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Static analysis of a P195/55 R16 85H radial tire developed from natural rubber/tea seed oil (*Camellia sinensis*) modified kaolin vulcanizates

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Abstract

This paper deals on the static structural analysis of a P195/55 R16 85H radial tire developed from Natural Rubber/Tea seed oil (*Camellia sinensis*) modified kaolin composite using ANSYS Workbench 14.0 software. The kaolin modification was achieved by intercalation in the presence of hydrazine hydrate as co-intercalate. The tire model investigated was developed using CREO Elements/Pro E and the geometry imported into ANSYS Workbench 14.0.The material parameters characterizing the linear isotropic elastic behaviour of rubber vulcanizates were established. The study was developed on maximum inflation pressure of 32psi (≡0.2206 MPa) and maximum Force of 5150N from the load index obtained from the tire load index. The 3D FE model computations for static loading of the tire gave reasonably good prediction of the functionality of the tire material developed, as the von Mises stress value of 878810 Pa obtained on maximum inflation is higher than the applied maximum inflation pressure of 32psi (≡ 0.2206 MPa) and the von Mises stress value of 611330 Pa obtained on application of vertical load of 5150 N is higher than the specified pressure on vertical loading.

Keywords

Radial tire, Stress, Strain, Finite Element Analysis, Natural Rubber, Kaolin

1. Introduction

Computational mechanics is the study concerned with the use of computational methods to study phenomena governed by the principles of mechanics. This study is now applied in vehicle tire studies following the emergence and proliferation of sophisticated CAD and FE softwares commercially in the market.

A tire is a complex composite structure which consists of many layers of synthetic polymer, flexible filaments of high modulus cord and glass fiber, which are bonded to a matrix of low modulus polymeric material that pneumatically supports the vehicle load. Tires are employed in most vehicles, such as bicycles, motorcycles, tricycles, cars, trucks, earthmovers and aircrafts.

The pneumatic tire is an elastic structure that holds the pressure of the inflated air together with the rim. Tires reduce vibrations from caused from unevenness in the road surface. The tire structure is covered with a wear resistant rubber compound, often styrene-butadiene, to protect the carcass and to build up the friction to the road [1].

Most Natural and synthetic rubbers produced in the world are utilized in the tire industry. The excellent air retention properties of butyl/halo butyl and chemically modified Natural Rubbers with incorporated clays are very well known in the tire industries as these composites are widely used in the inner tube, inner liner and sidewalls in vehicle tires for improving many properties such as tensile, tear resistance, rolling resistance, dimensional stability, improved flame resistance and enhanced air retention.

2. Background of the Study

Tire history could be traced to the discovery of the rubber vulcanization process by Charles Goodyear in 1839. In the year 1845, Robert W. Thomson patented the idea of using air-filled rubber tubes as tires but the invention did not last due to lower durability of the invented tire. John Boyd Dunlope in the year 1888 re-invented the pneumatic tire claiming of no knowledge about the prior patent. This new patent was mainly directed for bicycles, but the advantages of using pneumatic tires also for cars were successfully examined by many researchers including the Michelin brothers- André and Édouard Michelin. They competed with a car equipped with pneumatic tires in the 1895 Paris-Bordeaux road race. Although the Michelin brothers did not win the race; they gained a lot of interest due to the new type of tires developed [1-2].

A lot of studies and researches relating to Finite Element Modeling (FEM) and analysis of stress-strain distribution in vehicle tires of different shapes, sizes, material characteristics and operating conditions have been conducted. Finite element analysis (FEA) is a powerful and economical method that has been used widely for engineering design purpose [3]. FEA are employed in tire design to predict and improve the mechanical behavior and durability of tires. The initial tire models are always built for structural static analysis which is primarily used for checking the load capacity of tire, validity of finite elements and software or the level of mesh refinement [4].

Mohsenimanesh et al. [5] investigated the stress analysis of a tractor tire using Finite Element Analysis. In their study, the modelling process was based on the 3D pressure fields obtained from the non-linear static stress analysis of finite element tire model, which considers the structural geometry, the anisotropic material properties of multiple layers and the nearly incompressible property of the tread rubber block.

Ghoreishy et al. [6] developed a 3D finite element model for the modeling of a P155/65R13 steel-belted tire under inflation pressure, vertical static (footprint) load, and steady state rolling. The model was created for the ABAQUS/Standard code and used to carry out a series of parametric studies.

