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Viewpoint Paper

On the load-bearing efficiency of open-cell foams: A comparison of two architectures related to two processes

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Abstract—Using a simple beam element, this study estimates the elastic stiffness of two isotropic open-cell foam architectures that approximate, respectively, the space between tightly packed fluid bubbles and that defined between densified solid particles, and finds little difference between the two microstructures above a relative density of a few per cent.

Keywords: Foam porous material mechanical properties; Elastic behavior; Micromechanical modeling; Finite element analysis architecture

1. Introduction

The architecture of solid open-cell foams consists of, by definition, a network of solid struts that connect at solid nodes and surround interconnected pores [1]. The specifics of this architecture matter: how the struts and nodes are shaped and arranged governs much of the performance of open-cell solid foams.

Methods of producing solid structures of polymer or metal now exist with considerable freedom in the definition of their architecture; examples include solid freeform fabrication, the bonding of shape-optimized trusses, together with precision investment casting for metals. Such methods open the way, by the freedom that they afford the designer, for the production of open-cell periodic structures that are optimized for performance in, for example, their ability to resist elastic deformation or to conduct and transfer heat [1–14].

Shape-optimized "designer" structures are, however, still costly to produce; there are other less flexible but more expeditious ways to produce open-cell foams. One is foaming: if a swarm of similar close-packed bubbles is created within a liquid that is later solidified and subjected to reticulation (by which cell walls are broken or removed), a relatively regular open-cell solid foam results [1,15]. Another method is replication: here, the pores are created by a bonded particulate solid space holder that is eventually removed, typically by dissolution, once open pores between the space holder particles have been filled with solid [16,17].

In such "simple" man-made open-cell foams, the architecture is sub-optimal, somewhat stochastic, and governed by the process. Both processes produce struts that have a more or less triangular cross-section, since struts are in both cases defined as the tunnel situated between three touching bubbles or space-holder particles. The struts also generally connect four at a time and in roughly tetrahedral fashion at each node, since most nodes are defined as the space between four touching bubbles or particles. And, since the two nodes at each end of a given strut are defined by the same three touching bubbles or particles, the orientation of each set of three struts to which the central strut is connected at either end has to be roughly the same.

In both foamed and replicated microcellular solids, the structure is also random: each pore is surrounded by a variable number of struts, the length of which is not regular, the shape of which is in general slightly curved with an uneven cross-section, and which are not strictly tetrahedrally connected. Some nodes are also more complex in shape: for example, if these are defined where two bubbles or particles were close, yet did not touch.

Still, despite irregularity in its arrangement and dimensions, the most basic architectural building block (or "brick") of foamed and replicated open-cell microcellular solids remains the assembly of one strut of more or less triangular cross-section, connected at each of its ends to a node at which three other similar struts emanate, the

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four struts at each node making roughly equal angles with one another. In this building block, the cross section of each strut is oriented so as to have one of its edges in the common plane defined by the axes of two neighbouring struts.

The present study examines to what extent realistic extreme variations in the shape of this basic building block, as determined by contrasting specifics of the two processes of foaming or replication, influence the stiffness of the resulting open-celled foam. This question has its importance: strut tapering has been shown, in periodic unit-cells of assembled struts, to influence the elastic stiffness of periodic open-cell foams, while leaving the scaling exponent N between the stiffness and relative density near $N = 2$ if the overall strut shape is kept constant with changing relative density [18–23]. Noteworthy in the context of this study is the work of Gong et al. [20], who measured and simulated the solid distribution along struts of a polymer and a metal open-cell foam, to show that capillary forces, which govern the distribution of the liquid between bubbles in the foam precursor and thicken the struts somewhat near the nodes, improve the material stiffness by as much as 70% compared with what would be obtained with beams of uniform cross section [20].

