

Design of Cellular Shear Bands of a Non-Pneumatic Tire -Investigation of Contact Pressure

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ABSTRACT

In an effort to build a shear band of a lunar rover wheel which operates at lunar surface temperatures (40 to 400K), the design of a metallic cellular shear band is suggested. Six representative honeycombs with aluminum alloy (7075-T6) are tailored to have a shear modulus of 6.5MPa which is a shear modulus of an elastomer by changing cell wall thickness, cell angles, cell heights and cell lengths at meso-scale. The designed cellular solids are used for a ring typed shear band of a wheel structure at macro-scale. A structural performance such as contact pressure at the outer layer of the wheel is investigated with the honeycomb shear bands when a vertical force is applied at the center of the wheel. Cellular Materials Theory (CMT) is used to obtain in-plane effective properties of a honeycomb structure at meso-scale. Finite Element Analysis (FEA) with commercial software ABAQUS is employed to investigate the structural behavior of a wheel at macro-scale. A honeycomb shear band designed with a higher negative cell angle provides a lower contact pressure along the contact patch associated with an in-plane shear flexible property.

RESEARCH MOTIVATION

Elastomers are commonly used in tire components for a driver and passenger's comfort purpose due to their unique properties: relatively low modulus, high elongation properties, and high impact resistance. Considering that the glass transition temperature (T_g) of common elastomers ranges from 180 to 210K, they do not appear to function as elastomers at lunar surface temperatures (40 to 400K). It may hinder NASA's space exploration mission in designing and building lunar rover wheels requiring for high dynamic impact absorption while the wheels are rolled on unpaved lunar surfaces. In this manner, Engineers at Clemson University have been developing a rubber like cellular

material made of a metal (e.g., Aluminum alloy, 7075-T6) that is able to function as a shear band while enduring at the harsh temperatures of the Moon.

Analytical, numerical, and, experimental methods for predicting thermo-mechanical and thermal properties of cellular materials have been investigated for three decades [1,2,3,4,5,6,7,8,9,10,11,12,13]. The practical applications of cellular solids have been focused primarily on i) high energy impact energy absorption applications such as military armors and helmet and ii) ultra light weight design associated with high strength and low density such as light weight components used in automobile and aerospace structures. Thus, the research has focused on tailoring the geometries of cells to maintain required effective bending, tensile, and compressive stiffness and/or local impact resistance.

A notable absence in the literature on design and characterization of cellular materials is an exploration of performance under shear loading, which is the main mode of the shear band component of a lunar rover wheel. Our previous study on tailoring dual target properties, e.g., effective shear modulus and effective shear yield strain, with cellular structures shows a possibility in building flexible cellular structures with polymers and metals [14-15].

One of the main functions of the elastomeric shear bands is a low contact pressure to enable passengers inside automobile to be comfortable. The requirement of a lower contact pressure may not be critical in the lunar rover wheel. However, a higher contact pressure should always be avoided to prevent high peak under dynamic loadings that may cause a damage of tire and automobile components. In this paper, we investigate contact pressures of metallic cellular shear bands to see if elastomers can be replaced with metallic cellular materials. Auxetic honeycombs, having a negative Poisson's ratio show a low contact pressure when they are

designed to be a shear band. A higher negative cell angle show a lower contact pressure due to its shear flexible property.

MODEL DEVELOPMENT

I). DESIGN OF CELLULAR SHEAR BAND

Cellular shear bands can be designed to have a target effective property by controlling geometries and materials. For example, the authors have shown that cellular structures with polycarbonate can be tailored to have a shear modulus of 4 to 8MPa, which is a shear modulus of elastomers [14]. In this study, cellular shear bands are designed with aluminum alloy, 7075-T6, to have the same effective shear modulus of ~6.5MPa, which is a comparable shear modulus of an elastomer. The Young's modulus, shear modulus, yield strength, Poisson's ratio and density of 7075-T6 are 70GPa, 27GPa, 500MPa, 0.33, and 2700 kg/m³, respectively.

Unit cell geometries, typically used in the cellular materials theory (CMT), with conventional and auxetic hexagonal honeycombs are shown in Figure 1. The critical geometric parameters include the cell angle (θ), the vertical cell length (h), the inclined cell length (l), and the cell wall thickness (t).