Yan et al. [7] performed a research on the analysis of a radial tire using a Finite Element Method. In their study, a new mathematical model on extension propagation of interface crack in complex composite structures was developed.

In this present study, the FE software (ANSYS 14.0) was employed in the static analysis of a P195/55 R16 85 H radial tire subjected to maximum inflation pressures. The main objective of the study is to determine the functionality of Natural Rubber/Tea Seed Oil (*Camellia sinensis*) modified Kaolin vulcanizates as tire material under maximum inflation and static loading for the specified tire size. A 3D geometric model was developed using CREO element/Pro E and was imported into FE software for analysis and simulation.

3. Methodology

3.1. Materials

Kaolin (BCK grade) used in this work was obtained from English Indian Clays Ltd. Thiruvananthapuram, India; Tea seed oil (TSO) and Natural Rubber (RSS V grade) were provided by NIIST, CSIR, Thiruvananthapuram, India; Laboratory grades of Sodium hydroxide (MERCK) and Hydrazine hydrate (FINNAR) were obtained from local suppliers.

3.1.1. Conversion of TSO into its Sodium Salt

Sodium salt of tea seed oil (Na-TSO) was synthesized by reacting 2.8 mL of TSO with 2.7 mL of 20% NaOH in an ice bath with constant stirring for 12 hours and kept for 1 day to allow for curing to take place. The pH of the resulting solution was maintained at 8-9. TSO was then introduced into a separating funnel and washed with water to remove excess base. This was then dried in a hot air oven to remove residual moisture and powdered [8-9].

3.1.2. The Synthesis of TSO-Modified Kaolin

9.8 g of Kaolin was slowly added to a mixture-containing 2 g of Na-TSO, 7mL hydrazine hydrate with vigorous stirring at 20^{o}C. The mixture was homogenized well using an Art-MICCRA D-8 (Germany) homogenizer, and the sample was dried using a freeze drier [HetroTrap-CT60e, JOUAN]. The sample was designated as MTK [8-9].

3.1.3. Preparation of Rubber Vulcanizates

Natural Rubber was first laminated for about 10 minutes in an open two-roll mill to a temperature of 40 °C. The rubbers were further blended with accelerants, activators, the TSO modified kaolin, softeners and finally, Sulphur was added. The mixtures were plasticized for about 15 minutes and thin-passed several times at 90°C. The obtained Natural Rubber/TSO modified Kaolin compounds were allowed to cure. Rubber vulcanizates sheets of were prepared by compression molding of the mixes at 140°C for 10 min on an electrically heated, semi-automatic hydraulic press (MODEL INDUDYOG DS-SD-HMP/25) at 400 Pa and curing takes place at the same temperature and pressure [9]. Replicates of the vulcanizates were prepared by melt blending and subjected to uniaxial tensile tests to ascertain their material properties as explained in the composition of Table 1.

Table 1. *Composition of the Rubber Compounds*

Ingredients (phr)	MTK
Natural Rubber	100
Zinc Oxide	5
Stearic Acid	2
MTK	10
MBT	2
Sulphur	2

MTK is the TSO-modified Kaolin; MBT is Mercapto Benzothiazole.

3.2. Failure Computations

The Hencky-von Mises stress (otherwise known as the Distortion Energy Theory (DET)) is chosen for the FE implementation and is expressed as [10]:

$$\tau_0 = \frac{1}{3}[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2]^{1/2} \quad (1)$$

This can be expressed in terms of orthogonal component stresses as

$$\tau_0 = \frac{1}{3}\left[\left(\sigma_x-\sigma_y\right)^2+\left(\sigma_y-\sigma_z\right)^2+(\sigma_z-\sigma_x)^2+ 6\tau xy2+\tau yz2+\tau zx212 \right. \quad (2)$$

The distortion energy at yielding for a tensile test is obtained as:

$$U_d = \frac{1+\mu}{3E}(\sigma_1^2+\sigma_2^2+\sigma_3^2-\sigma_1\sigma_2-\sigma_2\sigma_3-\sigma_1\sigma_3) \quad (3)$$

The term σ' is referred to as the von Mises stress.

Where,

$\sigma_1, \sigma_2, \sigma_3$ = are the ordered principal stresses,

$\sigma_x, \sigma_y, \sigma_z$ = are the orthogonal stresses in x, y and z-directions respectively,

$\tau_{xy}, \tau_{yz}, \tau_{zx}$ = are the orthogonal shear stresses,

S_y = uniaxial yield stress,

σ' = von Mises stress,

n =design safety factor.

