

Static Contact Behaviors of a Non-Pneumatic Tire with Hexagonal Lattice Spokes

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ABSTRACT

A non-pneumatic tire (NPT) has two advantages over a conventional pneumatic tire; it is flat proof and maintenance free of air-pressure. In this study, while determining other advantages inherent in NPTs, the static contact behavior of NPTs with hexagonal honeycombs is investigated as a function of vertical loading and is compared with that of a pneumatic tire. A finite element based numerical simulation is carried out on the contact pressure of NPTs with cellular spokes and the local deformation of cellular spokes. A commercial finite element code, ABAQUS, is used to vary the vertical forces and lattice spoke geometries. A lower contact pressure is obtained with the NPTs than with the pneumatic tire due to the decreasing spoke stiffness of the NPTs when they are designed to have the same load carrying capability. An NPT with hexagonal lattice spokes having a higher cell angle shows a lower local cell wall stress in the spokes, associated with the flexible honeycomb property in uni-axial compression.

KEYWORDS: non-pneumatic tire (NPT), honeycombs, cellular spokes, contact pressure

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INTRODUCTION

Since the initial design by Dunlop, the pneumatic tire has been used for more than 100 years due to its relatively low vertical stiffness, low contact pressure and low mass [1]. However, pneumatic tires have several disadvantages; they can suffer from catastrophic damage (i.e. flats) while driving, they require the air pressure to be continually checked and maintained, and the manufacturing processes are complex [1]. From a structural standpoint, the high contact stress peaks at the contact edges in the lateral direction due to the interaction of air pressure on the road surface cause high contact pressure differences between the shoulder and the crown [2, 3, 4, 5]. This problem has been resolved by controlling the shape of the tread [6]. Contact pressure distribution has been an important issue for tire design due to its significant effect on passenger riding comfort, vehicle

handling, wear, and noise. High contact pressure results in rapid tread wear due to the high contact stresses. It also negatively affects passenger ride comfort. High contact pressure differences cause rapid tread wear due to the high cyclic shear stress in the longitudinal and lateral contact directions [7]. On the other hand, low contact pressure causes a difficulty in tire control [1, 9, 10]. Uneven contact pressure is also known to be a source of noise [8]. Therefore, an appropriate contact pressure level with a low contact pressure peak is required for the optimum tire contact pressure design.

Several tire engineers have attempted to develop non-pneumatic tires by filling an elastomer into the space for air or by building polygon typed spokes to replace the air of a pneumatic tire [11, 12, 13, 14]. According to recently disclosed non-pneumatic tire (NPT) prototypes, the current strategy being employed uses flexible polygon spokes and an

elastomer layer having inner and outer rings [13, 14]. However, there is a need to explore other polygon geometries in order to find the ideal flexible spokes for optimal tire performance. Macro and local cellular properties of hexagonal honeycombs have been extensively studied [15, 16, 17, 18, 19], and some hexagonal honeycombs are known to be flexible in the in-plane direction [20, 21]. Beginning with several hexagonal geometries, we are motivated to find optimal spoke geometries.

A structural analysis of an NPT is rarely found in the literature [15, 16]. Ju et al. developed finite element (FE) models of non-pneumatic tires with a cellular shear band and investigated one dimensional contact pressure [15] and tire-soil interaction properties for extraterrestrial tire applications [16]. In this study, NPTs with hexagonal cellular spokes are designed to have a load carrying capacity and their contact pressures are analyzed as a function of vertical loading. Due to the computational complexity of the hyperelastic material and large deformation induced geometric nonlinearity, a commercial FE code, ABAQUS, is used for the numerical computation of the NPT contact pressures. This study proposes an optimal shape of hexagonal honeycomb spokes through a comparison of contact pressures between pneumatic and non-pneumatic tires.

ANALYSIS OF A PNEUMATIC TIRE

In this section, a pneumatic tire is revisited and its static contact behavior is investigated. The general components of a pneumatic tire are shown in [Figure 1](#). The entire inner layer of cord fabric, called the carcass, acts to support air pressure and vertical load, and absorb shocks. The bead attaches the tire to the rim and wraps the end of the cord fabric. The tread, made of a thick rubber ply, is the part that comes in direct contact with the road surface. The shoulder, located between the tread and the sidewall, consists of the thickest rubber, which allows for an easy diffusion of heat generated while driving [1]. The flexible sidewall, located between the shoulder and the bead, protects the carcass and enhances the ride with a flexible buckling movement [1]. The belt, a cord layer placed between the carcass and the tread, functions as a strong reinforcement for the tire.

