Rate-Dependent Compressive Behavior of Open-cell Elastomeric Foam

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Abstract. Open cell polymeric foams have widespread use due to their unique deformation properties, or cushioning under load, making them particularly appealing for impact protection applications. This work presents microstructure to property behavior of a commercially obtained polyurethane foam specifically used as helmet liners in military helmet systems. The response under compression at quasi-static ($0.02\ s^{-1}$), intermediate ($2\ s^{-1}$) and dynamic ($10^2\ s^{-1}$) strain rates is presented utilizing a standard material load frame, and a modified Kolsky (split-Hopkinson) bar system for low impedance materials. High-speed imaging and in-situ optical microscopy, along with full-field imaging is used to track the characteristic linear elastic, plateau, and densification stress-strain regimes. Additionally, 3D computer microtomography (CT) and morphological characterization software is used to quantify the microstructure by fitting the open cells with characteristic ellipsoids, as well as map the degree of anisotropy and heterogeneous cell-wall structures. Current theories for open-celled foams suggest that the distinction in load deflection changes are between cell-wall (or strut) bending and buckling, and this work aims to quantify a morphological justification for the plateau and subsequent nonlinear collapse of the bulk response across strain rates.

Introduction

The characteristic compressive stress-strain response of foams comprises of an initial linear elastic region, followed by a plateau, and finally a densification region. This response makes foams excellent candidates for energy absorption under impact scenarios; yet their bulk behavior critically depends on how the cellular structure, and more specifically the individual cells and cell-walls deform and interact under load. For elastomeric foams, the linear region is attributed to bending of the cell-walls under compressive loading, whereas the plateau region is thought to be caused by a meta-stable elastic buckling collapse of different bands of cells through the thickness of the material. Densification follows the cell collapse once cell-walls make contact and impinge, with the response reaching asymptotically the stiffness of the constituent material [1,2]. The extent of the different regions is strongly correlated to the relative density of the foam.

The present study utilizes 3D computed microtomography together with morphological image processing to analyze volumetric structural properties of a polyurethane open-cell elastomeric foam, in order to capture and explore the deformation mechanisms responsible for the bulk quasi-static compressive response across strain rates.

Methods

Polyurethane elastomeric foam samples (provided by Team Wendy™) were prepared using a die-cut and hydraulic press, along two different orientations. The first batch of samples is cut along a plane perpendicular to the "rise" direction and is denoted as the normal direction. The second batch is cut along a plane that is parallel to the "rise" direction and is denoted the parallel direction. Rectangular cross-section specimens of 30mm length and width, and 9mm height, were subjected to quasi-static compression using a load-frame (Shimadzu AG-IC 50kN) at a cross-head speed of 18mm/min corresponding to a strain rate of $0.02s^{-1}$, as shown in Fig. 1a, and at 1080 mm/min, corresponding to a strain rate of $2s^{-1}$. X-ray microtomograph (Bruker Skyscan 1172) is used for CT-imaging of the foams with a spatial resolution of 3μm. The reconstructed image-stack was further analyzed by using an open-source image analysis software (i-Morph) [3] for the extraction of morphological structural properties of the foam. Samples 12mm length and width, and 9mm height are examined under dynamic compression using an aluminum Kolsky (split-Hopkinson) bar system instrumented with quartz force transducers to test low impedance materials. Two transducers, one at each bar and material interface, are used to track the material response as the bar strain gauges often contain substantial acceleration components that are not representative of the stress within the sample [4].

Results

The quasi-static compression engineering stress-strain response of the foam is shown in Fig.1b. The two different orientations of foam specimens show the same initial linear behavior and critical stress value at which the plateau region ensues. Their responses remain similar up to about 40% nominal compressive strain after which the specimens that were cut at a plane parallel to the "rise" direction are transitioning earlier towards the densification regime, compared to the specimens cut normal to that direction.

