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The mechanical response of a syntactic polyurethane foam at low and high rates of strain

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ABSTRACT

Quasi-static and dynamic experiments are conducted to characterise the mechanical response of a syntactic foam comprising hollow glass microballoons in a polyurethane matrix. Stress versus strain histories are measured in uniaxial tension and compression as well as in pure shear, at strain rates ranging from 10^{-4} to $10^{3}\,s^{-1}$, via non-standard experimental techniques; quasi-static *in-situ* tests are conducted to visualise the deformation mechanisms in tension and compression. The material displays a pronounced sensitivity to the imposed strain rate and relatively high tensile and shear ductility at both low and high strain rates. A tension/compression asymmetry is displayed in quasi-static tests but is lost at high rates of strain.

1. Introduction

Polymer matrix syntactic foams (PSF) are a class of lightweight materials that comprise thin-walled hollow particles (micro-balloons) dispersed in a polymeric matrix material [1,2], offering lower density and, in certain cases, higher modulus than the pure matrix material [3]. Major advantages of PSF are their ease of manufacturing, their high compressive strength-to-weight ratio and the possibility to tailor material properties by adjusting the size, wall thickness, volume-fraction as well as size distribution of the hollow particles. Typical areas of applications of PSF are within the marine, aerospace and ground transportation industries, where their low density and adjustable mechanical properties are of considerable advantage. PSF can be used as the core material in sandwich construction or to fill hollow lightweight structures in order to achieve mechanical damping and delay the onset of buckling instabilities.

The mechanical performance of PSF has recently received considerable interest from researchers, who have investigated the dependence of material properties on the microstructure ([3,4]), the possibility of creating functionally graded foams ([5,6]) and damage mechanisms on micro-balloons due to mechanical loading [7]. Most available studies on the mechanical response of PSF focused on their quasi-static compressive loading ([8,9]) or compressive and tensile loading ([3,10,11]). Some research has focused on the high strain rate response in compression, and these studies reported significant strain rate sensitivity ([12–17]). Few or no studies investigated the tensile and shear response of relatively soft PSF at high rates of strain, due to the difficulties associated with these measurements [18–24].

On the other hand the tensile and shear response of these materials are substantially different from their compressive response, and this information is needed to inspire and motivate the development of accurate and effective constitutive models for these materials. In order to overcome this gap in the current literature, we employ low-impedence metallic Hopkinson bars to measure the dynamic material response in tension, compression and shear. Three different bespoke Hopkinson bar setups and corresponding specimen designs are employed in order to generate valid stress versus strain histories at high rates of strain. The dependence of the mechanical responses upon the imposed strain rates is analysed.

Material and specimens are described in Section 2, while Section 3 presents the experimental techniques employed and the associated measurements. Results are discussed in Section 4.

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2. Material and specimens

The material under investigation is a syntactic foam comprising a polyurethane matrix and reinforcing hollow glass micro-balloons (Eccosphere 311 SID) of external diameter ranging from 10 to 130 μm and average wall thickness of 1.15 μm. The volume-fraction of the reinforcing balloons (intended as the ratio of the volume occupied by the spheres and the total volume) was of approximately 0.5 and the overall material density was measured as 700 kg m^{-3}. The foam was produced by Huntsman Advanced Materials[1] and was received in the form of thick plates of dimensions 200 × 200 × 50 mm. The foam was easy to machine and test specimens were extracted from these plates via conventional subtractive methods.

The specimens employed in tension and compression tests are shown in Fig. 1(a). Compressive specimens were circular cylinders of diameter 4 mm and height 6 mm. For the tensile tests, axisymmetric dogbone samples were manufactured, of gauge diameter 10 mm and gauge length 6 mm. An integral M16 thread was machined at the end of these foam specimens to allow mechanical connection to the different test rigs employed in this study.

In order to measure the response in shear, torsion specimens were produced in the form of hollow, thin-walled circular cylinders as illustrated in Fig. 1(b). The wall thickness of these cylinders was substantially reduced in the central portion in order to obtain a gauge section of uniform thickness; this had external diameter 50 mm, wall thickness 2.5 mm and height 4 mm. The specimen ends were then bonded using an epoxy-based adhesive to steel holders; these had the form of a thin plate with an integral hexagonal nut at the centre, produced via CNC milling. Holes were drilled in the flat, thin portion of the holders in order to reduce their mass.