For finite element (FE) modeling, each component is designed in accordance with their characteristics. The bead, the side wall, and the tread are modeled with an eight node linear brick type solid element (C3D8R in ABAQUS). The carcass and the belt are modeled with a four node doubly curved shell element (S4R in ABAQUS). [Figure 1\(b\)](#) shows a full FE model of a pneumatic tire.

[Table 1](#) shows the material properties of each component; the belt, the carcass, and the ground made of steel cord, polyester, and concrete, respectively.

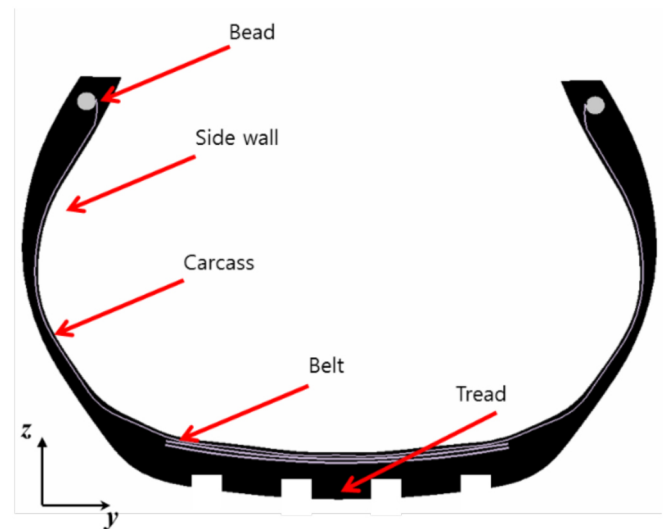


Figure 1. Cross-section of a pneumatic tire

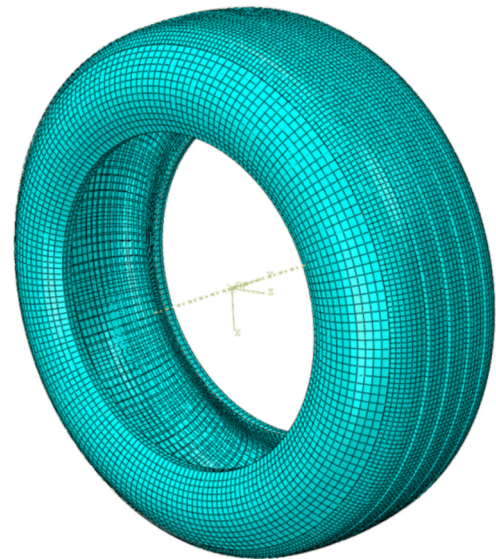


Figure 2. 3D FE model of a pneumatic tire

Table 1. Properties of components of a pneumatic tire

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

A typical passenger car air pressure of 210kPa is used in this study. In order to simulate the contact pressure of a pneumatic tire with ABAQUS, a two-step loading is applied: A pneumatic tire is inflated to an internal air pressure of 210kPa, followed by a vertical load of 4000N at the rim center.

The deformed shapes and contact patch of the pneumatic tire as a function of vertical loading are shown in Figure 3. Elliptical contact patches are obtained with the pneumatic tire. The maximum contact pressure values are 1.1 and 0.57MPa at vertical forces of 1000 and 4000N, respectively. Figure 4 shows the vertical force-deflection curve of the pneumatic tire. As can be seen in Figure 4, the curve shows a nonlinear force-deflection behavior; the slope of the force-deflection curve increases with an increase in vertical force. That is, the vertical stiffness of the pneumatic tire increases with an increasing vertical load, resulting in a concave force-deflection curve.

