Design and Comparative Analysis of Non-Pneumatic Tires for a Tractor

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***Abstract*: The purpose of this article is to design non-pneumatic tires with a large diameter for its application in a tractor and carry out a thorough comparative analysis of different spoke structures based upon various parameters. The three major types of tires which are studied in this article are Michelin Tweel, Honeycomb structure by Resilient Technology and Airless Tire concept introduced by Bridgestone. The designing was carried out in SolidWorks and the static analysis was conducted in Ansys Workbench. The corresponding graphs were plotted from the obtained values from simulations where total deflection, contact pressure, and maximum shear was determined by varying design parameters. This will help in defining the relationship between the three major parameters i.e. spoke thickness, reinforcement layer thickness and total deformation under similar loading conditions.**

***Index Terms*: Ansys, Michelin, Non-Pneumatic Tires, Static Analysis, Tractor, Tweel.**

I. INTRODUCTION

The concept of airless tires was introduced by Michelin, a French tire manufacturing company. In this article, we will be considering three specific types of non-pneumatic tires i.e. Michelin Tweel [1], Airless tires concept by Bridgestone [2] and the honeycomb structured airless tires developed by Resilient Technology [3]. The Tweel by Michelin is based on the concept of joining the inner and the outer component of the wheel with the help of radially placed flexible spokes. In Bridgestone concept, there are two rows of spokes in opposite direction separated by a gap in the middle of the wheel. The concept introduced by Resilient Technology makes use of honeycomb structure.

II. PROBLEM STATEMENT

The pneumatic tires which are currently used in tractors are unable to give better performance due to their deflation phenomenon and heavyweight. The agricultural fields have coarse surfaces which contain many small irregularities such as stones which contribute to the wear and tear of tires and thus reducing their life. This drawback of getting puncture can be completely eliminated with the help of non-pneumatic tires with better handling and increased surface traction.

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III. PROPOSED SOLUTION

Designing a non-pneumatic tire for the specified model of tractor. Conducting comparative analysis on the three designs based upon spoke thickness and the reinforcement layer [4]. Thus deciding which spoke structure will be more beneficial under specified circumstances. The analysis is done in static structural under varying load to mimic actual conditions of standing load and shock load. There are other advantages of using non-pneumatic tires such as the elimination of blowout, involves less maintenance and has low rolling resistance. Also, the materials used for the manufacturing of shear and spokes are recyclable and have a service life 3-4 times [5] that of conventional tires.

IV. MAIN BODY

A. *Vehicle Specifications*

The reference model taken here is Mahindra Yuvo 275 DI [6]. It is the most commonly used tractor for agricultural works in India and has a wide variety of equipment attachments available and thus it was chosen as a reference model.The specifications of the vehicle are provided below (Table 1).

Table 1. Specifications of the reference vehicle.

Parameter	Value
Horse Power	39BHP @2100 RPM
Weight	1790 kg
Wheel Base	1880 mm
Rear Tire Specification	340/85R28
Front Tire Specification	215/85R16

B. *Material Properties*

The Tweel by Michelin mainly consists of three parts. It consists of a rubber tire which is blended with tread, a shear layer just below the tread and then there are series of energy absorbing spokes which are made of Polyresin based on Polyurethane which is connected to the hub at thecenter to the shaft. There are mainly two kinds of materials used in these wheels. They are:

1) Elastic, orthotropic materials which are part of the shear beam and reinforcement layer, which provide structural support to the collapsible spokes and thus

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helps in uniformly distributing the load. The values used as D matrix [7, 8] for this orthotropic material is

$$D(x) = \begin{bmatrix} 0.01 & 0 & 0 & 0 & 0 & 0 \\ 0 & 4135.12 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.01 & 0 & 0 & 0 \\ 0 & 0 & 0 & 42.87 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Alternatively, if an isotropic material has to be used that resembles similar characteristics [9] as above it should have Young's modulus of 319 MPa and Poisson's Ratio of 0.49. The density of the shear layer used is 1125 kg/m^3. The main objective for using the reinforcement layer is to provide high stiffness to wheel in the tangential direction which is provided by coated wires wound inside the layer.

