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Strain rate dependent compressive properties of glass microballoon epoxy syntactic foams

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ABSTRACT

Lightweight glass microballoon epoxy syntactic foams have a high strength-to-weight ratio, making them attractive for transport applications. A better understanding of the compressive properties of such foams is required to improve predictive modelling tools and develop novel formulations. In this study, the response of a foam to compressive loading was experimentally investigated over strain rates from 0.001 to 4000 s^{-1}. The stress–strain response, deformation/damage history and volume change were examined quantitatively and/or qualitatively; all of these parameters exhibit strain rate sensitivity. Combined finite element stress analysis and microscopic observations reveal that heterogeneous (localised) damage arises in the foam due to the coexistence of two failure modes: (i) crushing of glass microballoons dominating in the central part and (ii) shear cracking of the epoxy matrix that forms and propagates from the corners. As the strength of the epoxy matrix increases with increasing strain rate, cracking of glass microballoons begins to dominate over the matrix/microballoon debonding, resulting in macroscopic strain rate dependency of compressive properties.

1. Introduction

Glass microballoon epoxy syntactic foams have been increasingly used in automotive and aerospace applications due to their high strength-to-weight ratio, good impact resistance and excellent energy dissipation capacity. In order to simulate the service performance of syntactic foam components, a predictive tool requires accurate mechanical properties as input data. The mechanical behaviour of syntactic foams is intrinsically determined by basic material properties (e.g. chemical composition of matrix materials) and the unit cell structure (e.g. geometry of glass microballoons and their distribution) [1–6]. Extrinsic factors such as strain rate also significantly influence the mechanical response of cellular materials [2,3,5,7–9]. Therefore, a better understanding of compressive properties of glass microballoon epoxy syntactic foams at a wide range of loading rates is required to improve the predictive model and develop novel formulations in the future.

Most studies of the compressive properties of metallic or polymeric syntactic foams have focused on quasi-static conditions (e.g. at a strain rate of 0.001 s^{-1}) [1,6,10–12]. These reports characterise the stress–strain response, damage evolution, failure features and energy dissipation capacity, and extensively explore the effect of intrinsic factors such as matrix material properties [1], geometry and volume fraction of microballoons, which in turn govern the relative density of the foam [6,12]. However, there is a paucity of studies in the literature focusing on the dynamic properties of glass microballoon epoxy syntactic foams, despite their applications at high loading rates [5,13,14]. These studies have demonstrated the strain rate dependency of the peak strength of syntactic foams [5,13], but none of them went to large enough strain to examine the energy dissipation capacity under deformations at different loading rates, an important characteristic of foams when used for packaging and protection. In addition, the strain rates available in these investigations are typically too sparse to develop a more complete constitutive equation necessary for structural analysis of components made of syntactic foams.

To predict accurately the safety and service behaviour of a structural component also requires characterisation of volume (or density) history during compressive deformation [15–18]. The volume change in the plastic stage is an important parameter to quantify the constitutive response of cellular materials. However, this is not an area that has been addressed for the materials of interest here.

The aim of the study reported in the current paper is to investigate the strain rate dependent compressive behaviour of glass microballoon epoxy syntactic foams, including stress–strain response, deformation history, failure mode and energy dissipation. The effect of strain rate on compressive properties was examined at

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a number of strain rates ranging from 0.001 to 4000 s^{-1}. An empirical constitutive equation was developed to quantitatively describe the strain rate dependency of peak and plateau stresses, two key features to determine the fracture resistance and energy dissipation capacity of syntactic foams, respectively. The volume change history during compression was also quantified as a function of strain rate so as to provide information for more accurate structural impact simulation of syntactic foam components. The deformation/failure mechanisms involved during crushing of the foam were clarified using finite element stress analysis and microscopic observations, thus explaining the macroscopic stress–strain behaviour.

2. Experimental methods

2.1. Materials

The syntactic foam was fabricated by mechanically mixing glass microballoons (thin-walled closed pore material) and epoxy resin pastes (matrix system) with very slow stir speed to minimise the damage of microballoons. Syntactic foam slabs were then cast, after which the resin was cured.

The microstructure of the syntactic foam is almost homogeneous; a typical scanning electron micrograph is shown in Fig. 1. The entrapped air porosity was minimal. The glass microballoons, with an individual diameter of ~100 μm, a bulk density of ~300 kg/m^3 and a bulk crushing strength of ~30 MPa, were evenly distributed in the foam with a volume fraction of approximately 70%. The relative density (ρ^*) of the foam can thus be estimated to be ~30%. Good contact was observed between the epoxy matrix and the surface of the microballoons.