$\mu =$ Poisson's ratio

This means that with the following material properties: Elastic modulus E and Poisson's ratio μ, the orthogonal stresses and principal stresses can be determined in a finite element solver system. The strain-displacement relationships which are also determined by the FE solver are expressed as:

$$\varepsilon_x = \frac{\partial u}{\partial x}, \varepsilon_y = \frac{\partial v}{\partial y}, \varepsilon_z = \frac{\partial w}{\partial z} \quad (4)$$

In this study, the following assumptions were made in the development of the model:

- Linear isotropic elastic stress-strain behaviour is assumed for the tire material investigated.
- The tire model developed is assumed to have a smooth tread pattern to avoid of excessive computational time and efforts.
- A maximum inflation pressure of 32psi (≡ 0.2206 MPa) for vehicle tire size, P195/55 R16 85H was used in the analysis.
- The maximum load capacity from the tire's load index which was found to be 515kg was applied to the tire.

The vehicle tire sidewall gives useful details about the tire. The alphanumeric ISO Metric tire designation for the tire size P195/55 R16 85H investigated is as follows:

P: Passenger tire, 195: Nominal Section Width (measured in millimeters), 55: Aspect Ratio (ratio of the height of the tire's cross section, to its width), R: Carcass construction (R for Radial), 16: Rim Diameter (measured in inches), 82: Load Rating (Service Description, from Load Index table = 515Kg), H: Speed Rating (Service Description, from Speed Symbol table=210km/h).

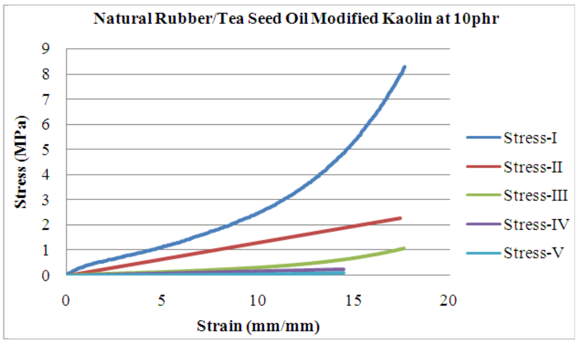

Figure 1. *Stress-Strain plot of Natural Rubber/Tea Seed Oil modified Kaolin composites at 10phr*

Table 2. *Material Properties of Natural Rubber/Tea Seed Oil modified Kaolin composites*

Property	Value
Elastic modulus, E	0.022MPa
Poissons ratio, v	0.47
Ultimate tensile strength S_{ut}	0.7875MPa
Yield strength, S_{yt}	0.04MPa

3.3. Finite Element Tire Model

3.3.1. Tire Geometry

The new tire material developed is a hyperelastic material with very large deformations upon loading. The element type selected for FEA of the 3D tire model is SOLID186 which was implemented on ANSYS 14.0 workbench program. The 3D model of the vehicle tire was developed by means of Creo Elements/Pro 5.0. Figure 1 illustrates 3D physical model for the radial pneumatic tire developed using Creo Elements/Pro 5.0 program, which takes into consideration all the details on tire sizes as shown in table 3. The geometrical model developed using Creo Elements/Pro 5.0 program was imported in ANSYS 14.0, this results into the meshed model of FEM analysis in Figure 3. The 3D meshed tire model has 12082 nodes and 2158 elements.

