Design and Analysis of Non – Pneumatic Tyre by using Composite Materials

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Abstract— Recently, the development of non-pneumatic tires (npt) such as the Michelin tweel is receiving increased attention due to potential advantages over pneumatic tires such as low mass, no run flat, good contact pressure distribution, and low rolling resistance (rr). This study focuses on the design of an npt based on properties of vertical stiffness, contact pressure, and rolling energy loss. Using a finite element (Fe) model, a parametric study is conducted to study the effect on vertical stiffness, contact pressure, and rolling resistance (RR) response considering three design variables: thickness of the spokes, the shear band thickness, and shear modulus of the shear band and spokes of the npt. The first two design variables are geometric parameters of the npt while the third design variable is a material parameter. Using the three design variables, a design of experiments (doe) is performed to study the effect on RR, contact pressure, and vertical displacement. Results from the doe are used to create response surface models (rsm) for the objective function (minimal RR) and constraints on vertical deflection and contact pressure. The analytical rsm function is optimized for minimizing the rolling loss subjected to the given constraints. In addition, a design sensitivity study is performed to evaluate the influence of the design variables on the output response. Results indicate that all the design variables have significant effect on RR, with the shear band thickness and shear modulus having the greater effect.

Key words: Tyre, Composite Materials

I. INTRODUCTION

The development of non-pneumatic tires (NPT) such as the Michelin Tweel is receiving increased attention due to potential advantages over pneumatic tires. Pneumatic tires have been in use for more than a century, yet they have limitations still, such as high rolling resistance, low durability, susceptibility to running flat due to punctures, and a need for regular checking to maintaining correct air pressure. To overcome these problems, a non-pneumatic tire design was proposed by Michelin. Research has been undertaken at Clemson University in collaboration with Michelin over the past few years in developing many analytical and numerical models as well as prototypes to study the various characteristics of the NPT.

II. LITERATURE REVIEW

Development of a two-dimensional model of a compliant non-pneumatic tire Amir Gasmi a, Paul F. Joseph a, Timothy B. Rhyne b, Steven M. Cron b

An analytical model for a compliant non-pneumatic tire on frictionless, rigid ground is presented. The tire model consists of a thin flexible annular band and spokes that connect the band to a rigid hub. The annular band is modeled using curved beam theory that takes into account deformations due to bending, shearing and circumferential extension. The effect of the spokes, which are distributed continuously in the model and act as linear springs, is accounted for only in tension, which introduces a nonlinear response.

The quasi-static, two-dimensional analysis focuses on how the contact patch, vertical tire stiffness and rolling resistance are affected by the stiffness properties of the band and the spokes. A Fourier series representation of the shear strain in the annular band and the complex modulus of the material were used to predict rolling resistance due to steady state rolling. From the analysis point of view, when the wheel is loaded at its hub, the following three distinct regions develop:

(1) a support region where the hub hangs by the spokes from the upper part of the flexible band, (2) a free surface region where the spokes buckle and have no effect, and (3) a contact region where the flexible band is supported by the ground without the effect of the spokes. The angular bounds of these three regions are determined by the spoke angle and the contact angle, which are respectively the angle at which the spokes start to engage in tension and the angle that defines the edge of contact. Closed-form expressions of contact stress, stress-resultants and displacements at the centroids of the cross-sections of the flexible band are expressed in terms of these angles, which must be determined numerically.

A thorough parametric analysis of quantities of interest for the tire is presented, which can be used to help support the optimal and rational design of compliant non-pneumatic tires. The model was validated by comparison with two computational models using the commercial finite element software ABAQUS and by experimental rolling resistance data.

III. OBJECTIVE OF THE THESIS

In conventional pneumatic tires, cords, rubber matrix and steel bead wires are the major components. Loses in cords and steel bead wires are small and can be neglected. Rubber on the other hand is a viscoelastic material which contributes largely to the energy loss in conventional tires. In case of NPT, the main component contributing to the energy loss of the NPT is the shear band due to the shear loading at the contact area. Other components that contribute to the energy.

Fig. 1.1: Model of Tyre

It is the design of shear beam and spokes which allows for the potential to achieve a relatively uniform surface contact distribution with the ground under load. The spokes and ring are manufactured in a mold with imbedded reinforcements. A rubber tread is bonded to the outer ring to provide traction. Use of PU for the spokes and the shear band having low viscoelastic energy loss than rubber may result in design of NPT with low rolling resistance. The use of hyper elastic materials such as PU is important because of their shearing properties that contribute to the flexibility, energy loss, damping, and the pressure distribution between the NPT and the road.

