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The variation in elastic modulus throughout the compression of foam materials

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ABSTRACT

We present a comprehensive experimental study of the variation in apparent unloading elastic modulus of polymer (largely elastic), aluminium (largely plastic) and fibre-reinforced cement (quasi-brittle) closed-cell foams throughout uniaxial compression. The results show a characteristic "zero-yield-stress" response and thereafter a rapid increase in unloading modulus during the supposedly "elastic" regime of the compressive stress–strain curve. The unloading modulus then falls with strain due to the localised cell-wall yielding or failure in the pre-collapse stage and the progressive cell crushing in the plateau stage, before rising sharply during the densification stage which is associated with global cell crushing and foam compaction. A finite element model based on the actual 3D cell structure of the aluminium foam imaged by X-ray computed tomography (CT) predicts an approximately linear fall of elastic modulus from zero strain until a band of collapsed cells forms. It shows that the subsequent gradual decrease in modulus is caused by the progressive collapse of cells. The elastic modulus rises sharply after the densification initiation strain has been reached. However, the elastic modulus is still well below that of the constituent material even when the "fully" dense state is approached. This work highlights the fact that the unloading elastic modulus varies throughout compression and challenges the idea that a constant elastic modulus can be applied in a homogenised foam model. It is suggested that the most representative value of elastic modulus may be obtained by extrapolating the measured unloading modulus to zero strain.

1. Introduction

Foam materials, made of polymers, metals and other engineering or natural materials, are being used increasingly in many engineering fields for energy absorption, thermal insulation, acoustic damping and sandwich cores. In contrast to condensed solid materials, foams normally have an apparent elastic modulus that is quite different from the initial loading slope of the uniaxial compressive stress–strain curve, even when the deformation is small and the strains are well within the commonly recognised "elastic regime" [1–7]. Non-linearity in the stress–strain curve and elastic hysteresis may also occur during unloading-reloading loops, making it difficult to idealise and quantify the elastic properties of foams.

Consequently, the international standard [8] for compression testing of porous and cellular metals is cautious in giving guidelines for the measurement of elastic modulus. It defines an elastic gradient as the slope of a straight line connecting two points in the unloading–reloading curve and states that "the elastic gradient represents a porosity-dependent rigidity, not a modulus of the material, and generally changes during the course of compression". The complex nature of the elastic behaviour has caused much confusion and uncertainty when a homogenised foam model is to be defined, and therefore, this issue should be clarified.

Despite the lack of a recognised standard method, Ashby et al. [7] recommended that a constant unloading slope can be used to characterise the elastic modulus of metal foams. Furthermore, they suggested the following equations for the correlation between the elastic modulus and the structural parameters of a cellular material

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$$\text{Open-cell foam}: \quad E = C_1 E_s \left(\frac{\rho}{\rho_s}\right)^2 \tag{1}$$

$$\text{Closed-cell foam}: \quad E = C_2 E_s \left[0.5\left(\frac{\rho}{\rho_s}\right)^2 + 0.3\frac{\rho}{\rho_s}\right] \tag{2}$$

where E and E_s are the elastic modulus of the foam and the constituent material, respectively, ρ/ρ_s is the relative density, and C_1 and C_2 are material constants that range from 0.1 to 4.0 and 0.1 to 1.0, respectively. Although their recommended equations have been accepted by many researchers for different types of foams [2,3,5,6,9,10], the unloading slope has been determined at different compressive strains to obtain the elastic modulus and the material constants in Eqs. (1) and (2). For instance, Jeon and Asahina [11] used the unloading slope at a strain of 0.06 for aluminium Alporas foam while Andrew et al. [2] determined it when the stress reaches 75% of the expected plastic collapse stress. These previous studies assumed that the elastic modulus is invariant at small strains, but variations in modulus with strain have been observed even well before the collapse (or yield) strain, see Fig. 4 in Ref. [5]. Therefore, a more reliable method should be used to accurately determine the elastic modulus for cellular solids based on a better understanding of its variation with strain.