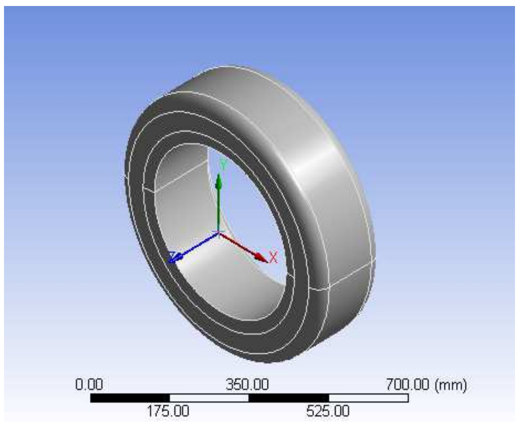

Figure 2. *Physical tire model*

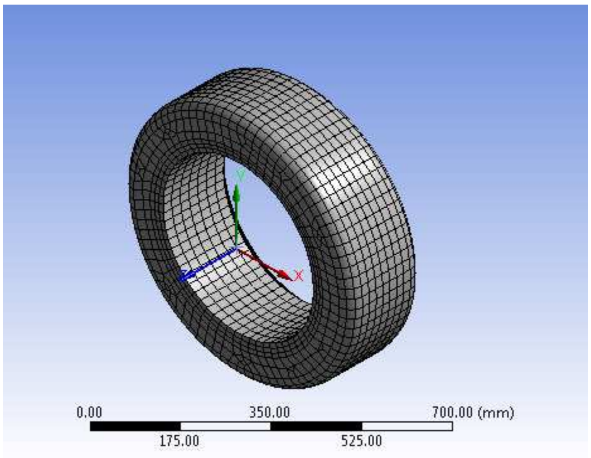

Figure 3. *Meshed tire 3D model*

Table 3. *Tire geometry specification for a P195/55 R16 85H*

Specification	Dimension(mm)
Sectional width	195
Rim diameter	410
Outer diameter	624

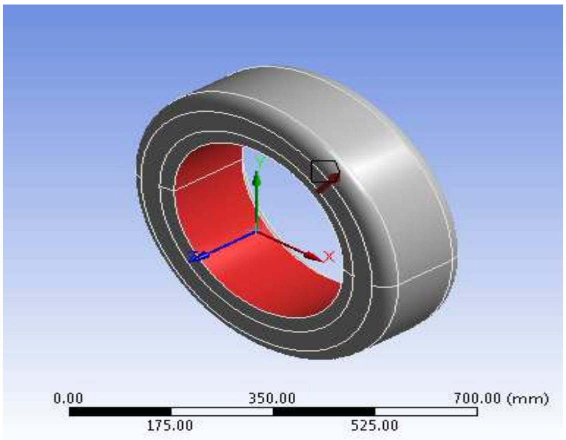

Figure 4. *Maximum inflation pressure applied*

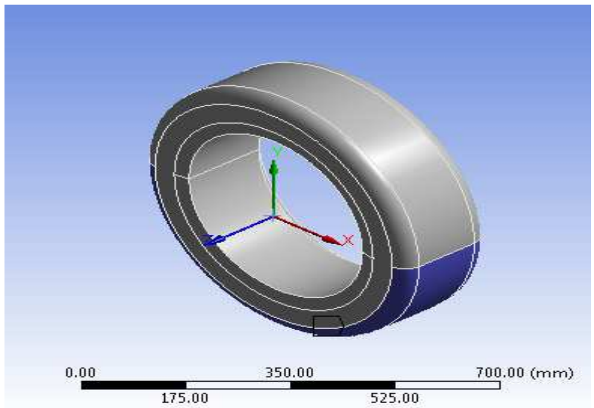

Figure 5. *Constraint applied to tire model internally*

3.3.2. Boundary Conditions

A uniform maximum inflation pressure of 0.2206MPa was applied on the internal surface of the tire investigated. A constraint was applied on the tire ground surface and a force of 5.15 KN which is the maximum load carrying capacity for the tire as stipulated in the tire's load index was applied on the same surface to simulate real conditions of loaded tire.

3.3.3. Numerical Analyses

The analyses were performed using ANSYS 14.0 Workbench based on static structural analysis. The inflation analysis was performed on the 3D model. The static analysis of the tire also involves the application of a vertical force on the tire.

4. Results and Discussions

4.1. Total Deformation of the Tire

The total deformation of the 3D tire model and the magnitude of inflated shape displacements and vertical loading are shown in Figures 6 and 7. The deformation under maximum inflation is large in the area of sidewalls with a maximum value of 15.561 m and very small in the constrained tread area with 0 m. This observation may be due to increased reinforcement layers under the tread area.