When the NPT is loaded at the hub center, the composite ring flattens in the contact area, forming a contact patch. The deformable spokes buckles due to the applied load. The spokes out of the contact area do not undergo deformation and remain in tension. Figure 1.2 shows the buckling phenomenon of the NPT due to the application of static load.

IV. DESIGN OF NPT

The NPT concept described in consists of a composite ring, with at least two circumferential reinforcements separated by a radial distance. The composite ring is called as shear beam and it has a low modulus material is sandwiched between the reinforcements. During rolling, the material between the reinforcements is subjected to shear loading and deforms primarily in pure shear. A uniform, yet discrete, distribution 2 of spoke pairs is designed to connect the ring to the hub of the wheel and they deform due to buckling. Figure 1.1 shows the structure of the NPT.

V. MATERIAL PROPERTIES

A. *Existing Properties*

Part	Material	Young’s Modulus	Poisson's ratio
Belt	Steel cord	172.2gpa	0.3
Carcass	Polyester	9.87gpa	0.33
Ground	Concrete	48gpa	0.2

B. *Proposed Material Properties*

- Tensile Strength, Ultimate -28.0 MPa
- Elongation at Break -100 - 800 %
- 100% Modulus -0.00150 GPa
- Shear Modulus -0.000500 GPa

C. *Natural Rubber*

1) *Physical Properties*

- Density -0.956 g/cc

2) *Mechanical Properties*

- Hardness, Shore A -30 - 100
- Hardness, Shore D -30 – 45

D. *AL 7075-T6*

1) *Physical Properties*

- Density -2.81g/cc

2) *Mechanical Properties*

- Hardness, Brinell -150
- Hardness, Knoop -191
- Hardness, Rockwell A -53.5
- Hardness, Rockwell B -87
- Hardness, Vickers -175
- Tensile Strength, Ultimate -572 MPa

E. *AISI 4340*

1) *Physical Properties*

- Density -7.83g/cc

2) *Mechanical Properties*

- Hardness, Brinell -217 - 248
- Modulus of Elasticity -207 GPa

F. *Aluminium*

- Hardness, Vickers -15
- Modulus of Elasticity -68.0 GPa
- Poissons Ratio -0.36
- Shear Modulus -25.0 GPa

VI. DESIGN USING CREO SOFTWARE

A. *Definition of Element Type (Solid)*

Basically in this Project Non pneumatic tyre is developed in Pro-E and is further imported into the Ansys Package for Analysis Phase. So here the two Software‘s used are

1) Creo
2) Ansys 15

B. *Introduction about Creo*

CREO, PTC's parametric, integrated 3D CAD/CAM/CAE solution, is used by discrete manufacturers for mechanical engineering, design and manufacturing Created by Dr. Samuel P. Geisberg in the mid-1980s, CREO was the industry's first successful parametric, 3D CAD modeling system.

The parametric modeling approach uses parameters, dimensions, features, and relationships to capture intended product behavior and create a recipe which enables design automation and the optimization of design and product development processes. This powerful and rich design approach is used by companies whose product strategy is family-based or platform-driven, where a prescriptive design strategy is critical to the success International journal of Mathematics and Engineering 206 (2013) 1994 – 2027 1Gantla Shashidhar Reddy and 2 N. Amara NageswaraRao 2002 of the design process by embedding engineering constraints and relationships to quickly optimize the design, or where the resulting geometry may be complex or based upon equations.

C. Part Modeling

In Part modeling you can create a part from a conceptual sketch through solid feature-based modeling, as well as build and modify parts through direct and intuitive graphical manipulation. The Part Modeling Help introduces you to the terminology, basic design concepts, and procedures that you must know before you start building a part.

Part Modeling shows you how to draft a 2D conceptual layout, create precise geometry using basic geometric entities, and dimension and constrain your geometry. You can learn how to build a 3D parametric part from a 2D sketch by combining basic and advanced features, such as extrusions, sweeps, cuts, holes, slots, and rounds. Finally, Part Modeling Help provides procedures for modifying part features and resolving failures.

D. About Part: Pro/Engineer

Part enables you to design models as solids in a progressive three dimensional solid modeling environment. Solid models are geometric models that offer mass properties such as volume, surface area, and inertia. If you manipulate any model, the 3-D model remains solid.