2.2. Mechanical testing

Cylindrical specimens of diameter $d = 5.0$ mm and length $l = 5.0$ mm were cut from the syntactic foam slab. The linear dimension of the specimens, at ~50 times the cell size (microballoons: ~100 μm in diameter), was large enough to ensure that the specimen behaviour is representative of bulk material. For cellular polymeric materials with high volume fraction of porosity (e.g. >60%), specimens with aspect ratio (l/d) of up to 1.0 should be used to avoid the formation of powdery fragments near cracks and thus achieve uniform compression [5,10]. However, a larger aspect ratio specimen can reduce friction and subsequent barrelling effect in compression tests. The friction coefficient between epoxy materials and steel platens could be as high as 0.1–0.25 [19,20]. Therefore, an aspect ratio of $l/d = 1.0$ was selected for the specimens in this investigation.

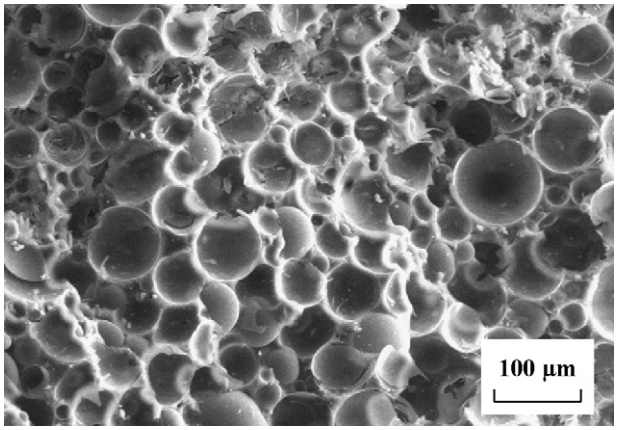

Fig. 1. Typical microstructure of glass microballoon epoxy syntactic foams.

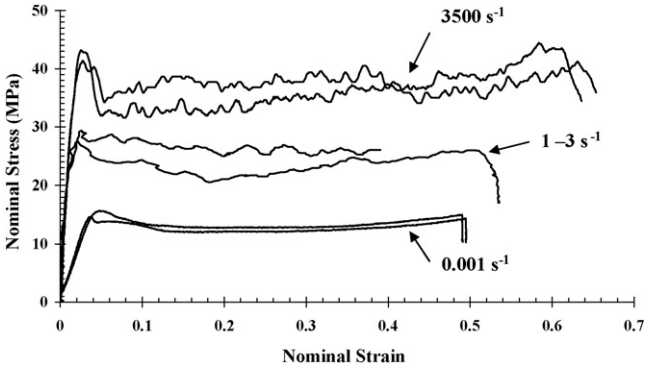

Fig. 2. Stress–strain curve at different loading rates. (*Note*: two representative test repeats are shown although more tests were performed for each loading rate; only three rates are shown in this figure, representing the full range of qualitative behaviour; stress levels at other rates are shown in Fig. 6.)

To achieve a wide range of strain rates, compression tests were conducted using (i) a commercial screw driven loading machine at quasi-static (low) loading rates (0.001–0.01 s^{-1}), (ii) a hydraulic loading machine at medium loading rates (0.5–200 s^{-1}), and (iii) Split-Hopkinson pressure configuration using Ø15 mm × 500 mm solid cylindrical steel bars at high loading rates (1000–4000 s^{-1}). The compressive deformation of a specimen was captured using various imaging systems with framing rates ranging from 0.25 to 250,000 frames s^{-1}. Full details of the test procedure can be found in a previous paper [21]. To minimise interfacial friction all specimens were lubricated with Castrol™ LMX grease,[1] which is widely used in high speed applications. At least three specimens were tested for each strain rate, allowing evaluation of the test reproducibility.

The strain rate for each test was maintained approximately constant by the prescribed velocity boundary conditions. The nominal stress and strain were calculated from the measured force and displacement (see Fig. 2). Each stress–strain curve was plotted to the end of loading at an approximately constant strain rate, even though densification of the foam is expected to occur at a strain $\varepsilon_d = \sim 0.6$ according to Gibson and Ashby [22]:

$$\varepsilon_d = 1 - 1.4\rho_*, \quad (1)$$

where the relative density, ρ^*, is ~30%. Elastic properties are not discussed in this study because it is well established that (i) for quasi-static experiments, elastic properties would typically be measured by using a specimen with a larger aspect ratio, e.g. $l/d > 2.0$ and (ii) high strain rate experiments do not produce an accurate representation of elastic modulus [21].

3. Results

3.1. Quasi-static compressive behaviour

Representative nominal stress–strain curves of the syntactic foam at quasi-static rates of strain (0.001 s^{-1}) are shown in Fig. 2. A good reproducibility of better than 5% in stress was achieved, indicative of consistent cell structure (glass microballoon distribution), specimen geometry and testing conditions between specimens. For clarity, Fig. 2 only shows a representative selection of stress–strain curves. A full set of data at all rates is given in Fig. 6.

An initial, approximately linear, region corresponding to the elastic behaviour of the foam is observed in the stress–strain curves

[1] Castrol™ is a registered trademark of Castrol Ltd., Swindon, UK.