Ideally, one would like to evaluate the elastic modulus at a small strain (approaching zero), but this can present experimental difficulties [11]. An unexpectedly low stiffness has been observed at small strains for aluminium foams and this is usually attributed to the premature local yielding of cell walls occurring well before macroscopic yielding, as shown by surface strain measurements [5] and realistic finite element simulations [12]. However, it is not yet clear whether other factors (e.g. weakened load transfer through uneven surface cells due to mechanical cutting) also make contributions. Furthermore, since uniaxial compression actually involves complex modes of cell deformation at the meso-scale, it is reasonable to ask whether the discrepancy in initial loading and unloading stiffness values is an intrinsic characteristic of aluminium foams or an experimental observation depending on test conditions. It is also worthwhile to examine other types of foam (e.g. polymer and cement foams) to evaluate how generic this behaviour is and to identify the underlying mechanisms.

When compression proceeds into the so-called plateau stage at which the stress is almost constant over a large range of strain, the unloading modulus has been found to decrease with strain until the densification stage begins. This has been observed for aluminium [4,10] and polymer [13] foams. McCullough et al. [4] attributed this to the change of cell geometry with deformation. Flores-Johnson et al. [13] suggested that the decrease in the elastic modulus arises from heterogeneous deformation (i.e. progressive cell crushing), proposing a formula for modulus degradation in terms of the nominal strain. For trabecular bone, Moore and Gibson [14,15] observed the accumulation of micro-damage (i.e. micro-cracks) under uniaxial compression and developed an analytical model to

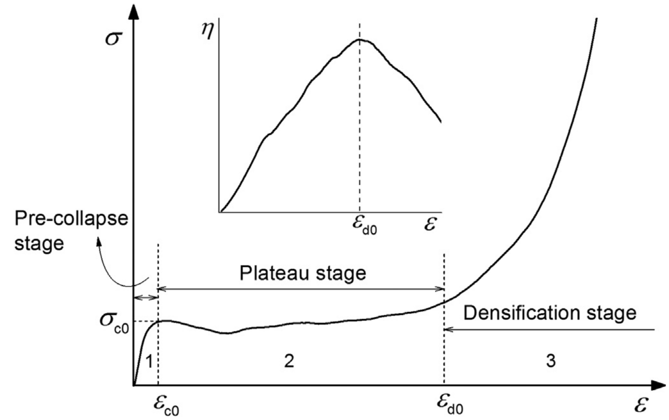

Fig. 2. Schematic diagram indicating the three compression stages (inset showing $\eta - \varepsilon$ curve).

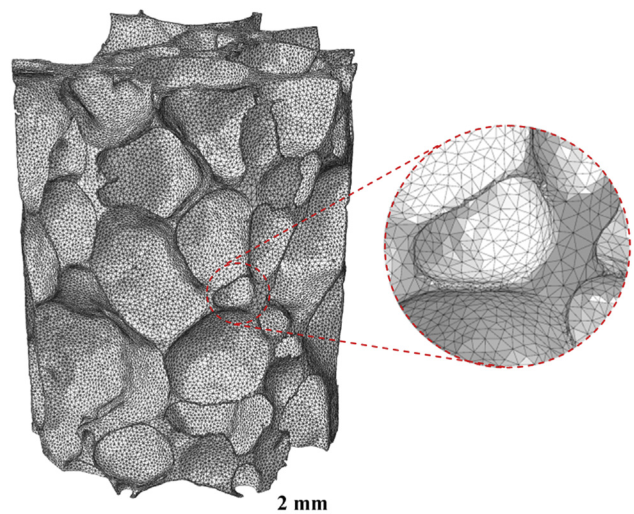

Fig. 3. Finite element model based on the actual cell structure obtained from the CT image of the aluminium foam.

Fig. 1. Photographs of the cement (left), aluminium (middle) and polymer (right) foams: (a) before compression and (b) after densification.