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Flexible cellular solid spokes of a non-pneumatic tire

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ABSTRACT

Non-pneumatic tires (NPTs) have been introduced with a compliant cellular solid spoke component which functions as the air of the pneumatic tire. In this paper, hexagonal honeycomb spokes for a high fatigue resistance design are investigated by seeking compliant hexagonal structures that have low local stresses under macroscopic uni-axial loading. Using the honeycomb mechanics, two cases of hexagonal honeycombs are designed: (i) the same cell wall thickness and (ii) the same load carrying capacity. The elastic limits of the hexagonal honeycombs are obtained from the ABAQUS finite element code considering the geometric nonlinearity of a cellular structure associated with the cell wall buckling and bending. The compliant cellular structures having low local stress values are applied to the honeycomb spokes of an NPT for the structural validation and the local stresses of the honeycomb spokes are investigated under the same vertical loading conditions. Hexagonal honeycombs with a highly positive cell angle have low local stresses and low mass under the same vertical load carrying capability; the Type C honeycomb spokes in this study.

1. Introduction

Since the release of the first commercial pneumatic bicycle tire by Dunlop in 1888, the pneumatic tire has been dominant in the world tire market for more than 100 years due to four major advantages it has over a rigid wheel: (i) low energy loss on rough surfaces, (ii) low vertical stiffness, (iii) low contact pressure, and (iv) low mass [1]. However, the pneumatic tire has several disadvantages as well: (i) the possibility of catastrophic damage – a flat while driving, (ii) the required maintenance for proper internal air pressure, and (iii) the complicated manufacturing procedure [1]. From the early 1920s, efforts were made to develop a resilient wheel by adding wire spokes in order to deliver a quality pneumatic tire while guaranteeing safety [2]. Since then, several engineers have also attempted to develop non-pneumatic tires (NPTs) by filling an elastomer or by building polygon-like spokes to replace the air of a pneumatic tire [3–15]. There have been recent innovations with respect to airless tires; NPTs have emerged consisting of flexible polygon spokes and an elastomer layer having inner and outer rings [12–14]. Considering the NPT structure, the spokes undergo tension–compression cyclic loading while the tire rolls [12–14]. Therefore, it is important to minimize the local stresses of spokes when under cyclic loading while driving. In other words, fatigue resistant spoke design takes on greater importance.

Two dimensional prismatic cellular materials of periodic microstructures are called honeycombs. Honeycombs have been primarily used in lightweight sandwich structures for which a high out-of-plane stiffness is desired [16,17]. In contrast to the highly stiff and strong properties of the out-of-plane direction (the longitudinal cell axes) associated with cell wall axial stiffness, the in-plane properties are two to three orders of magnitude weaker than those of the out-of-plane loading. For this reason, the mechanical properties which exist under in-plane loading have been thought to be the most limiting in terms of design applications. However, recently, there have been efforts to use lower in-plane stiffness for designing flexible honeycomb structures to be used in applications that require high deformation under targeted loads. Examples of such applications are flexible micro-electro-mechanical-system (MEMS) structures [18] and aircraft morphing structures [19–22].

Hexagonal honeycombs are cellular materials employed in various applications, and particulary in the design of light weight structures. Since the initial investigations conducted by engineers on the effective moduli and effective Poisson's ratios of hexagonal honeycombs based on the bending dominant structural property, of cell walls some more refined models have also been suggested [23–28]. Recently, in-plane effective moduli, yield strengths, and buckling strengths with different cell types – square, hexagonal, triangle, mixed squares and triangles, and diamond – have been investigated [29–35]. Triangular, Kagome, and diamond cell honeycombs are known to be extension dominant cell structures, which are good for high modulus structural designs [29]. On the other hand, square and hexagonal cell honeycombs are known to

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be bending dominant structures, which are good for flexible structural designs [31,32]. Hexagonal cell structures are known to be flexible in both axial and shear loadings [33–35]. Moreover, hexagonal honeycombs can easily be tailored to have targeted in-plane properties by changing the cell angle, the cell wall thickness, and the cell length. Therefore, some hexagonal structures have the potential for compliant structural design.

The spokes of an NPT are required to have both stiffness and resilience under cyclic tension–compression loading. In general, stiffness and resilience are conflicting requirements if a material has a high modulus, it shows a low elastic strain limit, and vice versa. The challenge, then, is to design materials that have both high stiffness and high resilience. Because there are no conventional materials to satisfy the desired property, the solution must be sought for through the huge design space afforded by cellular materials base materials and cellular geometries.

Finite element (FE) analysis has been utilized extensively in the simulation of tire models due to its capability to solve complicated structural behaviors combining the nonlinearity of a material and geometry [36–38]. In this study, a commercial FE code, ABAQUS is used for a numerical experiment with NPTs having hexagonal honeycomb spokes. The honeycomb spokes made of polyurethane (PU) are suggested as the key component of NPTs which adequately replace air-filled pneumatic tires. In Section II, uni-axial flexible hexagonal structures are introduced as the spokes of the NPT. Section III introduces the NPT structures and materials used. The structural performance of the designed honeycomb spokes for a fatigue resistant design is discussed in Section IV.