2) Hyper-elastic, isotropic material is used for spokes. The material used follows Mooney-Rivlin [8, 10] strain energy potential. The form is:

$$U = C_{10}(\bar{I}_1 - 3) + C_{01}(\bar{I}_2 - 3) + \frac{1}{D1}(J_{EL} - 1)^2$$

Values of the variable used for the purpose of analysis are as follows: C_{10} = 0.75MPa, C_{01} = 0, D_1 = 0.066 MPa^{-1} [11, 12]. The density of polyurethane is 1100kg/m^3. And Poisson's ratio of 0.42 coefficient of thermal expansion is 0.0002 ℃^{1} [13]. Due to this hyperelastic property spokes exhibit a unique buckling phenomenon when subject to variable loads. The below table (Table 2) shows the material composition [4] of Tweel by weight percentage.

Table 2. Material Composition of the wheel by weight percentage.

Raw Material	Spokes (Wt%)	Hub (Wt%)	Tread (Wt%)	Shear Layer (Wt%)
Steel	0	100	0	0
Polyurethane	100	0	0	70
Coated Wires	0	0	0	30
SyntheticRubber	0	0	42	0
Natural Rubber	0	0	3	0
Sulfur	0	0	1	0
Oil	0	0	10	0
Silica	0	0	27	0
Carbon Black	0	0	12	0
Stearic Acid	0	0	2	0

C. Calculation

a) Shaft design

Weight of the tractor = 1790 kg
Power = 35 PTO HP
Tire Diameter = 28 inches
RPM of tire = 224 (at 30km/hr., assumed)
Material = Cast Iron
Tensile stress = 520 N/mm^2
Bending stress = 270 N/mm^2
Shear Stress = 100 N/mm^2
Bending Moment, M = 5880 Nm
Twisting Moment, T = 3000 Nm
By using the below formula we get,
Te = (M2 + T2)1/2
Therefore we get the value of Te by substituting the values of M and T, as:
Te = 12298.6 Nm ≈ 12300 Nm
Now by using the below equation
Te = π/16 * 100 * d3
On substituting the value of Te in the above equation we get
d = 85 mm

b) Dimension of Hub

di = Inner diameter of hub
do = Outer diameter of hub
ds = Shaft diameter of hub
di = ds = 85 mm
do = 1.5ds + 25 = 1.5*85 + 25 =152.5 mm
[Safe limit, do = 2ds = 175 mm]

c) Dimension of key

d' = 0.2 ds
d' = 17 mm

d) Design of Rim

Material = Structural Steel
Outer Diameter= 712 mm
ρ = 7700 kg/m^3, Poisson's ratio = 0.28
Velocity of Rim (v) = 30 km/hr (assumed)
Stress = ρ*v
Substituting the values, we get
Stress = 64166.66 N/m^2
V = πDN/60
= 221 RPM < RPM of tire
Hence Design Parameters are safe.

e) Rim thickness

t= D/200+6
t= 0.712/200+6
t=6.0035 mm.

D. Designing using SolidWorks

a) Design Parameters

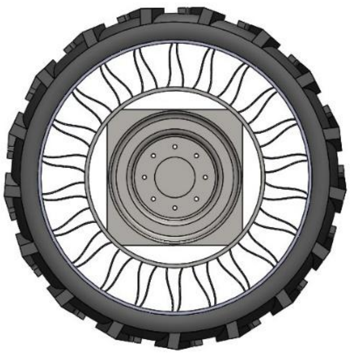

Fig. 1 Tweel based design for the rear wheel of a tractor.

The basic design of the Tweel based wheel is shown in Fig. 1. Designing is done using SolidWorks [14]. The wheel consists of 5 parts hub, rim, spokes, a reinforcement layer, and rubber treads. All parts are separate bodies for

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the purpose of analysis with solid merge feature turned off.

Table 3, Design specifications of the wheel for analysis purpose.

Component/Part	Dimension(mm)
Outer diameter of rubber layer	1290
Inner diameter of rubber layer	1082
Spoke length	172
Spoke curve offset	5
Spoke thickness	4-8
Rim outer diameter	712
Rim thickness	6
Hub diameter	175
Shaft diameter	85
Reinforcement layer	2-10

b) Designs used for Analysis

Three designs were used for static analysis purpose these are Tweel by Michelin (Fig. 1), Airless concept by Bridgestone (Fig. 2) and a honeycomb structured spoke by Resilient Technology (Fig. 3).

