Static Analysis of Tyre Model developed from Natural Rubber Vulcanizates

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Abstract—This paper is on the static analysis of a tyre model developed from Natural Rubber vulcanizates using ANSYS Workbench 14.0 software. The pristine kaolin used as filler material in the Natural Rubber vulcanizates was oleo chemically modified from Rubber Seed Oils (Heveabrasiliensis) by intercalation which was achieved in the presence of hydrazine hydrate as co-intercalate. A typical P195/55 R16 85H tyre model was developed and the factors describing the linear isotropic elastic behaviour of rubber vulcanizates were established. The Finite Element Analysis was developed on maximum inflation pressure of 0.2206 MPa and maximum load capacity of 515kg obtained from the tyre size specification load index. The results obtained from the study show that the tyre material developed from Natural Rubber/Organomodified kaolin will perform well under static structural analysis, as the von Mises stress value of 1.0105MPa obtained on maximum inflation is lower than the applied maximum inflation pressure of 0.2206 MPa and the von Mises stress value of 0.9448 MPa obtained on application of vertical load of 5.15kN is lower than the specified pressure on vertical loading.

Index Terms—Tyre, Stress, Natural Rubber, Kaolin

I. INTRODUCTION

Tyres are utilized in many types of vehicles, such as bicycles, motorcycles, tricycles, cars, trucks, earthmovers and aircrafts. It enhances vehicle performance by providing traction, braking, steering, and load support. Tyres cushion the effect between the vehicle and the road, and make a comfortable ride. The vehicle tyre has many functions which include supporting the load of the vehicle and providing load carrying capacity; transmission of the forces which drive brake and guide the vehicle, acting as the secondary suspension to absorb the effect of road irregularities before transmitting the forces to the vehicle suspension, provision of cushioning and dampening effects, provision of cornering force, provision of dimensional stability, resistance to abrasion, low rolling resistance, minimum noise, and minimum vibration and durability throughout the expected life span [1].

The structure of the tyre is very complex. It consists of several layers of synthetic polymer, many flexible filaments of high modulus cord, and glass fiber, which are bonded to a matrix of low modulus polymeric material. A tyre acts as a spring between the rim and the road. This spring characteristic is very important to the vehicle's ride.

II. BACKGROUND OF THE STUDY

There are several studies conducted on Finite Element Modeling (FEM) and analysis of stress-strain distribution in vehicle tyres of different shapes, sizes, material characteristics and operating conditions. FEM can be used in tyre design to predict and improve the mechanical behavior and durability of tyres. The initial tyre models are always built for structural static analysis which is primarily used for checking the load capacity of tyre, validity of finite elements and software or the level of mesh refinement [2].

With the availability of different FEA software's and solvers, the use of FEM for the analysis of vehicle tyres is still a major challenge in the field of computational mechanics. FEM for pneumatic tyres is a complex process which involves complicated 3D geometry of the tyre size to be analyzed, the material properties of the composite materials which constitute the tyre, the various loading and boundary conditions and finally the very large deformations and large strains.

Ghoreishy [3] conducted a study on Finite Element Analysis of a 6.45-14 bias tyre under contact load. In his study, a nonlinear Finite Element model was developed for the bias tyre under inflation pressure and contact loads which was implemented using a pre-processor program for NSTAR which is the nonlinear module of COSMOS/M software. Mohsenimanesh et al. [4] conducted a study on the stress analysis of a tractor tyre 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 tyre model, which considers the specimen structural geometry, the anisotropic material

Manuscript received March 22, 2016; revised April 08, 2016. This work was supported by National Institute for Interdisciplinary Science and Technology, Thiruvananthapuram, Kerala, India.

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ISBN: 978-988-14048-0-0
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

properties of multiple layers and the nearly incompressible property of the tread rubber block.

Yan et al. [5] performed a research on the analysis of a radial tyre using a Finite Element Method. In their study, a new mathematical model on extension propagation of interface crack in complex composite structures was developed. A number of commercial finite element (FE) softwares have been used for the analysis of vehicle tyres such as PAM SHOCK, LS DYNA NASTRAN, ALGOR, ADINA, MARC, ABAQUS, COMSOL Multiphysics, COSMOS/M, MIDAS NFX, and ANSYS [6-9].

