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Size effects in foams: Experiments and modeling

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A B S T R A C T

Mechanical properties of cellular solids depend on the ratio of the sample size to the cell size at length scales where the two are of the same order of magnitude. Considering that the cell size of many cellular solids used in engineering applications is between 1 and 10 mm, it is not uncommon to have components with dimensions of only a few cell sizes. Therefore, both for mechanical testing and for design, it is important to understand the link between the cellular morphology and size effects, which is the aim of this study. In order to represent random foams, two-dimensional (2D) Voronoi tessellations are used, and four representative boundary value problems – compression, shear, indentation, and bending – are solved by the finite element (FE) method. Effective elastic and plastic mechanical properties of Voronoi samples are calculated as a function of the sample size, and deformation mechanisms triggering the size effects are traced through strain maps. The modeling results are systematically compared with experimental results from the literature. As a rule, with decreasing sample size, the effective macroscopic stiffness and strength of Voronoi samples decrease under compression and bending, and increase under shear and indentation. The physical mechanisms responsible for these trends are identified.

Contents

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1. Introduction

The mechanical behavior of a cellular material depends on its relative density (typically raised to a power between 1 and 3), the properties of the cell wall material, and the cell geometry (i.e., the number, shape, and thickness of cell walls and faces). Moreover, the individual response of cells to a loading is strongly influenced by their location in the material: deformation of cells located in the bulk, surrounded by other cells, or located near the edges where kinematic boundary conditions are applied, are more constrained compared to cells adjacent to stress-free boundaries. If the length, width, and thickness of a foam sample are all large enough to include many cells, the differences in per-cell response to a macroscopic loading are averaged out, leading to size-independent effective properties. If, however, one of the structural dimensions contains only a few cells, as is the case in many practical applications, the effective response of the foam is dictated by the individual excitements of the cells, resulting in a size-dependent mechanical behavior.

Early experiments exploring size effects in foams date back to the 1980's. Lakes [1,2] showed that the bending and torsional rigidities increase with decreasing sample size, for an open- and a closed-cell polymeric foam, respectively. For an open-cell reticulated vitreous carbon foam, on the other hand, Brezny and Green [3] showed that both the Young's modulus and the bending strength decrease dramatically with decreasing sample size. Similarly, Anderson et al. [4] and Anderson and Lakes [5] observed a reduction with decreasing sample size in the bending and torsional rigidities of a closed-cell polymethacrylimide foam, and of an open-cell copper foam, respectively. Most of the other bending experiments for foams concern sandwich panels, where a foam core material separates two face sheets of dense solids (see e.g. Bart-Smith et al. [6,7], Crupi and Montanini [8]). The deformation and the failure mechanisms of sandwich panels strongly depend on the foam core thickness (see e.g. Styles et al. [9]).

Bastawros et al. [10] conducted compression tests on closed-cell aluminum foams (trade name Alporas; Shinko Wire, Amagasaki, Japan), and Andrews et al. [11] on both closed-cell Alporas and open-cell aluminum foams (Duocel; ERG, Oakland, CA). Both studies showed that the compressive stiffness and strength of these foams reduce with decreasing sample size. Jeon and Asahina [12] tested Alporas samples without structural defects – such as partially coupled cells, missing cells, and collapsed cells, normally observed in Alporas foams – andn showed that the Young's modulus decreases with decreasing sample size, although the compressive strength was found to be size-independent. Several other researchers investigated the deformation mechanisms in a variety of metal foams under compression (e.g. Bastawros et al. [10], Bart-Smith et al. [13], Dannemann and Lankford [14], Hakamada et al. [15], Park and Nutt [16], Wang et al. [17]); they all reported that deformation localizes in narrow bands.

An increase in shear stiffness and strength with decreasing sample size is observed for aluminum foams (e.g. Andrews et al. [11], for both Alporas and Duocel; Chen and Fleck [18], only for Alporas). Rakow and Waas [19] analyzed size effects and deformation mechanisms under shear for an aluminum foam produced by the melt route. They showed that the average shear strain is much larger for the cells located in the bulk than it is for the cells bonded to the rigid platens – through which the shear load is applied. Kesler and Gibson [20] conducted three-point bending experiments on