Fig. 2 Wheel based on Bridgestone Airless concept.

Bridgestone's concept consists of curved spokes that are made with circular arcs forming exactly 108° with constant chord length [15] which can then be offset to form the desired thickness of spokes. Ideally, the spoke thickness is 4mm for reinforcement characteristics study. The third type of wheel design used is a honeycomb structure introduced by Resilient Technology. This structure is made using a regular hexagonal structure with 5mm sides each. Ideally, the thickness of spokes made using this structure is 4 mm for the reinforcement layer characteristic study. All three wheel designs are studied, first, by varying spoke thickness and keeping the reinforcement layer thickness (3.5 mm) constant and then by varying reinforcement layer and keeping the spoke thickness (4 mm) constant.

Fig. 3 Wheel based on the honeycomb structure.

E. Analysis Settings and Meshing.

For analysis purpose, a rigid support made of concrete was introduced and all the simulations [17,18] were carried out on top of it. Displacement in lateral and longitudinal directions were set constant thus displacement only in the radial direction was allowed. A gradually increasing load of 5000 N was applied radially downwards to resemble standing load of a tractor and a load of 15000 N was applied to mimic the shock load representing a maximum force that a vehicle has to face under fully loaded conditions. Contact surfaces were made between spokes, reinforcement layer, and hub. A mesh dependent study was also done and a maximum deviation of 7.4% was observed for general analysis. Meshing (Fig. 4) was done using tetragonal and quadrilateral mesh method with relevance set to 10, mesh function was set as constant, relevance center was set as fine and refinement was applied at contact surfaces.

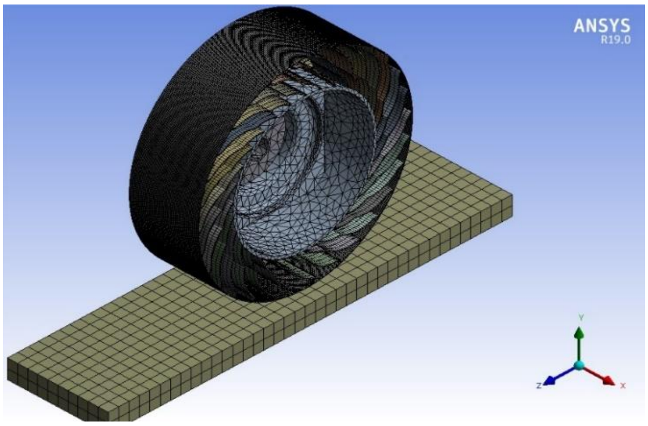

Fig. 4 Meshing in Airless Concept by Bridgestone, Reinforcement layer in direct contact with rigid support.

Deflection in spokes under different loads was taken and it was observed that deflection of all the designs varied significantly under similar loads. The following diagrams show deflection of different spokes design under the same loading conditions with the same spoke thickness and reinforcement layer thickness:

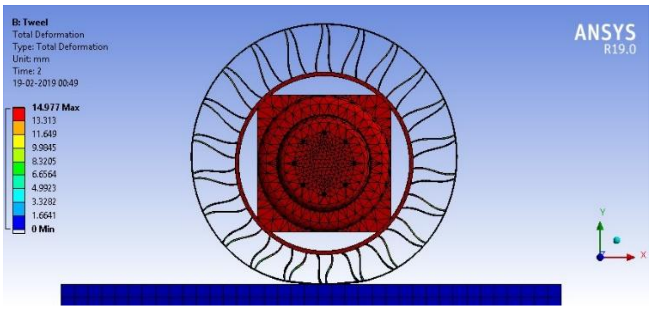

Fig. 5 Deflection in Tweel Design by Michelin

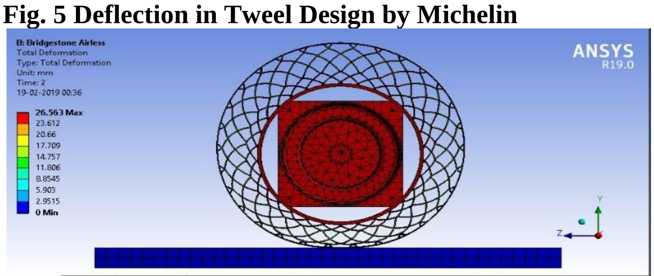

Fig. 6 Deflection in Airless Concept by Bridgestone

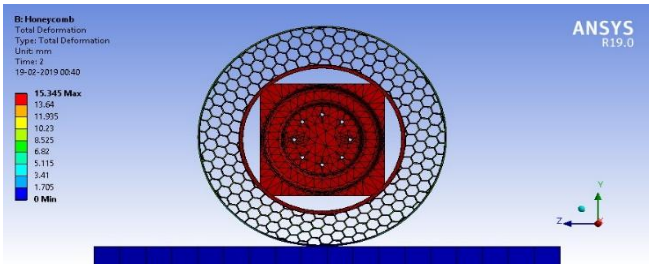

Fig. 7Deflection in Honeycomb Structure by Resilient Technology

Deflections in all the above structures were observed (Fig. 5, 6, 7) at a load of 15000 N, various parameters were calculated using the mathematical model which was generated and solved by Ansys. Different parameters such as Total Deformation, Directional Deformation, Maximum Shear Stress, and Contact Pressure were calculated using the workbench's solver and thus schematic comparison of different models were prepared.

V. RESULTS AND DISCUSSIONS

The analysis was done by varying two components from design i.e. spoke thickness and reinforcement layer thickness. Spoke thickness is varied from 4-10 mm and reinforcement layer is varied from 2-7.5 mm. All simulations were done under the same initial condition with the same load. Variation in deflection and stress were observed.

A. Analysis of Tweel

Deflection on Tweel is observed with varying loads. A load of 15000 N is applied as maximum load assuming the wheel is at maximum load condition i.e. 3/4th of the weight of vehicle which is supported by the rear wheel at that instance. The below graph (Fig. 8) shows the relation between force and deflection in Tweel for a varied thickness of reinforcement material. It can be observed that the graph does not follow a linear path rather this characteristic is due to the fact that the spokes are made of non-linearhyperelastic material, thus the path of the curve could not be effectively determined using conventional algorithms. As can be seen, the line with minimum deflection is the one with the thickest reinforcement layer as the reinforcement layer itself is made of coated wires. Thus it significantly reduces the deflection of the wheel. The spokes of Tweel are spline curves with a 5 mm distance from a reference line on either side. It can be seen that least deflection is with 7.5 mm reinforcement of about 4.41 mm which is very low considering other non-pneumatic tires.

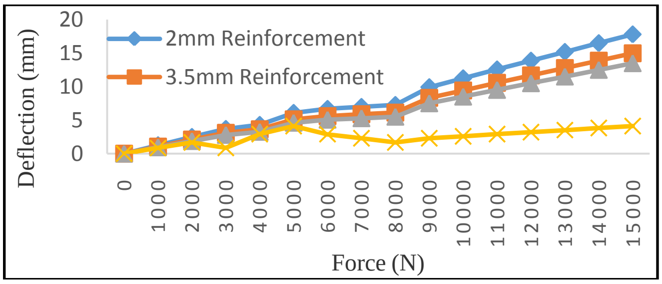

Fig. 8 Graph between Force (N) and Deflection (mm) for Tweel with varying thickness of reinforcement layer where 4 mm spoke thickness is constant.

It can be seen that the peak deflection on the graph is for 2 mm reinforcement and is 17.81 mm for a load of 15000 N. Similarly, the reinforcement layer with 3.5 mm and 5 mm thickness closely resembles the 2 mm curve.

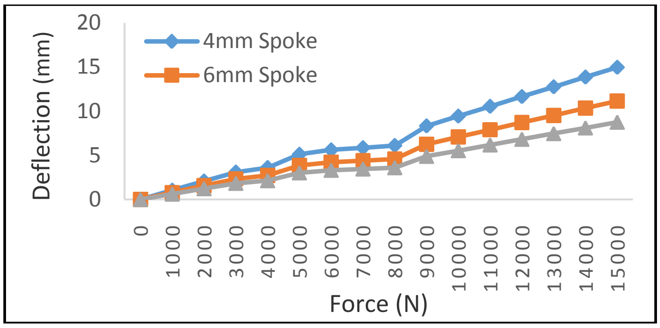

Fig. 9 Graph between Force (N) and Deflection (mm) for Tweel with varying spoke thickness where 3.5 mm reinforcement layer thickness is constant.