E. Design Concepts

You can design many different types of models in Pro/ENGINEER. However, before you begin your design project, you need to understand a few basic design concepts: Design Intent—before you design your model, you need to identify the design intent. Design intent defines the purpose and function of the finished product based on product specifications or requirements. Capturing design intent builds value and longevity into your products. This key concept is at the core of the Pro/ENGINEER feature-based modeling process.

F. Feature-Based Modeling—CREO

Part modeling begins with creating individual geometric features one after another. These features become interrelated to other features as you reference them during the design process. Parametric Design—the interrelationships between features allow the model to become parametric. So, if you alter one feature and that change directly affects other related (dependent) features, then CREO dynamically changes those related features.

VII. ANALYSIS USING ANSYS SOFTWARE

A. ANSYS

Acp Tool-Its Use for Anlysing Composite Materials
Overview of ACP
The following sections provide an overview of ACP

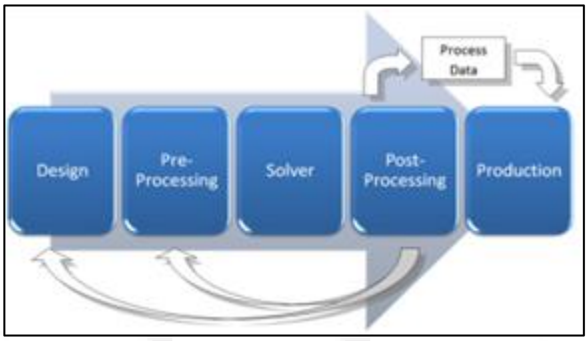
1) Introduction
2) Principle
3) First Steps

B. Introduction

Composite materials are created by combining two or more layered materials, each with different properties. These materials have become a standard for products that are both light and strong. Composites provide enough flexibility so products with complex shapes, such as boat hulls and surfboards, can be easily manufactured. Engineering layered composites involves complex definitions that include numerous layers, materials, thicknesses and orientations. The engineering challenge is to predict how well the finished product will perform under real-world working conditions. ANSYS Composite Prep Post provides all necessary functionalities for the analysis of layered composite structures.

C. Principle

ANSYS Composite Prep Post (ACP) is an add-in to ANSYS Workbench and is integrated with the standard analysis features. The entire workflow for composite structure can be completed from design to final information production as a result.

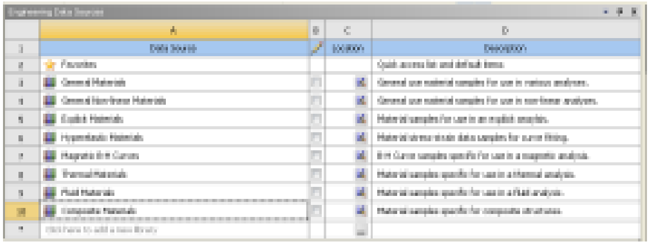


The geometry of the tooling surfaces of a composite structure is the basis for analysis and production. Based on this geometry and a FE mesh, the boundary conditions and composite definitions are applied to the structure in the pre-processing stage.

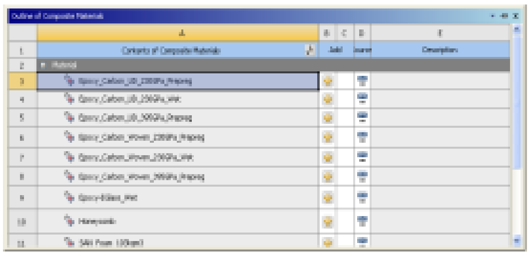
After a completed solution, the post-processing is used to evaluate the performance of the design and laminate. With the installation of ACP a new material catalog named Composite Materials is available in the databank. This catalog contains typical materials used in composite structures like unidirectional and woven carbon and glass, or core materials. Within the Workbench workflow of ACP, the materials have to be defined in the ED and not in ACP (Pre). Structures like unidirectional and woven carbon and glass, or core materials. Within the Workbench workflow of ACP, the materials have to be defined in the ED and not in ACP (Pre).