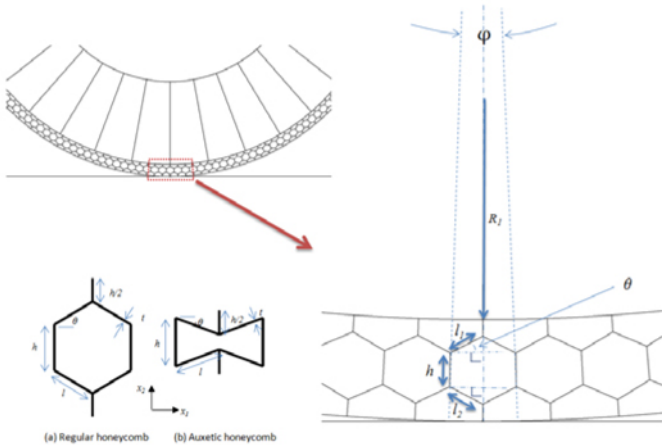


Figure 1. Geometry of i) Honeycomb Unit-Cells and ii) a Honeycomb Shear Band

In-plane effective moduli and effective yield strains from CMT are given by [1]:

$$E_{11}^* = E \left(\frac{t}{l} \right)^3 \frac{\cos \theta}{\left(\frac{h}{l} + \sin \theta \right) \sin^2 \theta} \quad (1)$$

$$E_{22}^* = E \left(\frac{t}{l} \right)^3 \frac{\left(\frac{h}{l} + \sin \theta \right)}{\cos^3 \theta} \quad (2)$$

$$G_{12}^* = E \left(\frac{t}{l} \right)^3 \frac{\left(\frac{h}{l} + \sin \theta \right)}{\left(\frac{h}{l} \right)^2 \left(1 + 2 \frac{h}{l} \right) \cos \theta} \quad (3)$$

$$\left(\varepsilon_{11}^* \right)_{\max} = \frac{\sigma^{\text{Yield}}}{E_{11}^*} \left(\frac{t}{l} \right)^2 \frac{1}{2 \left(\frac{h}{l} + \sin \theta \right) (\sin \theta)} \quad (4)$$

$$\left(\varepsilon_{22}^* \right)_{\max} = \frac{\sigma^{\text{Yield}}}{E_{22}^*} \left(\frac{t}{l} \right)^2 \frac{1}{2 \cos^2 \theta} \quad (5)$$

$$\left(\gamma_{12}^* \right)_{\max} = \frac{1}{4} \frac{\sigma^{\text{Yield}}}{G_{12}^*} \left(\frac{t}{l} \right)^2 \frac{1}{\frac{h}{l} \cos \theta} \quad (6)$$

where E_{11}^* and E_{22}^* are the effective moduli in the x_1 and x_2 directions, respectively. $(\varepsilon_{11}^*)_{\max}$ and $(\varepsilon_{22}^*)_{\max}$ are the maximum effective strains in the x_1 and x_2 directions, respectively. G_{12}^* is the in-plane effective shear modulus. $(\gamma_{12}^*)_{\max}$ is the maximum in-plane effective shear strain.

According to our previous study [14], discrete cellular geometries can be used to represent the whole structures by interpolating and extrapolating geometric parameters. In this study, six geometries are selected for $h=l$ and $h=2l$ (Figure 1). Three cell angles are chosen for $h=l$; $\theta=-20^\circ$, 30° , and 60° . And three cell angles are selected for $h=2l$; $\theta=-30^\circ$, -50° and -65° . We design a cellular shear band having an elastomer's shear modulus; e.g., a shear modulus of 6.5MPa. When cellular shear bands' height is 12.7mm (0.5inch) and they are designed to have the same effective shear modulus of 6.5MPa, the corresponding geometries and the in-plane effective properties are shown in Table 1. The effective shear modulus, G_{12}^* and the maximum effective shear strain, $(\gamma_{12}^*)_{\max}$ are the most important properties in designing cellular shear bands. However, for completeness of the in-plane mechanical properties of cellular shear bands, moduli and maximum effective strains in the x_1 and x_2 directions, effective Poisson's ratios, ν_{12}^* and ν_{21}^* , and relative densities are also shown in Table 1. It should be noted that the cellular

geometries whose effective Poisson's ratios are negative show high maximum effective shear strain, $(\gamma_{12}^*)_{\max}$.