The above graph (Fig. 9) shows the effect of spoke thickness on the deflection of the wheel. Deflection in Tweel is primarily due to buckling effect and this buckling effect can be used for efficiently increasing the area of contact of the wheel and thus increasing the traction of the tractor. Here it can be seen that maximum deflection is observed with spoke with 4 mm thickness which is 14.97 mm. A lower thickness spoke could not be used for tractor specification as it will show large deflection under running conditions.

B.Analysis of Airless Tire Concept by Bridgestone

The below graph (Fig. 10) clearly shows the relation between the thickness of the reinforcement layer and deflection. As the thickness of the reinforcement layer increases the deflection decreases. A deflection of 30 mm would be sufficient for the smooth functioning of the wheel.But as it can be seen, deflection of up to 50 mm is observed for reinforcement layer of 2 mm. Thus it can be clearly said that for Bridgestone's model, optimal reinforcement layer thickness should be 5 mm for a corresponding deflection of 37.53 mm.

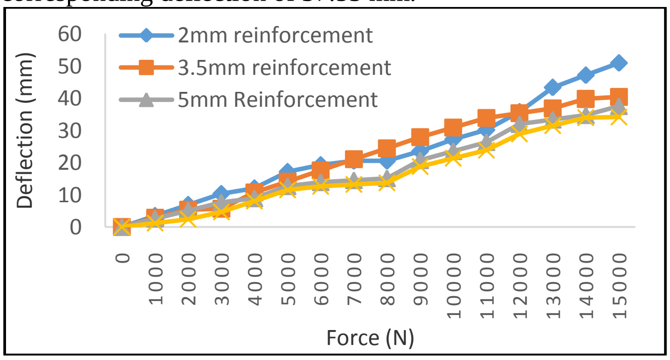

Fig. 10 Graph between Force (N) and Deflection (mm) for Airless concept by Bridgestone with varying thickness of reinforcement layer where 4mm spoke thickness is constant.

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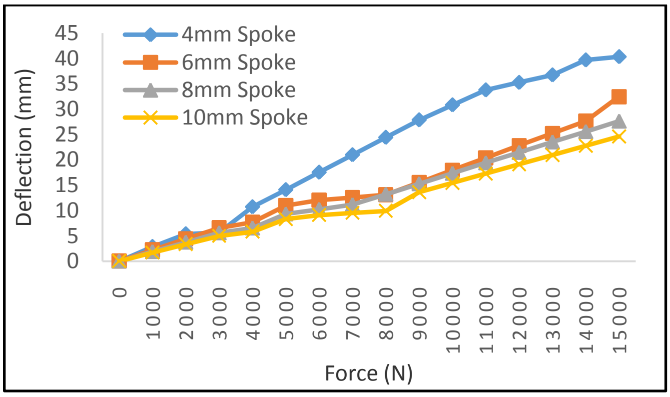

Fig. 11 Graph between Force (N) and Deflection (mm) for Airless Tire concept by Bridgestone with varying spoke thickness where 3.5 mm reinforcement layer thickness constant.

Deflection of the wheel based on spoke thickness can be seen (Fig. 11) most prominently in Bridgestone's non-pneumatic wheel concept. It reaches a maximum deflection of 40.35 mm under a load of 15000 N. Spokes with a thickness ranging from 6-10 mm exhibits similar characteristic deflection under similar load. Thus a spoke thickness of 6 mm would be sufficient for a smooth ride in tractor wheel.

C. Analysis of Honeycomb structure Tire.

In the below graph (Fig. 12) maximum deflection of the wheel from its ideal position under 15000 N is 26.56 mm. But strangely this deflection is observed in 3.5 mm thick reinforcement layer rather than the 2 mm reinforcement layer. This phenomenon can be accounted to interlocking of hexagonal spokes, this interlocking should have fluctuated the maximum deformation. At a load of 9000 N, it can be observed that both the curves cut each other beyond this load. Interlocking occurred due to buckling effect of hyperelastic material used.