D. Engineering Data (ED)

E. Engineering data sources

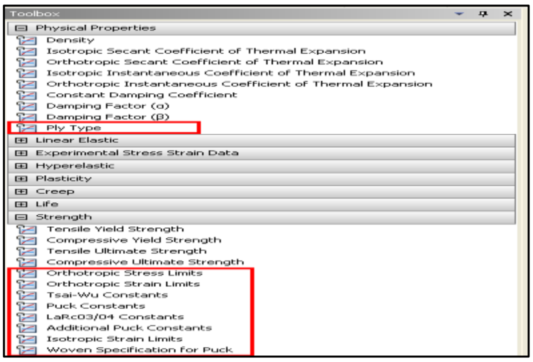


F. *Outline of Composite Materials*


Outline of Composite Materials

	A	B	C	D	E
1	Contents of Composite Materials		Add	Source	Description
2	⊟ Material				
3	Epoxy_Carbon_UD_230GPa_Prepreg				
4	Epoxy_Carbon_UD_230GPa_Wet				
5	Epoxy_Carbon_UD_395GPa_Prepreg				
6	Epoxy_Carbon_Woven_230GPa_Prepreg				
7	Epoxy_Carbon_Woven_230GPa_Wet				
8	Epoxy_Carbon_Woven_395GPa_Prepreg				
9	Epoxy-EGlass_Wet				
10	Honeycomb				
11	SAN Foam [illegible]				

G. *Material Properties for ACP*



⊟ Physical Properties
- Density
- Isotropic Secant Coefficient of Thermal Expansion
- Orthotropic Secant Coefficient of Thermal Expansion
- Isotropic Instantaneous Coefficient of Thermal Expansion
- Orthotropic Instantaneous Coefficient of Thermal Expansion
- Constant Damping Coefficient
- Damping Factor (α)
- Damping Factor (β)
- Ply Type

⊞ Linear Elastic
⊞ Experimental Stress Strain Data
⊞ Hyperelastic
⊞ Plasticity
⊞ Creep
⊞ Life
⊟ Strength
- Tensile Yield Strength
- Compressive Yield Strength
- Tensile Ultimate Strength
- Compressive Ultimate Strength
- Orthotropic Stress Limits
- Orthotropic Strain Limits
- Tsai-Wu Constants
- Puck Constants
- LaRc03/04 Constants
- Additional Puck Constants
- Isotropic Strain Limits
- Woven Specification for Puck

The new properties are:

1) *Ply Type*

Physical behavior of the material like core, unidirectional or woven ply.

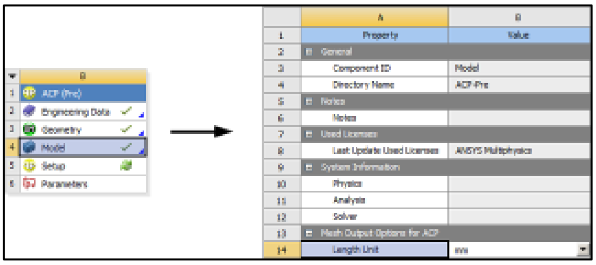
2) *Strengths*
- Orthotropic Stress Limits
- Orthotropic Strain Limits
- Isotropic Strain Limits

3) *Composite Failure Parameters*
- Tsai-Wu Constants
- Puck Constants
- LaRc03/04 Constants
- Additional Puck Constants
- Woven Specification for Puck.

H. *Geometry and Units*

The unit system in ACP is defined by the length unit in the mesh output options for ACP in the Work- bench project schematic. The length unit can be set in the properties of the Model cell that precedes the ACP (Pre) cell. The ACP unit system is independent from the unit system in the Mechanical application (User Interface or Solver). The transfer from the Mechanical application to ACP and vice versa automatically converts the data. The current unit system is displayed in the status bar of ACP at the bottom of the screen.

I. *Definition of Mesh Output Options for ACP*



	B
1	ACP (Pre)
2	Engineering Data ✓
3	Geometry ✓
4	Model ✓
5	Setup
6	Parameters

	A	B
1	Property	Value
2	⊟ General	
3	Component ID	Model
4	Directory Name	ACP-Pre
5	⊟ Notes	
6	Notes	
7	⊟ Used Licenses	
8	Last Update Used Licenses	ANSYS Multiphysics
9	⊟ System Information	
10	Physics	
11	Analysis	
12	Solver	
13	⊟ Mesh Output Options for ACP	
14	Length Unit	mm

J. *Named Selections and Elements/Edge Sets*

Named Selections based on bodies, surfaces and edges defined in the Design Modeller or the Mechanical application are transferred to ACP as Element Set and Edge Set, respectively.

