Ansys test results for Type B at maximum load showing Von-Mises Equivalent stress, Deformation, and Contact pressure in order.

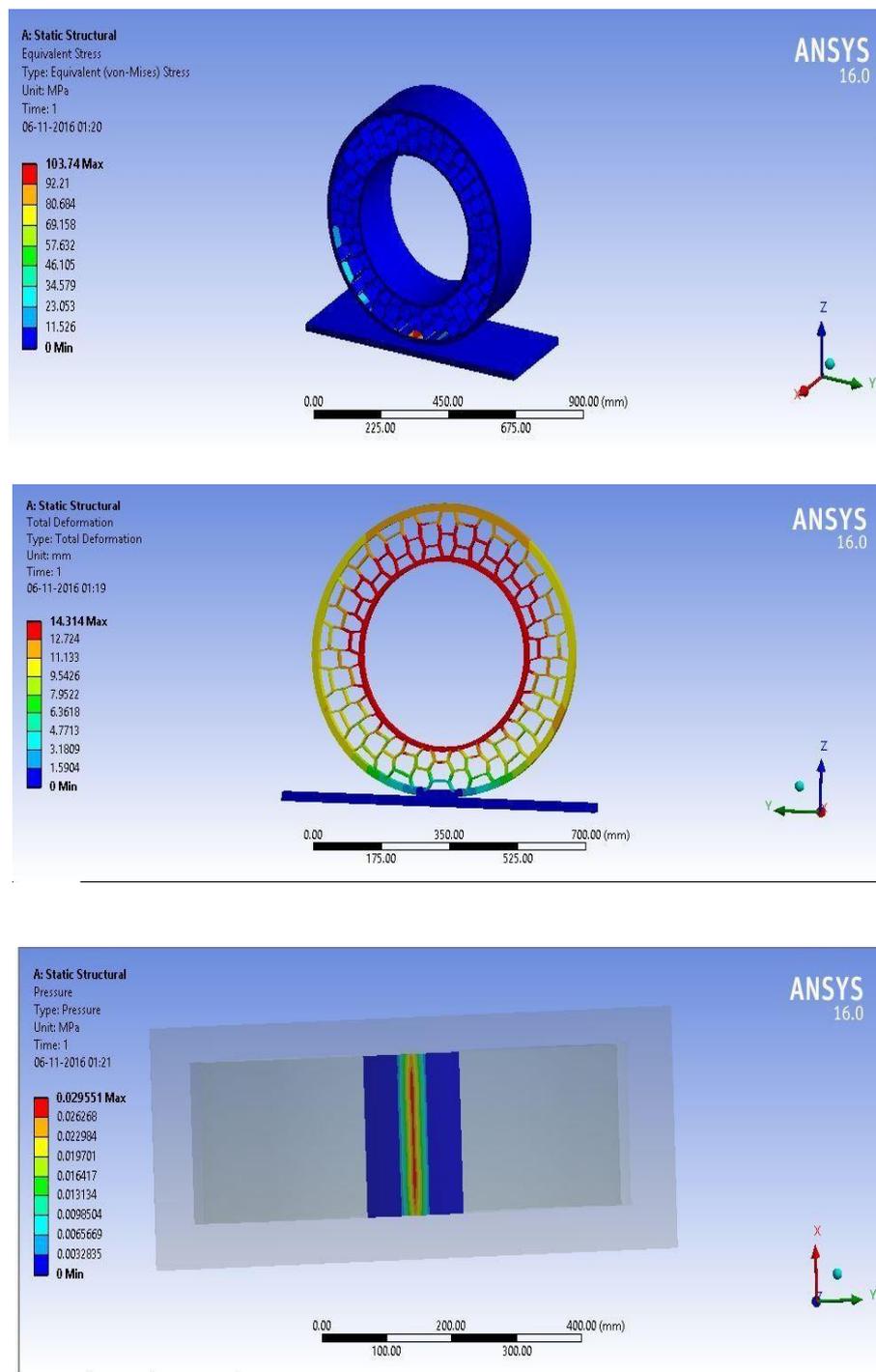


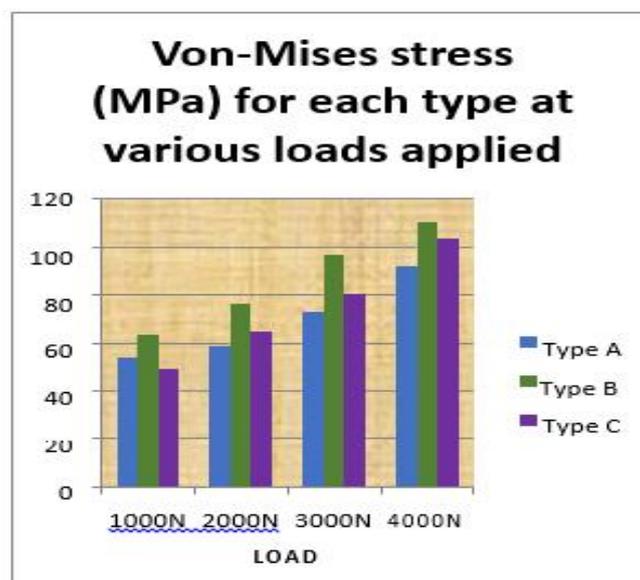
Figure 5. Ansys test results for Type C at maximum load showing Von-Mises Equivalent stress, Deformation, and Contact pressure in order.