2. In-plane flexibility of honeycombs subjected to uni-axial loading

Flexible honeycomb spokes along the radial direction of an NPT function as the air of a pneumatic tire. When designing flexible spokes, the structures should have both load carrying capabilities and resilience. The former property is identified with the modulus and the latter with the elastic strain limit. Unfortunately, those properties are the conflicting requirements in general materials; in other words, materials having a high modulus show a low yield strain. However, cellular solids have the potential to free themselves from these conflicting requirements when designing flexible structures because the cell geometry can be controlled. Considering the required cyclic loading of honeycomb spokes when the NPT rolls, a cellular geometry having lower local stresses is

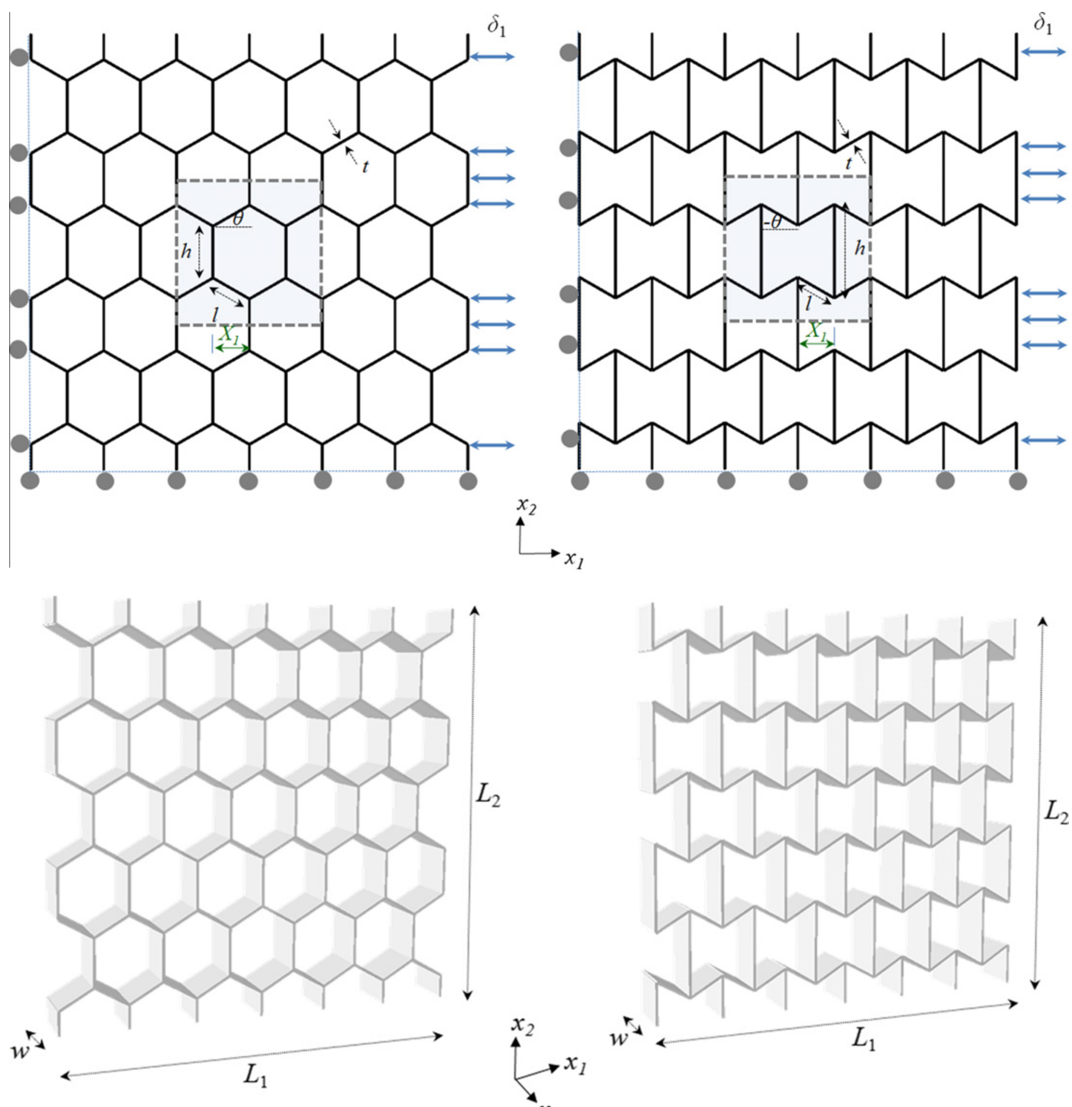

Fig. 1. Geometric parameters of hexagonal honeycombs and boundary conditions for tensile and compressive loadings.