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Mechanical response of cellular solids: Role of cellular topology and microstructural irregularity

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ABSTRACT

Rapid advance in additive manufacturing techniques promises that, in the near future, the fabrication of functional cellular structures will be achieved with desired cellular microstructures tailored to specific application in mind. In this perspective, it is essential to develop a detailed understanding of the relationship between mechanical response and cellular microstructure. The present study reports on the results of a series of computational experiments that explore the effect topology and microstructural irregularity (or non-periodicity) on overall mechanical response of cellular solids. Compressive response of various 2D topologies such as honeycombs, stochastic Voronoi foams as well as tetragonal and triangular lattice structures have been investigated as functions of quantitative irregularity parameters. The fundamental issues addressed are (i) uniqueness of mechanical response in irregular microstructures, and effects of (ii) specimen size, (iii) boundary morphology, (iv) cellular topology, and (v) microstructural irregularity on mechanical response.

1. Introduction

Although known and used for a long time, cellular solids are getting a growing attention due to their tremendous potential in diverse engineering applications in automotive, aerospace, naval and biomedical industries. So far, in overwhelming majority of applications, cellular solids have been used as space-filling core materials (e.g., aluminum honeycombs, metal or polymeric foams) in sandwich structures essentially to increase specific flexural stiffness of shell/plate elements [1,2]. In these conventional applications, lightweight and sufficient shear/compressive properties have been major requirements from cellular cores since they are not designed as primary load bearing members.

On the other hand, rapid progress in additive manufacturing processes such as solid freeform fabrication (SFF) opens new horizons for cellular solids as it makes possible to fabricate parts of any arbitrary material composition and internal micro-architectures at mesoscopic length scale, i.e., cell sizes in the range of 0.1–10 mm [3–9]. In other words, it offers us a unique tool to fabricate lightweight and functionally optimized cellular structures with unprecedented properties for novel applications. For example, guided tissue regeneration is gaining importance in the field of orthopedic tissue engineering as need and technology permits the development of site-specific engineering approaches [10]. Computer aided design (CAD) and finite element analysis (FEA), hybridized with manufacturing techniques such as SFF, is hypothesized to allow for virtual design, characterization, and production of not only scaffolds optimized for tissue replacement but also functionally optimized cellular structures (FOCS) for primary load bearing applications, where both material composition and cellular topology can be optimized for prescribed mechanical as well as non-mechanical functions.

However, our current state of understanding of the mechanical behavior of cellular solids is heavily based on first order approaches in which the relative density of cellular material is the dominant parameter employed in modeling. This strong

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relationship between the relative density and mechanical properties has been well documented by the comprehensive study of Gibson and Ashby [1]. On the other hand, the relationship between the details of inner cell structure (cellular topology and morphology) and macro-mechanical behavior still remains poorly understood. Now, with the forthcoming capability to fabricate any arbitrary cellular topology, the challenge is to develop a robust understanding and modeling of property–topology relationships for cellular solids, and identify the influence of the independent parameters of cellular topology – such as cell-based relative density (instead of overall relative density approach), cell wall connectivity, cell shape, cell size, regularity and distribution, etc. – on overall mechanical response. It is obvious that the hybridized design-analysis-manufacturing approach needs a strong knowledge base scientifically driven by topology–property research in order to realize the full potential of cellular solids.

Apart from the unique opportunities that additive manufacturing processes offer for cellular solids, the improvement of conventional manufacturing methods and associated cost reductions have also generated an increased and renewed attention in cellular solids due to their excellent shock attenuation and impact energy dissipation capabilities, which naturally involves high loading rates and large inelastic deformations [2,11–14]. One of the major driving forces behind this renewed interest in the dynamic behavior of cellular solids is the demand from automotive industry since these low density materials offer the potential of lightweight designs with improved crashworthiness and fuel economy [15–17].

In this perspective, it is fair to state that, today, cellular solids constitute an important and emerging part of the pool of engineering materials with their potential advantages in a variety of applications ranging from protective packaging of delicate electronic components (e.g., cell phones) to crash and blast mitigation in automobiles, aerospace and naval structures along with unique multifunctional applications in biomimetic prostheses. With this global picture and motivation in mind the present study reports on the preliminary results of a computational study that explores the existence of a relationship between the cellular microstructure and macro-mechanical response. In the following sections we first discuss the methodology for the generation of various cellular structures along with the details of finite element (FE) analysis and boundary conditions. Then, the influence of specimen size and boundary layer morphology on macro-mechanical response of cellular solid is analyzed in order to provide a proper setting for further parametric analysis and to prevent any possible misinterpretation of the results. This is followed by a detailed discussion of our parametric study designed to investigate the effects of cellular topology and microstructural irregularity in two-dimensional cellular solids.

2. Methodology

Cellular networks may have stochastic (e.g., foams) or periodic (e.g., honeycombs) topologies depending on the distribution of solid phase. Cellular solids with stochastic topologies have a tendency to exhibit isotropic properties mainly due to random shape and orientation of cells (reminiscent of polycrystals), while those with periodic topology usually have anisotropic properties (reminiscent of highly textured polycrystals).

For periodic topologies, mechanical models based on unit cell approach have proved to be useful in understanding some of the key aspects of the mechanical behavior of cellular solids such as the dependence of failure properties on relative density and on the failure mode of individual cells [1,18–22]. However, most cellular materials usually have random cells. Thus, despite their proven utility, unit cell models do not accurately represent the microstructure of most real foams. For better representation of microstructure in stochastic topologies, Voronoi tessellations and finite element analysis have been employed to study the elastic and uniaxial yield behaviors of 2D and 3D foam structures [23–27]. Voronoi tessellations have been long known and used in many diverse fields from crystallography to astronomy for modeling purposes. A comprehensive review of the concept and its applications can be found in [28].

2.1. Construction of Voronoi tessellations

It seems particularly suited to generate 2D or 3D foam-like cellular networks by Voronoi technique because of the strong similarity between the mathematical process of Voronoi cell construction and the physical process of foam growth. Solid foams are often formed by the nucleation and growth of bubbles. If the bubbles all nucleate randomly in space at the same time, and grow at the same linear rate, then the resulting structure is a Voronoi tessellation. According to this description, the topology of final Voronoi structure is completely and unambiguously determined by the initial distribution of the nuclei, or seed points. One way of generating n number of seed points is to randomly distribute them over a prescribed area A_0 without any constraints. This approach results in what is known as Poisson or Γ-distribution. Voronoi structures constructed by Γ-distribution have a tendency to exhibit irregular topology with significant variation in cell size. Alternatively, one can enforce the constraint that the distance between any two random generation points is larger than a minimum prescribed value, δ. This leads to δ-distribution by which more uniform cell size distribution can be achieved.

We will follow a procedure recently introduced by Zhu et al. [29] which allows describing a parameter to quantify the regularity of 2D Voronoi tessellations based on δ constraint. This procedure starts by first finding the constant distance d_0 between any two adjacent seed points if n number of regular identical hexagonal cells (honeycombs) is constructed in the square area A_0. This distance is given by

$$d_0 = \left(\frac{2A_0}{n\sqrt{3}}\right)^{1/2} \tag{1}$$