K. *Starting and Running ACP*

First, an ACP (Pre) component has to be defined in the Workbench project. Double-click on Setup to open ACP (Pre). You can also use the context menu and select dissipates some of this energy in the process in the form of heat. This dissipation is known as hysteresis. During rolling under the application of the load, the circumferential position of NPT keeps changing causing cyclic shear in the shear layer. Due to cyclic shear, material is loaded and unloaded periodically resulting in hysteresis Edit, or run a Python script in which the ACP commands are included, from the context menu. After defining the composite data in ACP (Pre), the user can return to the Workbench Project to proceed. The ACP data is saved with Save in the Workbench Project or any other Save Project command in the different components.

L. *Finite Element Meshing and Element Properties*

The inner/outer reinforcements and spokes are modeled with shear flexible Timoshenko beam elements since beam approximation will be suitable for suitable for simulating the behavior of reinforcements and spokes. The beam elements in the model are modeled as B21 (2-node linear beam). Approximate global seed size specified in ABAQUS is 0.006 for the beam elements. The number of elements along the length of spokes.

M. *Rolling Resistance*

Rolling resistance can be defined as the resistance offered by the tire when it rolls over a flat rigid surface. Primarily, it occurs due to the deformation of the tire at the contact zone and it is attributed to the use of viscoelastic material in the tire structure.

Viscoelastic materials are preferred due to their flexibility and their damping properties In order to achieve these benefits, some trade-offs are made in the design of tires. Unlike elastic materials, viscoelastic materials do not store 100% of energy during deformation.

N. *Previous Work*

Research has been undertaken in Clemson University in collaboration with Michelin for the development of Non-Pneumatic tire. The work presented in [23], is about the rolling resistance of NPT with porous composite elastomeric shear band. Porous composite shear band was formed by removing the material from the continuous shear band. The loss of stiffness was compensated by the use of composite materials in the porous shear band. Numerical experiments were conducted to study the energy loss of NPT with continuous layer shear band and porous composite shear band. It was shown that the rolling resistance of the NPT with porous elastomeric shear band was low in comparison to the rolling resistance of NPT with continuous shear band without compromising the stiffness of the structure.

O. Thesis Organization

A reference point is created at the center of NPT and is considered as the control point for the interaction. The rigid hub, spokes, inner reinforcement, shear layer, outer reinforcement and the tread are assembled together with the tie constraint.

P. Constraints and Interactions

Kinematic coupling is created in ABAQUS to define the rigid interaction between the center of NPT and the rim. Work presented in used analytical rigid surface in ABAQUS to create the ground.

Q. Loads and Boundary Conditions

The objective of the problem is to numerically measure the rolling resistance per unit distance (FR), vertical deflection (δ) and the maximum contact pressure (cpress) of the NPT (at a particular node at the contact zone) for different values of the geometric and material design variables. Quasi-static analysis is performed to study the time dependent viscoelastic material response of the NPT. Quasi-static analysis does not include mass and inertial effects. The analysis consists of two steps namely the Static Load and the Visco Roll.

Before performing the optimization, a parametric study is conducted to determine the effects of geometric design variable namely spoke thickness, shear band thickness and material parameter namely the shear modulus of PU, on the rolling resistance (RR) response, vertical stiffness defined by K = F / δ where F is the vertical force (=3000N) and δ is the vertical deflection of the hub center and maximum contact pressure (cpress). Vertical stiffness, contact pressure and RR are important design parameter of the NPT as it influences the vehicle performance characteristics.