In this present study, the FE software (ANSYS 14.0) was used to analyze a P195/55 R16 85 H radial tyre subjected to maximum inflation pressures and static loading. The main objectives of this study are to ascertain the functionality of the new tyre material developed under inflation and static loading for the specified tyre load index and the determination of the deformed shapes and stress components under loads. A three-dimensional finite element model was developed using CREO element/Pro E to simulate the structure of the tyre.

III. METHODOLOGY

A. Materials

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

B. Conversion of RSO into its sodium salt

Sodium salt of rubber seed oil (RSO) was prepared by mixing 33 mL of RSO with 100 mL of 20% NaOH solution in an ice bath along with continuous stirring for half a day. The resulting mixture was kept for 1 day to cure. The final pH of the resulting solution was adjusted to 8–9. The RSO was washed with water to remove excess of NaOH. This was followed by removal of excess water by heating at 120^{o}C for few hours in a hot air oven. The product was powdered.

C. Synthesis of RSO modified kaolin

9.8 g of Kaolin was slowly added to a mixture-containing 10 g of Na-RSO and 7mL hydrazine hydrate with vigorous stirring at 20^{o}C. The mixture was homogenized using an Art-MICCRA D-8 (Germany) homogenizer, and the sample was dried using a freeze drier [HetroTrap-CT60e, JOUAN]. The dried sample is designated MRK.

D. Preparation of Rubber Vulcanizates

Natural Rubber was initially masticated for 5-10 min in the open two-roll mill around 30–40 °C and blended with accelerants, activators, the RSO modified kaolin, softeners and lastly, Sulphur was added. The recipe of the mixes is given in Table 1. The mixture was homogenized by passing six times end on at room temperature. The obtained Natural Rubber/RSO modified Kaolin compounds were allowed to mature at room temperature for 24 hours. Rubber vulcanizates sheets were prepared by compression molding 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 pressure. Specimens of the vulcanizates were punched out from the molded sheets and subjected to uniaxial tensile tests to ascertain their material properties.

Table 1 Recipe of the Rubber Compounds

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

MRK is the RSO-modified Kaolin; MBT is MercaptoBenzothiazole.

E. Failure analysis

The classical failure theory adopted for the FE implementation is the distortion-energy (or Hencky-von Mises) theory (DET) which 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

$$\tau_0 = \frac{1}{3}\left[\left(\sigma_x-\sigma_y\right)^2+\left(\sigma_y-\sigma_z\right)^2+(\sigma_z-\sigma_x)^2 + 6\left({\tau_{xy}}^2+{\tau_{yz}}^2+{\tau_{zx}}^2\right)\right]^{1/2} \quad (2)$$

However, the limiting value of the octahedral shear stress is that which occurs during uniaxial tension at the onset of yield. This limiting value is expressed as:

$$\tau_0 = \frac{\sqrt{2}S_y}{3} \quad (3)$$

Re-expressing equation (3) in terms of the principal stresses and a design factor, we have

$$\frac{S_y}{n} = \frac{3}{\sqrt{2}}[\tau_0]\text{lim} = \frac{1}{\sqrt{2}}[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2 + (\sigma_3-\sigma_1)^2]^{1/2} = \sigma^{'} \quad (4)$$

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

$$U_d = \frac{1+v}{3E}(\sigma_1^2+\sigma_2^2+\sigma_3^2-\sigma_1\sigma_2-\sigma_2\sigma_3-\sigma_1\sigma_3) \quad (5)$$

The term $\sigma^{'}$ 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,

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

S_y = uniaxial yield stress,

ISBN: 978-988-14048-0-0
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

σ' = von Mises stress,
n =design safety factor.
v = Poisson's ratio
This implies that with the material properties of elastic modulus E and Poisson's ratio μ, the orthogonal stresses and principal stresses can be estimated in a finite element solver system. Also implemented is the strain-displacement relationships expressed as:

$$\varepsilon_x = \frac{\partial u}{\partial x}, \varepsilon_y = \frac{\partial v}{\partial y}, \varepsilon_z = \frac{\partial w}{\partial z} \quad (6)$$

This analysis includes the evaluation of yield stresses obtained as von Mises stresses, orthogonal stresses and etc. In this work ANSYS 14.0 Workbench was used to solve for plane stresses and subsequently the yield stress distribution. Following the experimental data generated from stress-strain analysis of the material to establish the material property as shown in Table 2 and figure 1. The classical failure theory adopted for the FE implementation is the distortion-energy (von Mises) theory (DET).
The following assumptions were made in the development of this model:

- Linear isotropic elastic stress-strain behavior is assumed for the tyre material investigated.
- The tyre model developed is assumed to have a smooth tread pattern to avoid of excessive computational time and efforts.
- The maximum inflation pressure of 32psi for vehicle tyre size of P195/55 R16 85H was used in the analysis.
- The maximum load capacity from the tyre's load index which was found to be 515kg was applied to the tyre.
- The tyre contact surface is assumed frictionless surface in this analysis.

The tyre sidewall gives information about the tyre construction, dimensions, load carrying capacity, speed rating, and manufacturer production codes. The ISO Metric tyre designation for the tyre size **P195/55 R16 85H** investigated is as follows:
P: Passenger tyre, **195:** Nominal Section Width (measured in millimeters), **55:** Aspect Ratio (ratio of the height of the tyre'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).

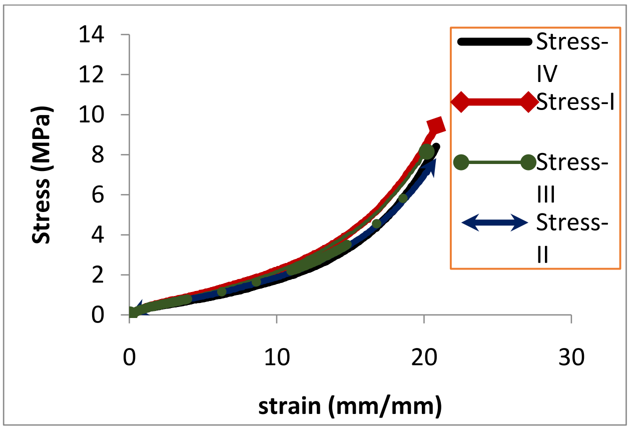

Fig. 1. Stress-Strain plot of NR/Rubber Seed Oil Modified Kaolin at 10phr

F. Finite Element Tyre Model
Tyre Geometry
The tyre material developed is a hyper-elastic material with very large deformations upon loading. The element selected for analyzing the rubber material was SOLID186. ANSYS 14.0 workbench program was used for the Finite Element Analysis of 3D model. The 3D model of the vehicle tyre was developed by means of Creo Elements/Pro 5.0. Figure 2 illustrates 3D physical model for the radial pneumatic tyre developed using Creo Elements/Pro 5.0 program, which takes into consideration all the details on tyre sizes as shown in table 3. The geometrical model developed using Creo Elements/Pro 5.0 program was imported in ANSYS 14.0.Figure 3 shows the meshed tyre model for FEM analysis. The 3D meshed Tyre model has 12082 nodes and 2158 elements.

Table 2 Material Properties of Natural Rubber/Organomodified kaolin Composites

Property	**Value**
Elastic modulus, E	0.0207 MPa
Poisson ratio, v	0.47
Ultimate tensile strength S_{ut}	1.3359MPa
Yield strength,S_{yt}	0.04MPa