Compared with recent models of the deformation of open-cell foams, this study takes a simplified approach, which is somewhat similar to that of Gibson and Ashby [1] in that it focuses on the tensile and bending deformation of a single elementary seven-strut building block. Thus, the present study does not consider complex periodic three-dimensional unit cells of several beams arranged in large random networks or along regular (e.g., Kelvin-cell) patterns (although this elementary building block can be stacked to produce a regular structure, namely the hexagonal diamond structure also known as Lonsdaleite [24]). Rather, it considers the deformation of a single beam and its immediate surroundings, as in early models of the deformation of open-cell solids, based on the reasoning that the stiffness of any assembly, be it regular or irregular, of such struts will scale as the bending stiffness of this seven-strut elementary building block. However, the beam itself is modelled with some sophistication, since the study considers deformation of the entire seven-strut building block and uses finite-element simulation to evaluate its stiffness.

2. Modelling

Several deformation modes can be considered for this building block; the present short contribution focuses on (i) tensile loading of the seven-beam structure parallel to its central, "body", beam and (ii) bending under shear loading, as was done by Gibson and Ashby [1]. Two extreme shapes are considered for the building block; these mimic one of the main differences between the two open-cell foam architectures that are produced by the two processes of foaming or replication.

When it is defined by bubbles in a foaming process, the building block shape is governed by capillarity: struts are plateau borders, and the nodes are smooth rounded concave transitions with the same overall curvature as the edges of the plateau borders (see Figs. 1.8, 2.7 and 6.6 in Ref. [15] for drawings of these shapes and Refs. [20,21,23,25] for examples in real microcellular polymer or metal of this class). Although somewhat tapered near the nodes (to the foam's structural benefit, as shown by Gong et al. [20]), the struts tend to be relatively straight. The nodes are furthermore small, and the "windows" that struts define between pores are close to polygonal (see for example Fig. 5.3 of Ref. [15] and micrographs or tomographs in Refs. [20,21,23,25,26]).

In replicated structures, by contrast, the struts and node surfaces are far from capillary equilibrium. Here the pores are defined, not by soft bubbles, but by the necks that form between hard solid particles after these have undergone partial densification by processes such as cold-pressing or sintering. If one assumes monomodal spherical solid place-holder particles, windows between pores are close to circular; hence, struts are strongly tapered, and nodes tend to be much thicker; see Figures 7 and 8 in Ref. [27] for an actual example in which the particles were spherical.

Thus, two extremes are considered, namely untapered struts defining polygonal pore windows, on the one hand, and strongly tapered struts that define circular windows between pores, on the other. The building block is simplified by taking the struts to be straight beams of triangular cross section, and the nodes to be regular flat-faced octahedra at which struts are connected at four regularly spaced faces, themselves separated by flat node surfaces (as in Ref. [28]). The angle between struts in such structures is dictated by their tetrahedral arrangement at each octahedral node: this angle, in turn, dictates that each window be surrounded by roughly five beams (in conformance with the average structure of dry foams [15]). Note that the average angle between struts in such a five-beam window is 72°, which is very close to the angle of 70.53° between struts in the present assembly.

To approximate the volume of each cell, it is assumed that pores are, on average, surrounded by 30 such beams and by 12 windows, in satisfaction of Euler's theorem for dry foams [15], and as in a pentagonal dodecahedron (regardless of the fact that regular pentagonal dodecahedra do not define a space-filling periodic element: the irregularities present in actual foams compensate for that). Each strut is shared with two other pores, such that the volume of solid per pore is that of 10 struts plus the corresponding node volume. The relative density of solid V_s is thus estimated as being the ratio of the volume of solid in one strut plus one-half of a node (i.e., one-quarter of the octahedral node at either end of the strut), divided by one-tenth of the volume of a pentagonal dodecahedron with an edge length equal to the distance a between the centroid of the octahedral nodes at each end of one strut. Examples of the basic building blocks thus constructed are given in Figure 1, at 1.7% and 20% relative density for each of the two geometries considered.

At the six far ends of peripheral struts, a tetrahedron was connected to the struts instead of an octahedral node; in this way, each strut presents a flat parallel surface at either end of the building block, while still preserving the overall building block proportions and shape (the volume of a tetrahedron is one-quarter that of an octahedron with the same edge length).