VIII. MODELS AND ANALYSIS

A. Creo Model

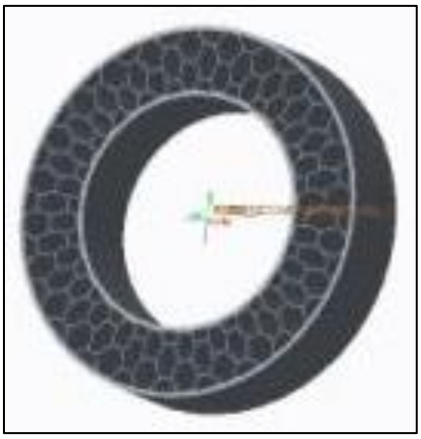


Fig. 7.1: Honeycomb Model

Fig. 7.2: Spokes Model

B. Ansys Work Bench Normal Analysis Report for Honeycomb Model

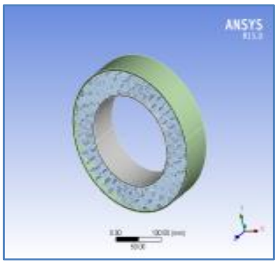


Fig. 7.3: Ansys Mode

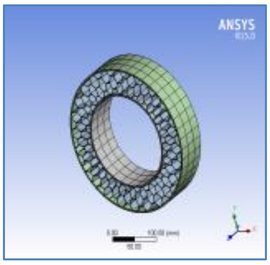


Fig. 7.4: Meshed Model

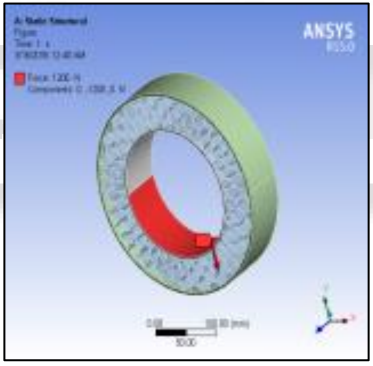


Fig. 7.5: Static Structure: Load Applied

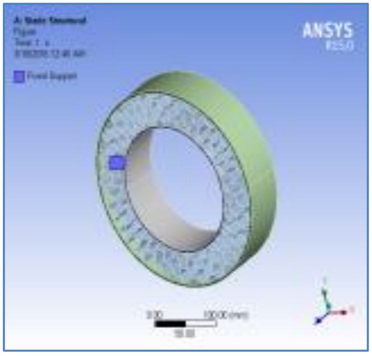


Fig. 7.6: Static Structure: Fixed Support

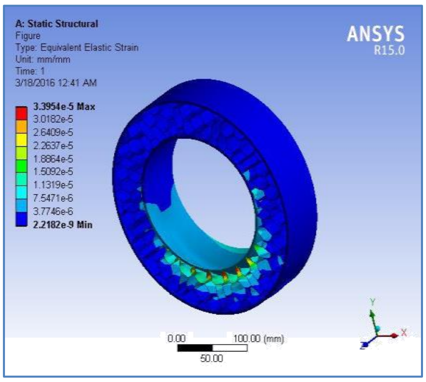


Fig. 7.7: Equivalent Elastic Strain

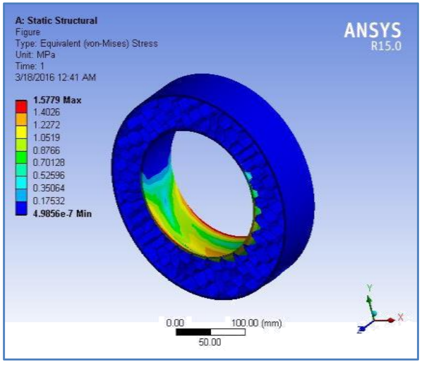


Fig. 7.8: Equivalent Stress

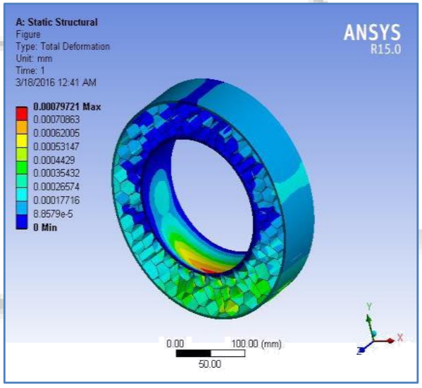


Fig. 7.9: Total Deformation

C. *Composite Analysis for Honeycomb Design*

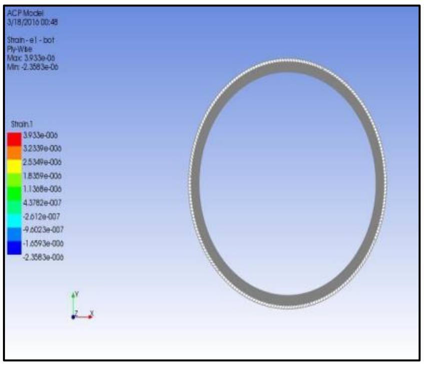


Fig. 7.10: ACP Model: Strain

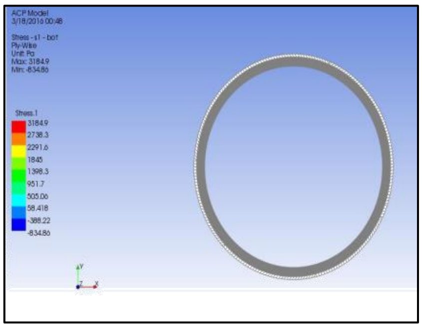


Fig 7.11 ACP Model: Stress

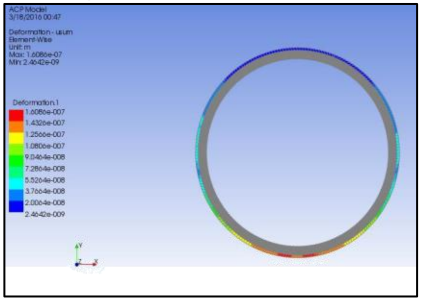


Fig 5.72 ACP Model: Deformation

D. *Ansys Work Bench Normal Analysis Report for Spokes Model*

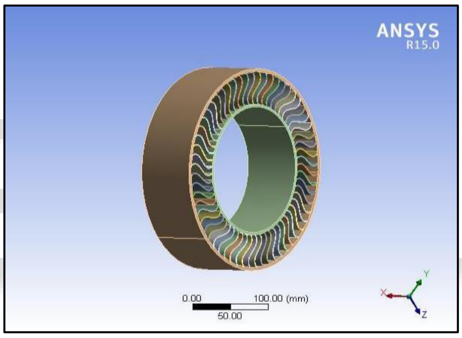


Fig. 7.13: Spokes Model

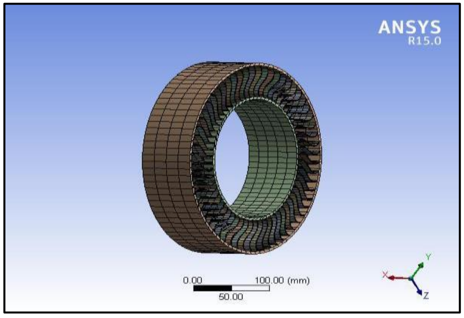