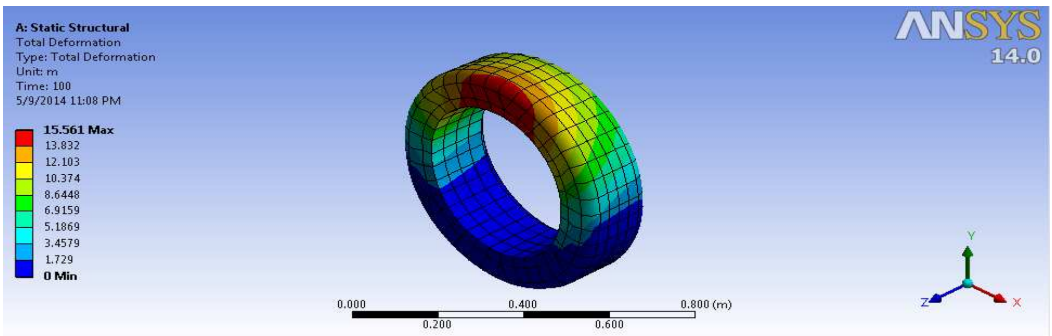

Figure 6. *Total deformation of inflated tire*

The shape of the 3D tire model in contact with the ground under the 5150 N load and the magnitude of tire vertical displacements are shown in Fig. 7.The total deformation obtained on the tire tread area under vertical loading of 5150N is 15.597 m.

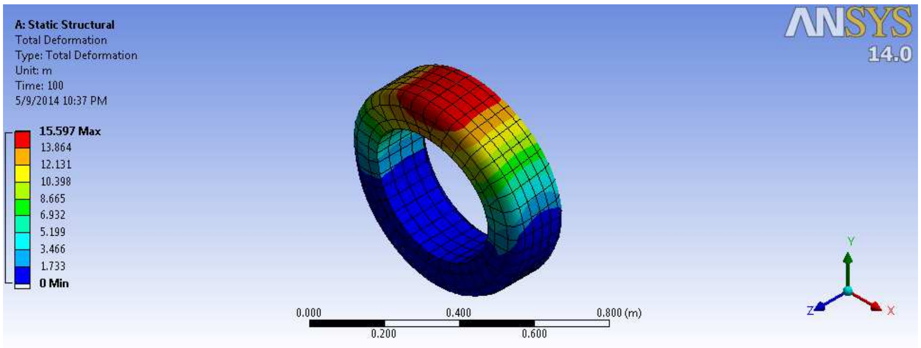

Figure 7. Tire Deformations under Vertical Load

4.2. Von-Mises-Hencky Stresses (Effective Stress) of the Tire

The von-Mises-Hencky stresses of the tire for maximum inflation tire and vertical loading are shown in Figures 8 and 9. The von-Mises stress was obtained as 0.87881 MPa for a maximum inflation pressure of 0.2206 MPa and 0.61133 MPa for the applied vertical load of 5150 N.

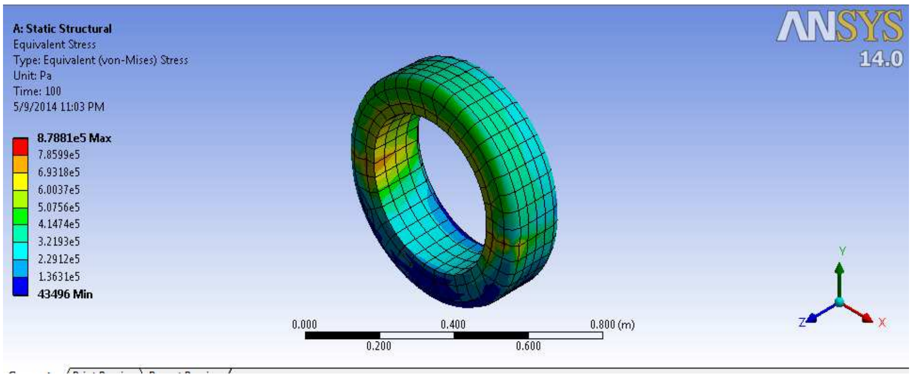

Figure 8. Von-Mises-Hencky Stresses for Maximum Inflation Pressure

The von Mises stresses obtained are within the limits of the ultimate strength of the material obtained as 0.7875MPa. When any of the local stresses is higher than the specified material's ultimate strength, prediction is recommended to be based on the Distortion Energy Theory (DET) that is the von Mises criteria or on the Maximum Shear Stress Theory (MSST) also known as Tresca yield criterion which states that a part subjected to any combination of loads will fail (by yielding or fracturing whenever the maximum shear stress exceeds a critical value.