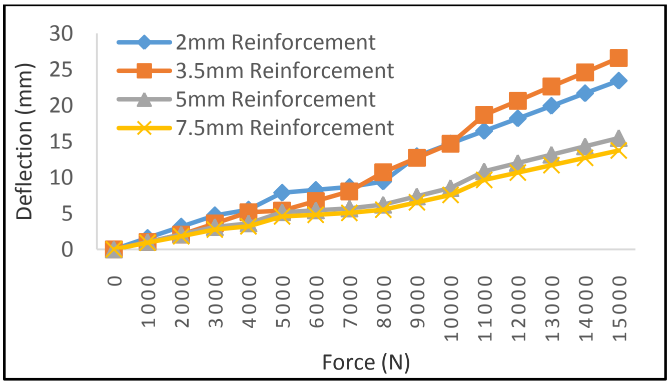

Fig. 12 Graph between Force (N) and Deflection (mm) for Honeycomb Structure with varying thickness of reinforcement layer where 4 mm spoke thickness is constant.

Graph (Fig. 13) shows the relationship between spoke thickness and deflection of the wheel for the honeycomb structure. Maximum deflection can be observed in spoke with minimum thickness i.e. 4 mm spoke.

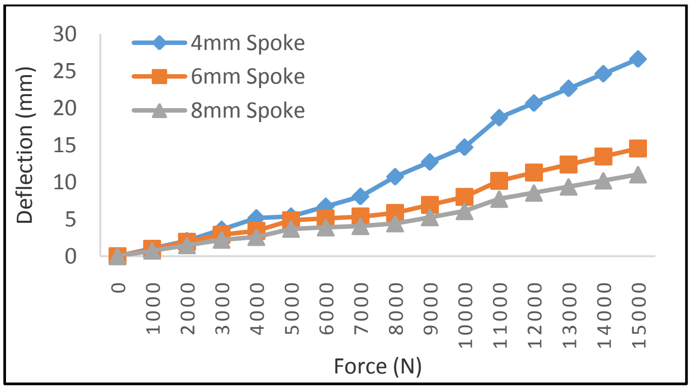

Fig. 13 Graph between Force (N) and Deflection (mm) for Honeycomb Structure with varying spoke thickness where 3.5 mm reinforcement layer thickness is constant.

It has a maximum deflection of 26.56 mm which is in expectable range. The 8 mm spoke shows a relatively low deflection of 11mm and thus it can be discarded among options. Thus 4 mm spoke in honeycomb structure shows near to ideal deflection range.

D. Comparison between the three designs

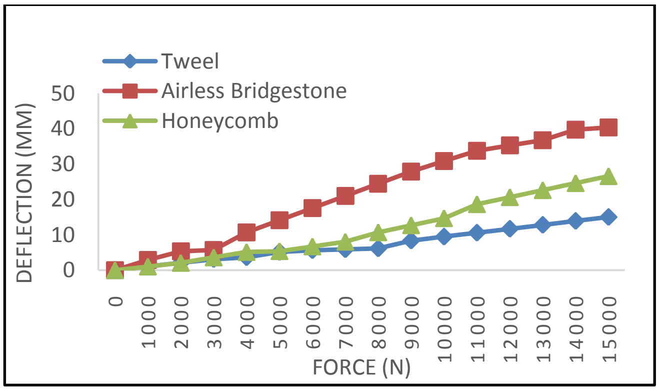

Fig. 14 Graph between Force (N) and Deflection (mm) for Tweel, Airless Tire Concept and Honeycomb Structure with a constant 3.5 mm reinforcement layer thickness and 4 mm spoke thickness.

The graph(Fig. 14) that is plotted above between force and displacement for different non-pneumatic tire designs is shown in figure 14. The maximum deflection of 40.35 mm can be observed in Airless tire because, in Bridgestone, the mid-section cut present in Airless Tire design contributes to the decrease in the overall area for force distribution. Also, the alternating direction of spokes helps in distributing the load more efficiently. Thus a higher deflection is observed. Honeycomb structure has the highest deflection after Bridgestone design. Honeycomb design exhibits both structural integrity as well as efficient load distribution. Thus having a maximum deflection of 26.54 mm. Tweel design by Michelin was found to have the least deflection under load that could be contributed to insufficient buckling that was observed with our assumed values but since actual composition and properties of polyresin used for manufacturing Tweel is still a trade secret, these properties can just be speculated.