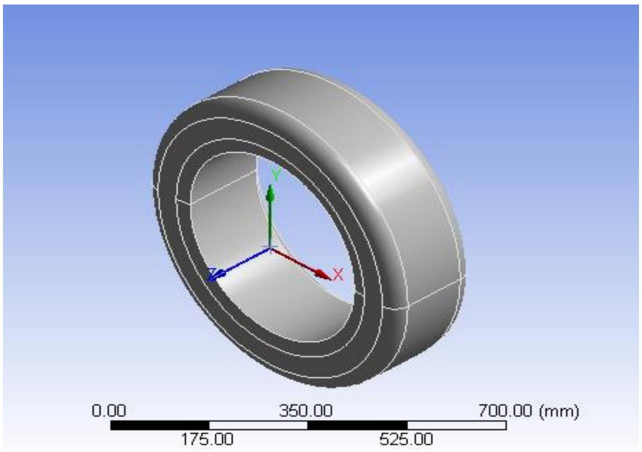

Fig.2. Physical Tyre model

ISBN: 978-988-14048-0-0
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

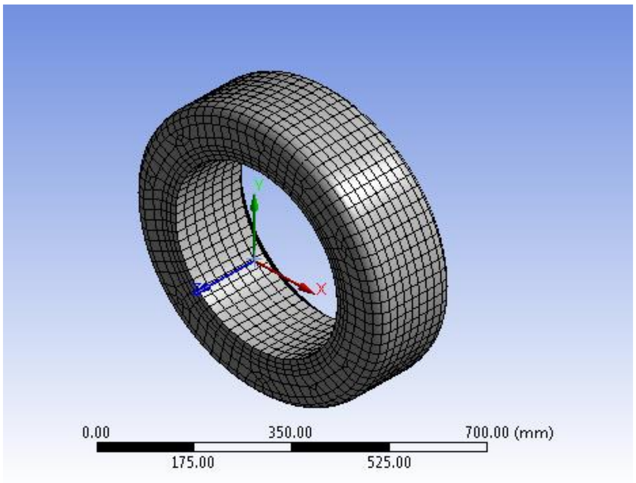

Fig. 3 Meshed Tyre 3D model

Table 3 Tyre geometry specification for a P195/55 R16 85H

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

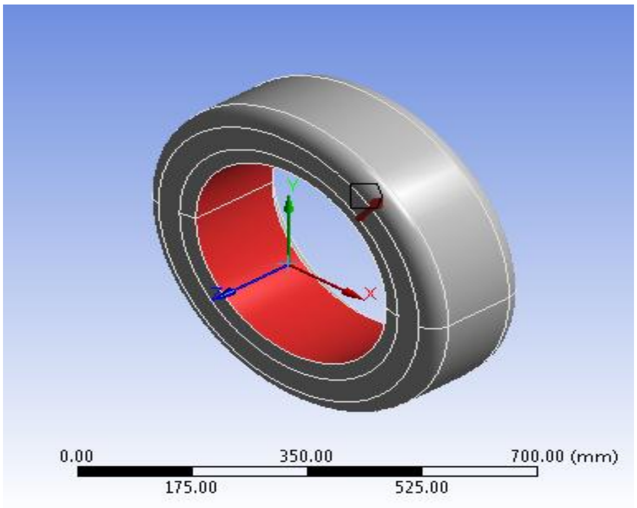

Fig.3. Maximum inflation pressure applied

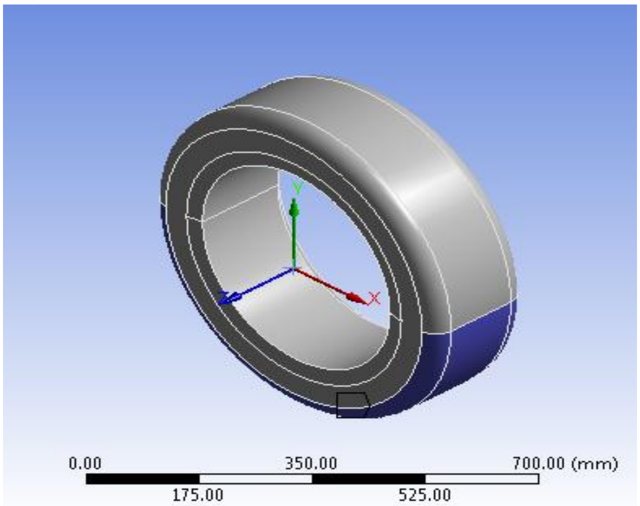

Fig.4. Fixed support applied to tyre model

G. Boundary Conditions

A uniform pressure of 220631.82 Pa which is the maximum inflation pressure for the tyre size investigated was applied on the internal surface of the tyre. A constraint was applied on the tyre ground surface. Then, a 5.15 KN force which is the maximum load carrying capacity for the tyre as stipulated in the tyre's load index was applied on the same surface to simulate real conditions of loaded tyre. Fig 4 shows the tyre model with maximum inflation applied while Fig 5 shows the tyre contact surface which is assumed frictionless in this analysis.

H. 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 tyre also involves the application of a vertical force on the tyre.

IV. RESULTS AND DISCUSSIONS

A Total deformation of Inflated Tyre

The total deformation of the 3D tyre model and the magnitude of inflated shape displacements are shown in Fig. 6. The deformations are large in the area of sidewalls with a maximum value of 12.33 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.

