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Research Paper

# Effect of solid distribution on elastic properties of open-cell cellular solids using numerical and experimental methods

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ABSTRACT

Effect of solid distribution between edges and vertices of three-dimensional cellular solid with an open-cell structure was investigated both numerically and experimentally. Finite element analysis (FEA) with continuum elements and appropriate periodic boundary condition was employed to calculate the elastic properties of cellular solids using tetrakaidecahedral (Kelvin) unit cell. Relative densities between 0.01 and 0.1 and various values of solid fractions were considered. In order to validate the numerical model, three scaffolds with the relative density of 0.08, but different amounts of solid in vertices, were fabricated via 3-D printing technique. Good agreement was observed between numerical simulation and experimental results. Results of numerical simulation showed that, at low relative densities ($<0.03$), Young's modulus increased by shifting materials away from edges to vertices at first and then decreased after reaching a critical point. However, for the high values of relative density, Young's modulus increased monotonically. Mechanisms of such a behavior were discussed in detail. Results also indicated that Poisson's ratio decreased by increasing relative density and solid fraction in vertices. By fitting a curve to the data obtained from the numerical simulation and considering the relative density and solid fraction in vertices, empirical relations were derived for Young's modulus and Poisson's ratio.



## 1. Introduction

Cellular solids are a complex of cells made of an interconnected network of edges and/or plates. They are usually categorized as 2-D and 3-D cellular solids. The former is known as honeycombs, and the later is known as foams. The foams are classified into open and closed cells. In contrast to closed-cell foams, fluid could pass through the media in open-cell foams.

Materials with cellular structure occur widely in nature as optimized solutions. Although they are highly acknowledged, optimization mechanisms have been poorly understood.

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Naturally, most of the structures are multifunctional and all functions should be optimized at the same time, which is known in mathematics and engineering as multi-objective optimization. Inspired by the nature, it can be concluded that cellular solids are a good candidate for the optimized use of materials both in structural or multi-functional applications. Gibson (2005) provided a good review of mechanical properties of some natural cellular solids. Meyers et al. (2008) properly reviewed the structure and properties of biological cellular materials. Banhart (2001) performed a proper survey on the manufacturing and application of metal foams. Gibson and Ashby (1997) presented an excellent introduction on cellular materials and their properties in conjunction with an analytical solution for predicting their properties.

Mechanical properties of cellular solids are mainly affected by four factors of (1) relative density, (2) material properties and microstructure of bulk material, (3) cell topology, and (4) shape and geometrical properties of cell walls. Most of the studies have focused on the effect of cell topology and relative density on the mechanical properties of cellular solids. Effect of cell geometry and irregularities has been extensively investigated by different researchers (Van Der Burg et al., 1997; Zhu et al., 1997, 2000, 2001; Roberts and Garboczia, 2001, 2002; Gan et al., 2005; Luxner et al., 2005, 2009; Amirkhani et al., 2012; Babaee et al., 2012; Alkhader and Vural, 2008; Gong et al., 2005; Jang et al., 2008). Voronoi tessellation is the most promising method for modeling irregular topologies. Recently Zhu et al. (2014) studied geometrical properties of Voronoi tessellation with various degrees of irregularities.

Zhu et al. (1997) derived analytical equations for elastic properties of open-cell foam with tetralaidecahedral unit cell. They concluded that tetrakaidecahedral was nearly isotropic. Using numerical simulations Luxner et al. (2007) investigated mechanical properties of scaffold with different topologies. They showed that scaffolds with Kelvin (tetrakaidecahedral) unit cell had less anisotropy in mechanical properties than other regular structures. Francois et al. (2014) investigated elastic properties of nearly isotropic stretch-dominated structure experimentally. They also conducted numerical simulations on image-based finite element models. Stretch-dominated structures show higher stiffness compared to bending-dominated ones at the same relative density. However, stretch-dominated structures show significant softening post-yield response due to buckling of struts (Deshpande et al., 2001). This behavior makes them less favorable in shock-absorbing applications.

Isotropic properties of scaffolds with tetrakaidecahedral unit cell make them favorable for designing bio-implants and other light weight components, which is due to the fact that the response of complicated geometries to various loading conditions could be more accurately predicted with less effort than anisotropic materials.

In addition to the topology of cells, shape of walls and ligaments could also affect the mechanical properties of cellular solids. Effect of the shape of cross-section on mechanical properties of cellular solids has been studied in many works, e.g. Zhu et al. (1997). But, the importance of material distribution between cell faces, edges, and vertices, which could alter the mechanical properties of cellular solids, has been neglected in most studies. Simone and Gibson (1998) studied this effect on the elastic properties and strength of honeycombs and closed cell foams and concluded that, in honeycombs, redistribution of materials from edges to plateau borders initially increased Young's modulus and strength. After a critical point, further shifting of the material to borders decreased the mechanical properties of the structure. Although not investigated by them, they suggested that open cell would show a similar behavior. In close cell foams, material redistribution from faces to borders had little influence on Young's modulus while reducing the peak strength.

Gong et al. (2005) demonstrated that considering the non-uniform cross-section of ligaments in finite element beam models increased predicted stiffness and strength of open-cell foams with tetrakaidecahedral unit cell. Lin et al. (2013) studied the effect of solid distribution on the out-of-plane elastic properties of honeycombs. Storm et al. (2013) investigated effect of geometrical details on mechanical properties of open-cell foam with kelvin unit-cell. They suggested that next to relative density, the geometry of ligaments influences mechanical properties of open-cell foams In addition; by comparing results of volumetric models by beam models they concluded that joint stiffness had substantial effect on stiffness of open-cell cellular solids. To the best knowledge of the authors, there has been no systematic study on the effect of solid distribution on mechanical properties of open-cell foams and no experimental study of the validation of numerical results for solid distribution has been done thus far. The thing that is especially important in designing scaffolds is that additive manufacturing process allows for easily changing the fraction of solid between vertices and edges. In bone implant scaffolds, elastic modulus of bone and scaffold should be matched; otherwise, the stress shielding effect would occur. Solid distribution provides additional freedom for altering the mechanical properties of scaffold in order to achieve the desired mechanical properties at the same relative density and with the same material. Results of this study would help in designing more optimized scaffolds for light weight structures and other tissue engineering applications.

The aim of this work was to evaluate the effect of material distribution on elastic properties of open-cell cellular solids with tetrakaidecahedral unit cell by numerical simulation and experimental testing. This paper is organized as follows. Section 2 provides information about generating 3D CAD models with various relative densities and solid fractions of tetrakaidecahedral unit cell. Finite element modeling and loading and boundary condition are also discussed. Experimental procedure along with fabrication and testing methods are presented in Section 3. Results of finite element simulation and experimental testing are discussed in Section 4. Finally, some concluding remarks are presented in Section 5.

## 2. Numerical simulation

### 2.1. Geometry

Kelvin polyhedral which was first proposed by Lord Kelvin (Thomson, 1887) as a solution for the problem of space-filling