Preliminary *in-situ* experiments were conducted in an environmental SEM by loading the material in compression and tension at quasi-static rates of strain. Cubes measuring 7 × 7 × 7 mm and small, flat dogbone specimens (of gauge section measuring 5 × 2 × 8 mm) were used in the *in-situ* compression and tension test, respectively.

It merits comment that in both tension and compression, as well as torsion, tests at different strain rates were conducted on identical specimens, in order to allow a direct comparison of the quasi-static and dynamic responses.

3. Experimental methods

3.1. Quasi-static in-situ experiments

The specimens described above were polished on one face down to the finish given by a 4000-grit abrasive paper and placed in a miniature, screw-driven tension/compression loading stage (Deben Microtest M5000). The stage was placed in a Hitachi environmental SEM microscope and the cross-heads of the loading stage were displaced at a velocity such as to achieve a nominal strain rate of 10^{-3} s^{-1}. Loading was interrupted occasionally in order to perform high resolution scans. Results of these tests are shown in Fig. 2; the figure illustrates the material microstructure (left-hand side), which comprised hollow spheres of different diameters; some surface damage, induced on the sample from the polishing procedure, is visible.

Fig. 2 also presents SEM photographs taken at a macroscopic nominal strain of approximately 15% and 5% for the compression and tension tests, respectively. In the compressed sample we observe evidence of fracturing of the microballoons, by wing-cracks propagating in the direction of loading, as expected for a brittle material in compression; microcracks are also visible in the polymeric matrix at this strain, propagating in the direction of loading. Repeated experiments showed that fracture of the glass spheres initiated at compressive strains as low as 4% and at the spheres of larger diameter. In contrast, in the tensile sample we observe straight cracks developing in the glass spheres in a direction perpendicular to loading; matrix cracking is also observed, triggered by the stress concentration at a large defect (a missing microballoon). Additional experiments showed that fracture of the microspheres initiates at strains of the order of 2%, again at the microballoons of larger diameter.

3.2. Quasi-static tests

Compression and tension tests were conducted at low strain rates in a screw-driven Zwick tensometer; the applied load was recorded by a resistive load cell while a non-contact laser extensometer was employed to record the compressive and tensile strains. A high resolution camera was used to video-record the macroscopic deformation mechanisms and to obtain additional measurements of the axial strains via image analysis; these matched those recorded by the laser extensometer. Preliminary experiments, conducted on specimens oriented along three perpendicular directions, revealed that the material was isotropic.

Static torsion tests were performed on a bespoke apparatus consisting of two circular, Titanium torsion bars supported in a horizontal position and free to rotate about their axis; the bars, of length 2.4 m and diameter 25.4 mm, were equipped with resistive strain gauges in order to measure the shear strains in the bars and deduce from these the applied torque, after a preliminary calibration. The hexagonal ends of the torsion specimens described in Section 2 mechanically engaged, via contact, with matching hexagonal groves machined at the end of the torsion bars. The free end of one of the bars was mechanically clamped while the opposite end of the bar system was driven to rotate at appropriate angular velocity by an electrical motor. The strains in the gauge portion of the sample were measured by analysing a high resolution video footage of the experiments via the commercial software GOM Aramis.[2] It was found that the shear strain was initially uniform in the gauge portion of the specimen; failure was triggered by an initial localisation of shear deformation on a plane perpendicular to the torsion axis, see Fig. 3; such localisation coincided with the initiation of microcracks oriented along the direction of maximum principal strain (at 45 degrees on the torsion axis); these microcracks subsequently coalesced to form a macroscopic crack perpendicular to the torsion axis, bringing the specimen to catastrophic failure.

3.3. Medium strain rate tests

In order to achieve strain rats of the order of 10 s^{-1} in tension and torsion, a bespoke hydraulic loading system was used. The rig consisted of a lightweight piston capable of quickly reaching a constant velocity of magnitude up to 2 ms^{-1}; details of this apparatus are described, for example, in Refs. [25,26]. Compression and tension tests were conducted at medium strain rates; the load history was measured by piezo-electric load cells mounted in series with instrumented rods. A digital high-speed camera (Vision Research Phantom v7) was used to measure the elongation of the specimens during the tests. Torsion experiments were not conducted at this strain rate.

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