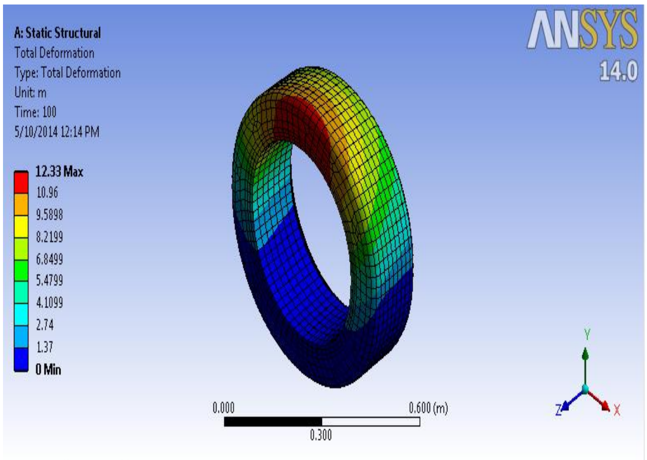

Fig. 6 Total deformation of inflated tyre

B. Tyre Deflection under Vertical Load

The shape of the 3D tyre model in contact with the ground under the 5.15kN load and the magnitude of tyre vertical displacements is shown in Fig. 7.The maximum deflections obtained on the tyre tread area under vertical loading of 5.15kN is 12.939 m

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ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

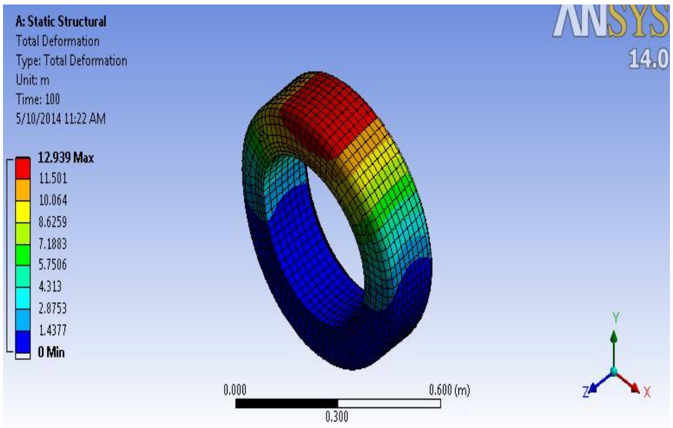

Fig. 7 Tyre Deflections under Vertical Load

C. von-Mises-Hencky stresses (Effective stress) of the tyre

The von-Mises-Hencky stresses of the tyre for maximum inflation tyre and vertical loading are shown in Figures 8 and 9. The von-Mises stress was obtained as 1.0105MPa for a maximum inflation pressure of 0.2206MPa and 0.9448MPa for the applied vertical load of 5.15kN