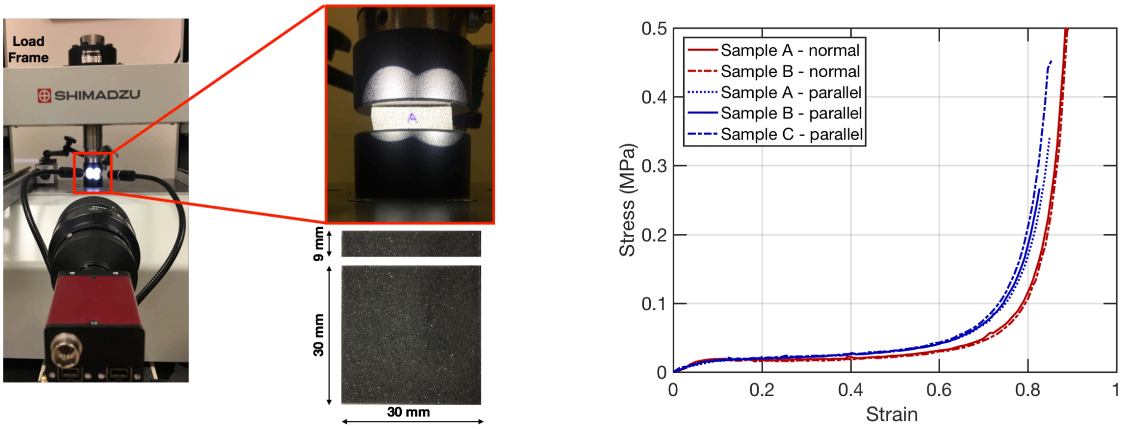

Fig 1. (a) Quasi-static compression experimental setup showing load frame, specimen sandwiched between the two platens, and a schematic with sample dimensions. (b) Compressive nominal stress-strain response of polyurethane foam at strain rate 0.02 s^{-1} (red curves correspond to samples cut along a plane normal to the "rise" direction, blue curves samples cut along a plane parallel to the "rise" direction).

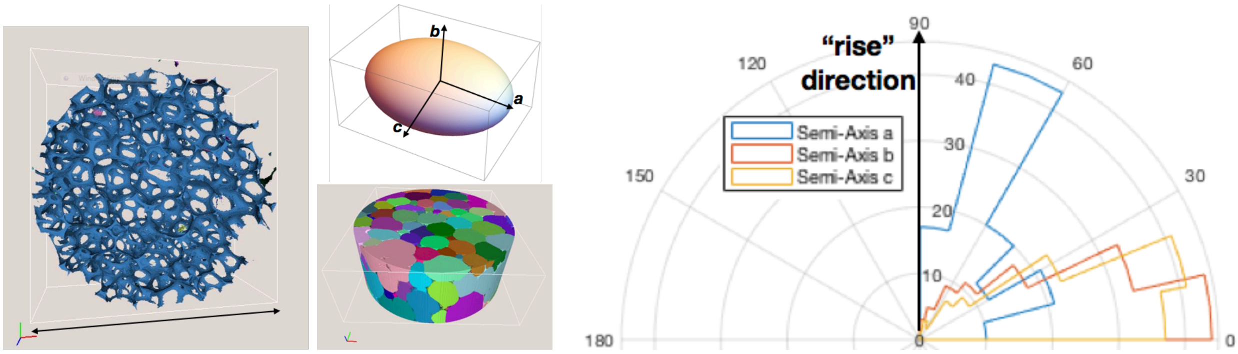

Fig. 2 (a) CT-scan rendition of foam structure and segmentation of cells. (b) Polar histogram of ellipsoidal principal axes (concentric circles represent frequency of occurrence of the polar angle).

The CT-scan images of the soft foam were reconstructed and analyzed. A rendition of the solid phase of a volume of interest of the foam along with an image illustrating the segmentation of the cells is shown in Fig. 2a. Individual measurements are made for each identified cell structure. Moreover, an ellipsoid is fit to each cell and the three principal axes of the ellipsoid in terms of lengths and orientations are extracted. Fig. 2b shows a polar histogram distribution plot of the orientations of the ellipsoid semi-axes *a*,*b,* and *c* with respect to the azimuth direction. We observe from the polar angle distribution of the semi-axis *a*, which is the largest principal axis of the ellipsoids, that the cells have a preferred orientation between 60-90 degrees (where 90 is the rise direction). This preferential orientation for the long axis of the ellipsoid can qualitatively explain the earlier transition towards the densification regime for the foam that is cut parallel to the rise direction, compared to the response of the foam cut normal to that direction. In other words, when the majority of the longest cell axes are oriented in the same direction as the compressive load, the transition to the densification regime is prolonged. This is due to the fact that the majority of the walls have further to travel before making contact. Conversely, when the longest cell axes are oriented perpendicular to the direction of the compressive load, the transition to the densification regime happens at a lower strain, as there is less distance for the cell walls to travel before impinging on one another.

Conclusion

Compression investigations of an open-cell polyurethane foam currently used in military helmet liners has demonstrated that morphological metrics obtained through CT-scan image analysis can lead to an improved understanding of the macroscopic response. Specifically, the early onset of the densification regime under load in samples cut parallel to the rise direction, relative to the normal direction, appears to be due to the preferred orientation of the longest cell characteristic length. This serves as a proof of concept for continued studies across strain rates, using full-field imaging to examine bands or pockets of high strain during local collapses in the plateau region, as well as morphological characterization to decouple cell-wall behavior from bulk response in the transition to densification.

References

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