4. Results and Discussions

Static analysis on three different NPTs were performed and the total deflection, von misses stress induced in spokes and the contact pressure developed for all the three models were found out and the results are shown in Table 3.

Table 3. Deflection, stress and contact pressure of NPTs.

Load (n)	Type	Maximum Deformation (mm)	Von mises Stress (mpa)	Maximum Contact pressure (mpa)
1000	A	12.5	54.05	0.011
	B	10.21	63.49	0.016
	C	7.16	49.45	0.013
2000	A	13.56	58.72	0.012
	B	12.24	76.65	0.019
	C	9.20	64.68	0.017
3000	A	16.75	73.07	0.015
	B	15.27	96.95	0.025
	C	11.24	80.37	0.022
4000	A	21.02	92.08	0.019
	B	17.31	110.38	0.028
	C	14.31	103.74	0.029

**Figure 6.** Von-Mises stress variation in MPa for each type

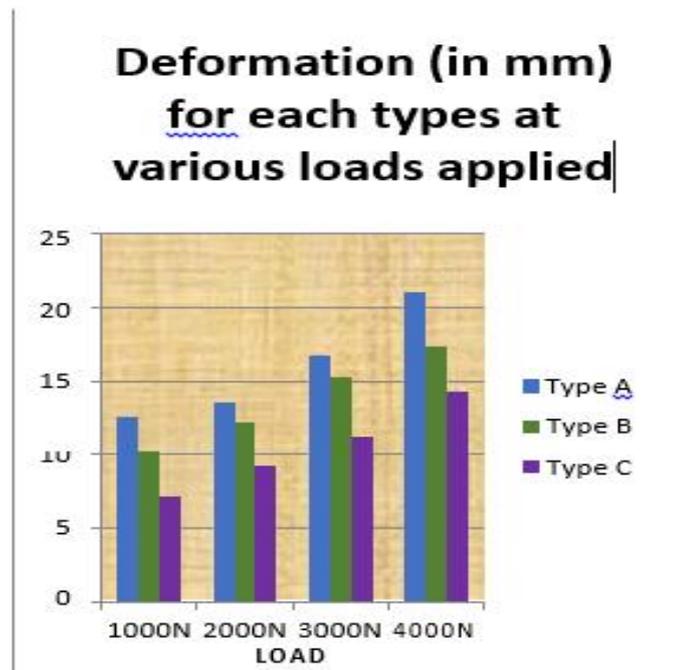


Figure 7. Deformation variation in mm for each type

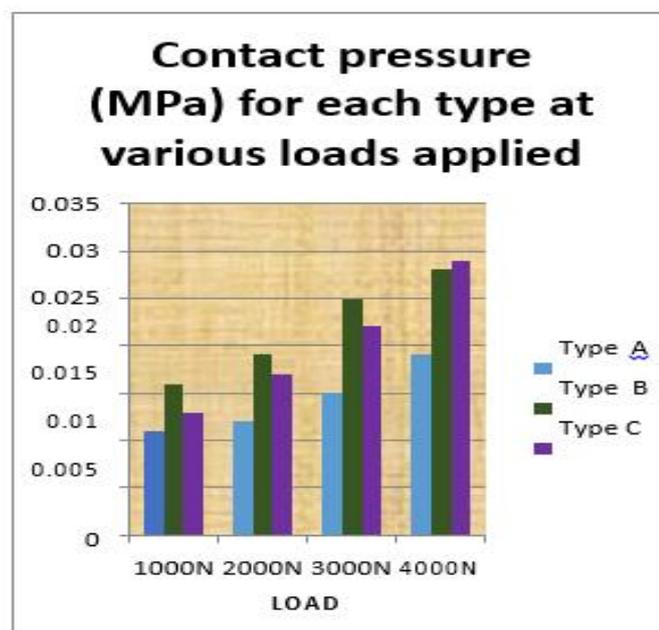


Figure 8. Contact pressure variation in MPa for each type.

5. Results and Discussions

A structural analysis of NPTs having spokes made of hexagonal honeycomb structures with same cell wall thickness was performed and the following conclusions were derived from the results obtained.

- NPT with honeycomb spoke with larger cell angle showed minimum stress concentration which is important for fatigue resistant designs.
- Ratio of inclined cell angle to cell height is an important factor which determines the flexibility of honeycomb structure under axial loading. Larger ratio induces high flexibility to structure.
- Due to decreasing vertical stiffness with load, NPTs with hexagonal spokes exhibit lower contact pressures.
- Type A design having the largest cell angle among the three designs exhibit least stress, maximum deflection and minimum contact pressure and performance best under static condition. The rolling resistance offered by this design needs to be studied to further optimize it.

Acknowledgement

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