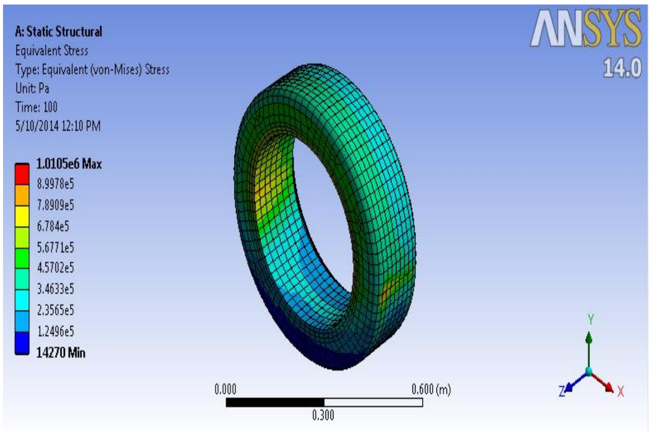

Fig. 8 von-Mises-Hencky stresses for maximum inflation pressure

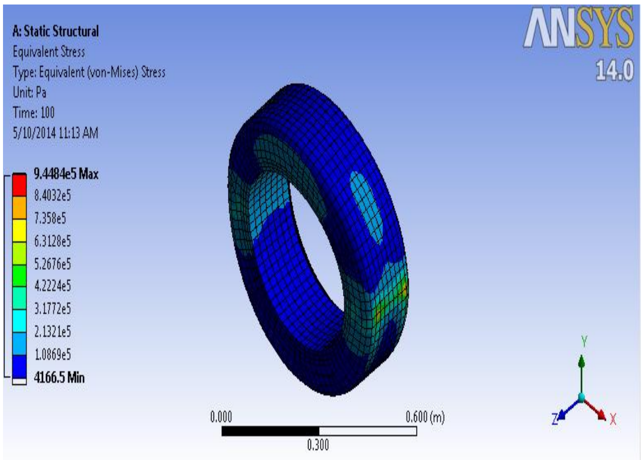

Fig. 9 von-Mises-Hencky stresses for vertical loading

This implies that the tyre material developed for tyre size P195/55 R16 85H can withstand loads and inflation pressures above the recommended values for this size. The result obtained is due to the kaolin reinforcement which is found to have better mechanical reinforcement properties over the traditional carbon black used in most vehicle tyres reinforcements.

D. Total Strain Energy of the Tyre

The total strain energies of the tyre on maximum inflation and vertical loadings are presented in figures 10 and 11. In the case of maximum inflation pressure, the maximum strain energy was found to be 277.49 J as shown in figure 10 while for vertical loading, the maximum value obtained was 122.4 J. In both cases their maximum strain energies were found to occur around the tyre tread area.

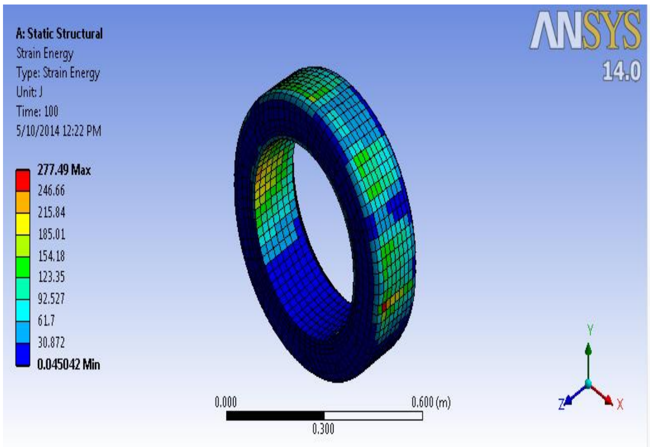

Fig. 10 Strain Energy for maximum inflation pressure

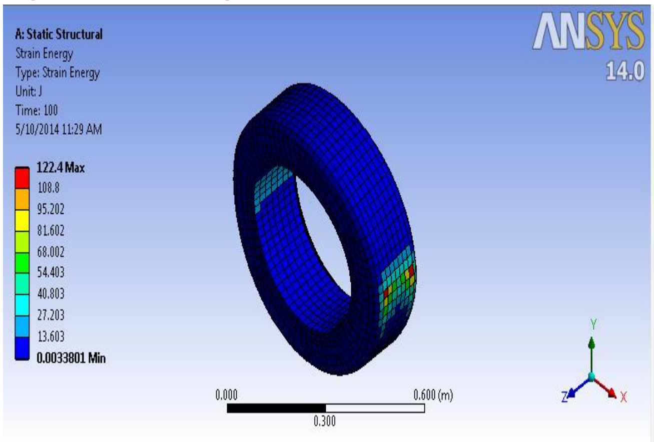

Fig. 11 Strain Energy for vertical loading

V. CONCLUSIONS

Finite element analysis was used for investigating the functionality of a pneumatic tyre developed from Natural Rubber/Organomodified kaolin subjected to static loading. From the present study, the following conclusions were made:

1. Static FEA offered a good analytical evaluation and an approximation of the tyre material studied and is recommended for the use in tyre design.
2. The vertical loading and maximum inflation pressures provided the total deformations of 3D tyre model.
3. The Organomodified kaolin filler was responsible for the noticeable improvements on the results of the pneumatic tyre studied.

ISBN: 978-988-14048-0-0
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

4. The P195/55 R16 85 H pneumatic tyres analyzed using the new material developed was found to require a higher load index over the load index specified for the tyre size.

ACKNOWLEDGMENT

The authors are grateful to Dr. Suresh Das, Former Director, National Institute for Interdisciplinary Science and Technology, (CSIR-NIIST), Trivandrum, India for generously providing materials and facilities for this work and to DST, Government of India for RTFDCS Fellowship awarded to one of them (C.O.M).

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