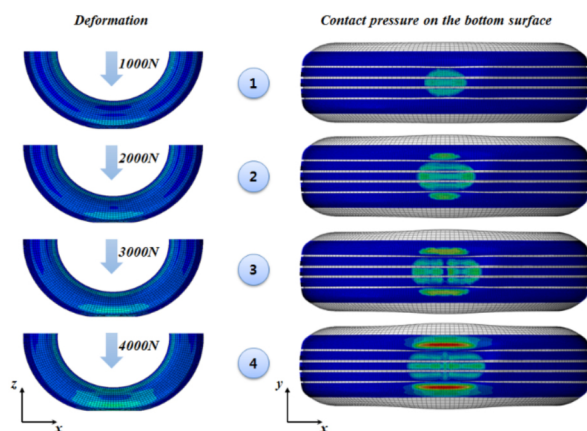


Figure 3. Deformed shapes and contact patch on the bottom surface of the pneumatic tire

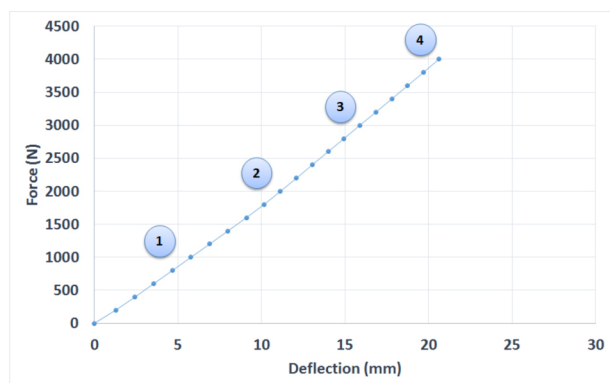
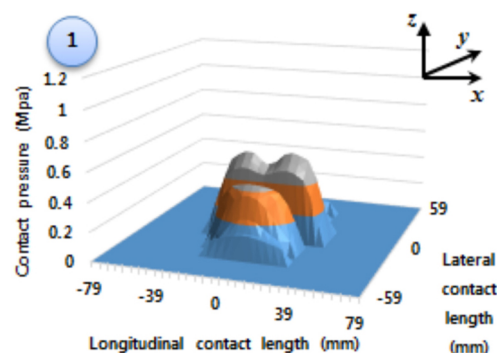
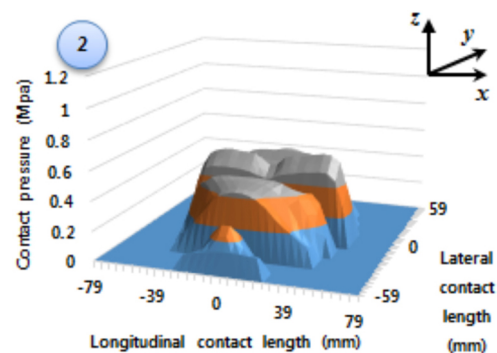


Figure 4. Force-deflection curve of the pneumatic tire

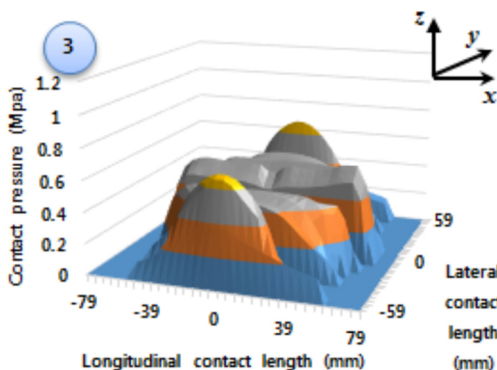
Figures 5(a), (b), (c), and (d) are 3D contact pressure profiles of the pneumatic tire when vertical forces of 1000, 2000, 3000, and 4000N, respectively, are applied. At a low vertical force, contact stress develops at the center point and subsequently expands in the radial direction as shown in Figure 2(a). As the vertical force increases, high contact stresses are developed at the contact edges in the longitudinal and lateral directions due to large deformations in the tread material (Figures 2(b), (c), and (d)).



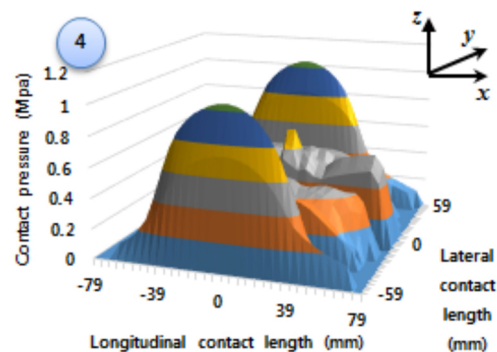
a. 3D plot of contact pressure for a vertical force of 750N



b. 3D plot of contact pressure for a vertical force of 1500N



c. 3D plot of contact pressure for a vertical force of 2250N



d. 3D plot of contact pressure for a vertical force of 3000N

Figure 5. Contact pressure of a pneumatic tire