Fig. 7.14: Meshed Model

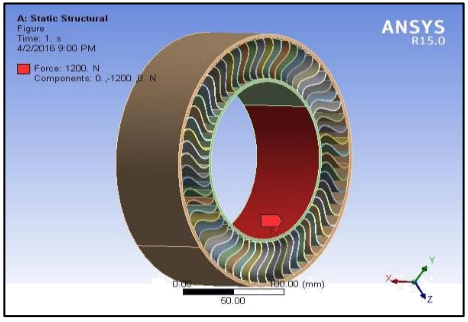


Fig. 7.15: Static Structure: Load Applied

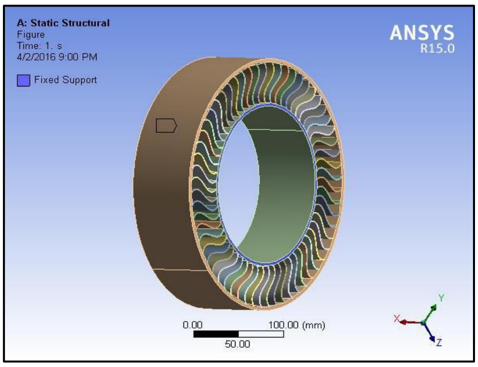


Fig. 7.16: Static Structure: Fixed Support

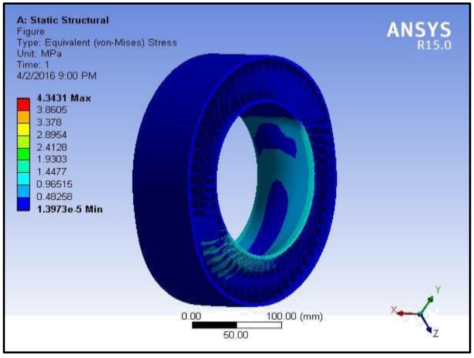


Fig. 7.17: Equivalent Stress

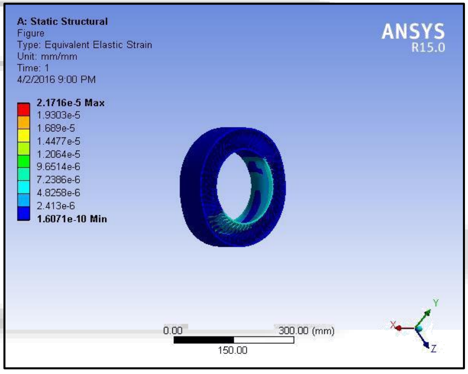


Fig. 7.18: Equivalent Elastic Strain

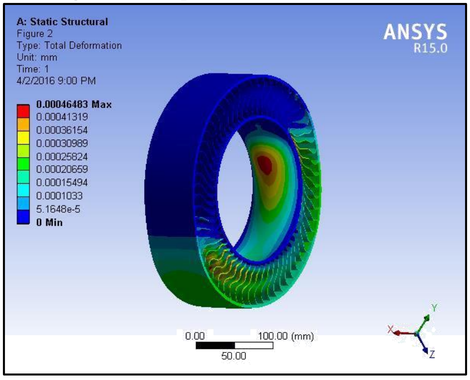


Fig. 7.19: Total Deformation

E. Composite Analysis for Spokes Design

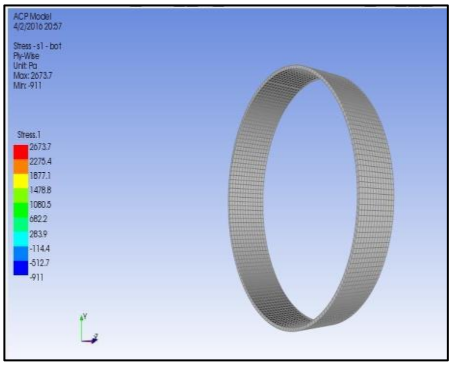


Fig. 7.20: ACP Model: Stress

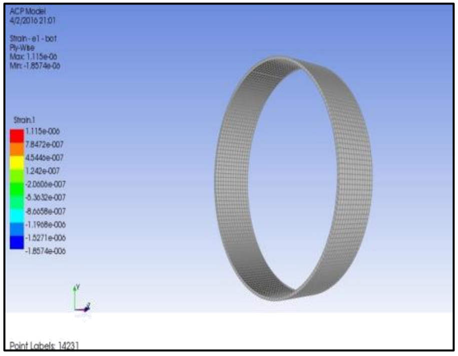


Fig. 7.21: ACP Model: Strain

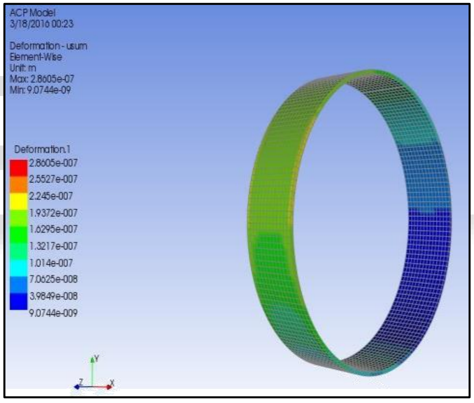


Fig. 7.22: ACP Model: Total Deformation

IX. RESULTS

A. Honeycomb Model

Test	Normal Analysis	Composite
Max Strain	$3.3954 \text{ X } 10^{-5}$ M/M	$3.933 \text{ X } 10^{-5}$ M/M
Max Stress	$1.5779 \text{ X}10^{6}$ Pa	3184.9 Pa
Max Total Deformation	0.00079721 Mm	$1.6086 \text{ X } 10^{-007}$ Mm

B. Spokes Model

Test	Normal Analysis	Composite Analysis
Max Strain	$2.1716 \text{ X } 10^{-5}$ M/M	$1.115 \text{ X } 10^{-06}$ M/M
Max Stress	$4.3431\text{x } 10^{6}$ Pa	2673.7 Pa
Max Total Deformation	$4.6483 \text{ X } 10^{-4}$ Mm	$2.8605 \text{ X } 10^{-4}$ Mm

X. CONCLUSION

In this paper, a structural application of the flexible in-plane properties of hexagonal honeycombs was suggested – the honeycomb spokes of an NPT to replace the air of a pneumatic tire. Cellular spoke geometries for an NPT were investigated with regular and auxetic honeycomb spokes using the compliant cellular design concept. The major findings are as follows the ratio of the inclined cell length, to the overall cell height, X1, is the key factor to determine the in-plane flexibility of hexagonal honeycombs under untaxed al loading. A high cell angle magnitude induces the high flexibility of the honeycomb spokes, resulting in a lowering of the reaction force of an NPT for a given vertical displacement loading. The honeycomb spokes with a higher cell angle magnitude show lower local stresses, which is good for a fatigue resistant spoke design, e.g., Types C and F. However, the honeycomb spokes of Type C are better considering both fatigue resistance and lower mass design. Experimental validation with prototypes of the NPTs is planned for future work.

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