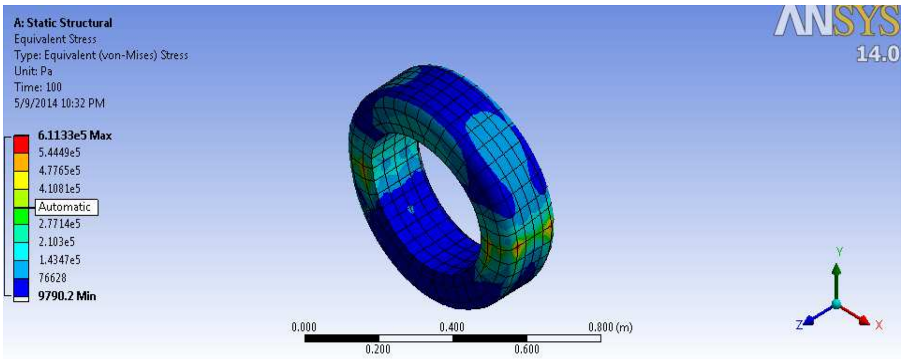

Figure 9. von-Mises-Hencky stresses for vertical loading

This result indicates that the tire material developed for tire size P195/55 R16 85H can withstand loads and inflation pressures above the recommended values for the tire size. The result obtained is due to the tea seed oil used for the organomodification of the kaolin fillers.

4.3. Directional Deformation of the Tire

The directional deformations of the tire are shown in figures 10 and 11 for the vertical loading and maximum inflation cases. The maximum directional deformation under vertical loading is 2.167m while the minimum directional deformation is -2.178m as specified in fig.10. For maximum inflation as specified in fig. 11, the maximum directional deformation is obtained as 4.603m while the minimum directional deformation is obtained as -4.597m all situated around the thread area and sidewalls.