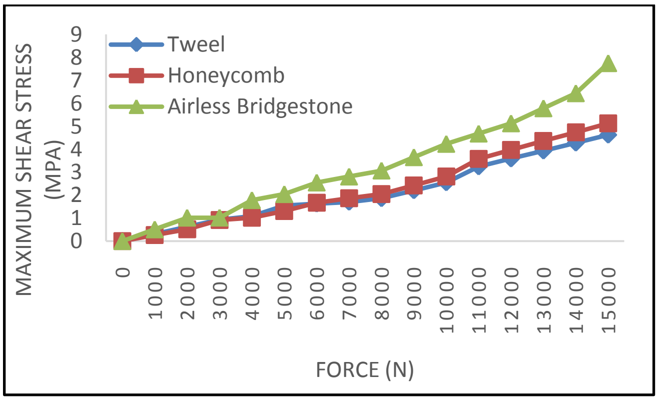

Fig. 15 Graph between Force (N) and Maximum Shear Stress (MPA) for Tweel, Airless Concept and Honeycomb Structure with a constant 3.5 mm reinforcement layer thickness and 4 mm spoke thickness.

The above graph (Fig. 15) shows the relationship between the applied force and the maximum shear stress observed in the spokes. Failure of spokes of non-pneumatic tire occurs due to fatigue stress developed in the spokes. When the spoke collapses repeatedly, it experiences shear stress and this shear stress leads to fatigue. Thus the failure of the spoke is due to the shear stress developed in it. Lower the shear stress developed, lower will be the chances of its failure. Based on this, Tweel spokes develop the least shear stress. Thus it has the least chance of having a shear failure.

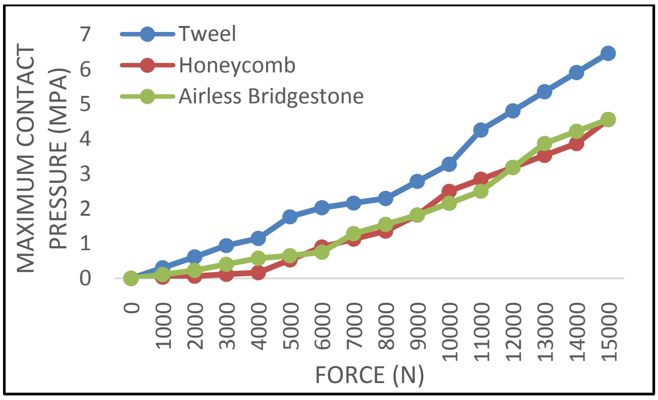

Fig. 16 Graph between Force (N) and Maximum Contact Pressure (MPA) for Tweel, Airless Concept and Honeycomb Structure with a constant 3.5 mm reinforcement layer thickness and 4 mm spoke thickness.

In the above graph (Fig. 16) is a plot between Force Vs Maximum Contact Pressure (MPa) is shown. As we know, Contact Pressure times Area gives load at that part, thus a lower contact pressure is always desirable. Here honeycomb structure and Airless Concept both follow an almost similar path. Thus both are better than Tweel in terms of lower contact pressure of about 4.55 MPa.

VI. CONCLUSION

The article presented here has three of the top non-pneumatic tire concepts with mathematical calculation and simulations using Ansys workbench. It is thus concluded that each tire concept, due to its distinct geometric structure, possesses different working characteristics for the same design parameters under specific requirements. Honeycomb structure by Resilient Technology performed superior with both adequate deflections on heavy load as well as lower shear stress development and lower contact pressure. Airless concept by Bridgestone showed the highest deflection with load and thus could be the best option for better ride comfort. It has to be stated that, presented conclusions are based on the material parameters assumed by us, as material properties of polyurethane based polyresin are still one of the best-kept company secrets. Thorough experimentation with both simulations and prototypes are needed to get to a concrete result.

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