<table 1 here>

A honeycomb shear band is modeled based on the geometry in Table 1. In Figure 1, the number of unit cells is defined to be

$$N = \frac{2\pi}{\varphi} \quad (7)$$

where $\varphi_{\text{lower}} \leq \varphi \leq \varphi_{\text{upper}}$ and $l_1 \approx l_2 \approx l$.

$$\varphi_{\text{upper}} = 2 \cdot \tan^{-1} \left(\frac{l_1 \cos \theta}{R_1 + \frac{h}{2} + l_1 \sin \theta} \right)$$

$$\varphi_{\text{lower}} = 2 \cdot \tan^{-1} \left(\frac{l_2 \cos \theta}{R_1 + \frac{3h}{2} + l_2 \sin \theta} \right)$$

It should be noted that l_1 and l_2 are not exactly the same due to the change of a circumferential length along the radial direction. However, the difference of lengths may be negligible; the maximum difference between l_1 and l_2 is 0.05mm for the given cellular geometries.

II). SETUP FOR FINITE ELEMENT ANALYSIS

A lunar rover wheel having a diameter of 482.6mm (19inch) and a width of 24.5mm (1 inch) is designed with a shear band height of 12.7mm (0.5inch). The thicknesses of the inner and outer layers and hub are fixed to 1mm. The thickness of spokes is 2mm. A schematic of the lunar rover wheel made up of a cellular shear band is shown in Figure 2. Every component is designed with a shear flexible quadratic beam element (B22 in ABAQUS) except spokes. Spokes are modeled with a linear truss element (T2D2 in ABAQUS) and they are supposed to support a tension force without supporting compression force. Spokes are tie constrained between the hub and the inner layer. The hub behaves as a rigid body under a rigid body constraint.

Clemson University and NASA JPL have designed a moon rover wheel to support a vertical force of 2500N for a four-inch wide wheel. Due to the manufacturing limitation of metallic cellular shear bands, four one-inch wide wheels are considered in this study and the four wheels will be tied together. Therefore, a single vertical force for a one-inch wide wheel is 625N (2500N/4).

The vertical force of 625N is applied at the center point of the hub as can be seen in Figure 2. When a vertical force of 625N is applied, the wheel structure is deformed and a contact interaction occurs between the shear band and the ground. Contact pressures along the outer layer of a shear band are investigated with the different cellular shear bands.

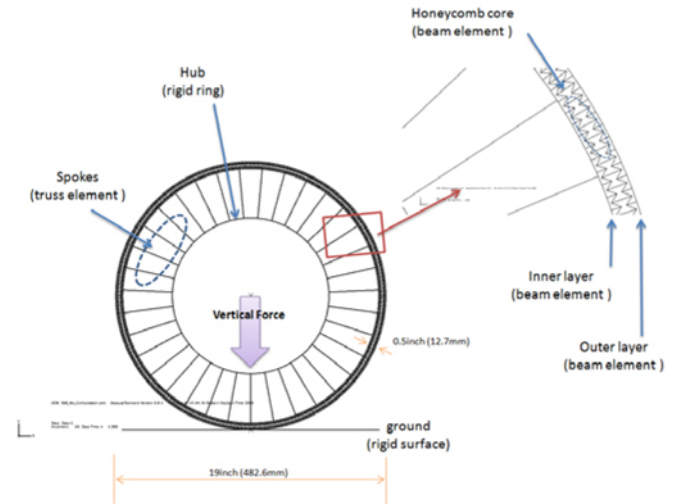


Figure 2. A Schematic of a Wheel Made Up Of a 7075-T6 Cellular Shear Band

DEFORMATION OF CELLULAR SHEAR BANDS AND CONTACT PRESSURE

When a vertical force of 625N is applied at the center of the wheel, the cellular shear bands having cell angles of 60° , 30° , and -20° , turned out to exceed the 7075-T6's yield strength of 500MPa. This is caused by a lower $(\gamma_{12}^*)_{\max}$ which is lower than 0.1. On the other hand, the cellular structures whose cell angles are -30° , -50° , and -65° show that the cellular shear bands are deformed within 7075-T6's elastic range when the vertical loading of 625N is applied.

Figure 3(a) and (b) show the deformed shape of the wheel and a cellular shear band ($\theta = -30^\circ$, $h = 2l$) when a vertical force of 625N is applied. The corresponding contact pressure on the outer layer of the shear band is also shown in Figure 3(c). The maximum von Mises stress is 472MPa at the middle vertical leg near the intersection between a vertical leg and an inclined leg near the edge of the contact zone where the shear effect is maximized as marked with dotted circles in Figure 3(a). The maximum contact pressure is about 0.47MPa at the center of the contact zone. Five peaks are shown with the cellular shear band and the peaks are getting lower, e.g., the contact pressure peaks are about 0.17MPa at the edge of the contact zone.