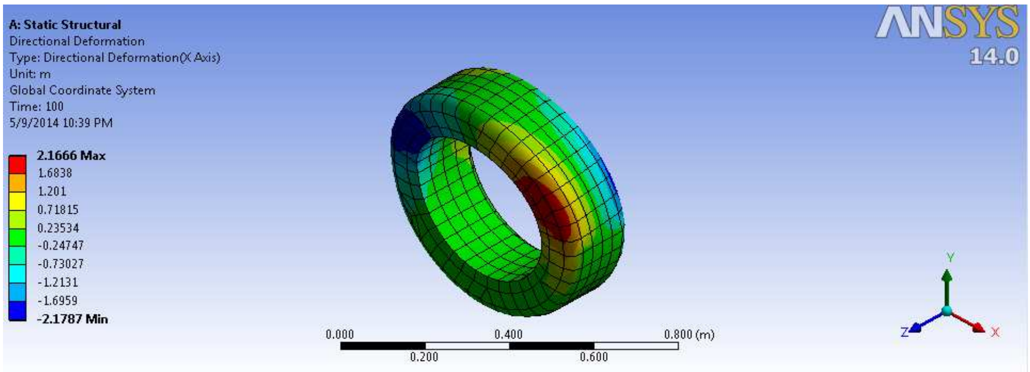

Figure 10. *Directional deformations for vertical loading*

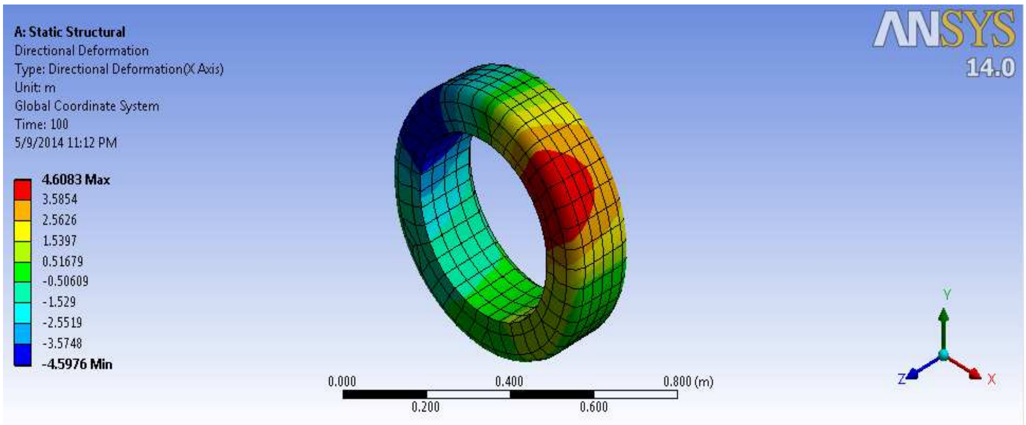

Figure 11. *Directional deformations for maximum inflation*

4.4. The Maximum Principal Stresses of the Tire

The maximum principal stresses of the tire are shown in figures 12 and 13 for vertical loading and maximum tire inflation respectively. The maximum principal stress is obtained as 0.8272MPa for vertical loading and 1.069MPa for maximum inflation. The obtained maximum principal stresses were found to be above the applied stress under inflation given as 0.2206MPa for the specified tire load index. The situation where the applied orthogonal and principal stresses are higher than the ultimate strength of material is unacceptable, so that design engineer must apply load based on von Mises stresses not exceeding the ultimate strength of material. However, the ultimate strength of the Natural Rubber/Tea Seed oil modified kaolin composites was obtained as 0.7875MPa from the tensile test conducted on a sample of the composite. This indicates that the material developed is within the design limits.

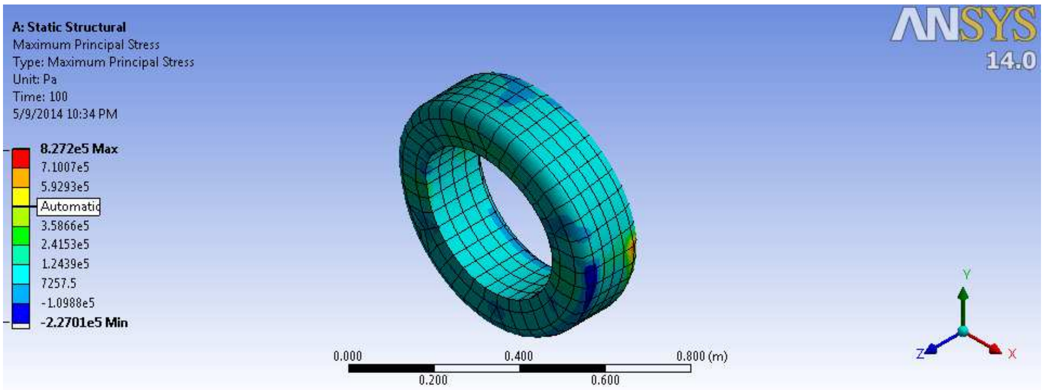

Figure 12. *Maximum Principal Stress for vertical loading*

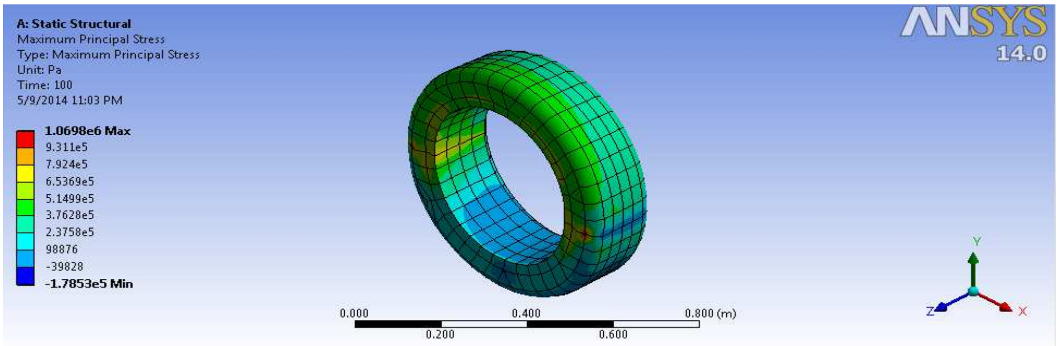

Figure 13. *Maximum Principal Stress for maximum inflation*

5. Conclusions

Finite Element method was employed for investigating the functionality of Natural Rubber/Tea seed oil Organomodified kaolin vulcanizates developed for P195/55 R16 85 H pneumatic tire subjected to static loading. From the present study, the following conclusions were made:

1. Static structural analysis performed in this study offered a good analytical evaluation of the tire material studied and is recommended for the use in tire design.
2. The vertical loading and maximum inflation pressures provided the total deformations of 3D tire model.
3. The P195/55 R16 85 H pneumatic tires analyzed using the new tire material developed was found to require a lower load index over the load index specified for the tire size.
4. It was also observed that the localized stresses obtained in this study such as principal stresses and von Mises stresses are acceptable and within the limits of the ultimate strength of the material investigated and can be used to improve the design of pneumatic tires.
5. Tea seed oil used in the organomodification of kaolin was found to be responsible for the outcome of the study in respect to obtained results.

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