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Effect of specimen size, compressibility and inertia on the response of rigid polymer foams subjected to high velocity direct impact loading

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ABSTRACT

The influences of specimen length-to-diameter ratio, material compressibility, and inertia on direct impact response of high density closed-cell polymeric foam are investigated. High speed photography and stereovision digital image correlation are conducted to measure the full-field deformation response of the material subjected to direct impact. Inertia stress developed in the specimen is calculated from the acceleration distribution obtained from full-field measurements. Total axial stress magnitude along the axis of the specimen is then reconstructed from inertia and boundary-measured stresses. It is clearly shown that there is an appreciable degree of spatial variability in strains, strain rates and stresses developed in the impacted foam specimens, whereas the degree of such axial variability is more significant at higher length-to-diameter ratios. The study is further extended to take advantage of such spatial variability to identify the rate sensitivity of the examined material over a wide range of strain rates from 1000 s^{-1} to 5000 s^{-1}. The approach proposed here is shown to facilitate the identification of viscoplastic constitutive response of low impedance materials using a minimum number of experiments.

1. Introduction

Rigid polymeric foams have gained extensive attention in several engineering applications that require excellent energy absorption with structural stability and significant weight reduction. Rigid polymer foams are widely used in applications such as cushioning, impact and crash mitigation, packaging, sandwich structures, etc., many of which entail high strain rate loading conditions [1]. Therefore, characterization of the mechanical response of foams under dynamic loading conditions has been an interesting subject of study for decades [2]. In this regard, several models have so far been proposed to characterize the phenomenological constitutive behavior of polymeric foams under large strain and various strain rate conditions [3–5].

From an experimental perspective, there are major challenges encountered during the study of deformation response of polymeric foams at high strain rate loading conditions [6]. The first and probably most important challenge is associated with the delayed stress equilibrium, which is due to the low mechanical impedance nature of these materials. There have been several solutions proposed to minimize the effect of such belated equilibrium conditions. For instance, application of polymeric bars [2,7,8] or hollow metallic transmission bar [9] in the split Hopkinson pressure bar (SHPB) experiments has been proposed with the purpose of reducing the impedance mismatch between the specimen and the bars, and hence to acquire more accurate transmitted signals. However, application of viscoelastic bars raises other challenges associated with wave propagation attenuation and dispersion due to the material rheological properties and the radial inertia stresses developed in the bars [10]. Different methods have been proposed and successfully practiced to correct the strain signals and restore the actual strain exerted at the interface of the specimen and the bars [11–15]. Pulse shaping technique has been established to provide an alternative solution in dynamic testing of low impedance materials. Application of pulse shaper has been established to ensure nearly constant strain rates, as well as the presence of dynamically equilibrated stress in the specimen [16,17].

A more general solution to minimize the effects of non-equilibrium stress state in dynamic testing of low impedance materials is reducing the length of the sample. In general, wave reverberation period is significantly reduced in short specimens, resulting in a faster stress equilibration within the gauge area [18,19]. In this regard, in the case of polymeric foams and similar cellular structures there is an additional challenge due to the representative volume element (RVE) size of the specimen, which requires a minimum number of cells to be present along the specimen length, in order to capture the continuum scale response of the material [6,20,21]; therefore limiting the minimum thickness of the tested

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specimen. None of the proposed solutions discussed above are capable of taking the local deformation, inertia and compressibility into account from an experimental perspective. Note that there are numerical simulations available in the literature that accurately describe the effects due to the aforementioned challenges on low impedance cellular materials, see e.g. Ref. [6]. However, from an experimental testing standpoint, there are still certain imitations that necessitate the development of alternative solutions to compensate for the above-mentioned restriction.

Recent advances in the areas of high speed photography and full-field measurements have facilitated the study of deformation and failure of different materials in a wide range of time and length scales by accounting for the local deformation information [22–26]. In this regard, extensive attention has been drawn toward the application of virtual fields method and non-parametric approaches in dynamic deformation analysis of low impedance materials [27–31]. For instance, a non-parametric approach was proposed by Othman et al. [29] with which the full-field stress–strain response of low impedance synthetic rubber specimens was retrieved. This approach is based on the direct calculation of local stress magnitude using the inertia stress computed from acceleration field, and the boundary measured stress. This non-parametric method was successfully implemented by the authors of the present work to characterize dynamic deformation behavior of compressible polymeric foams under direct impact and at strain rates of up to 2600 s^{-1} [30,31].

The main objective in this paper is to extend the previous works further by investigating the concurrent effects of specimen aspect ratio and the associated inertia effects and compressibility on the mechanical response of polymeric foams subjected to direct impact loading. Specimens with two different length-to-diameter ratios are subjected to direct impact loading using a modified shock tube apparatus. Deformation of the specimen is measured in-situ using high speed photography and digital image correlation. Using a non-parametric analysis along with displacement and acceleration fields acquired from image correlation, local stress–strain curves along specimen axis are extracted. It is observed that the transient deformation state creates a high variability in the local strain rate response over the length of the specimen. Local stress–strain curves are extracted at several positions along the specimen axis, each position with a different strain rate history. Attempts are made to utilize the entire set of constitutive data to extract useful stress–strain responses for the material over a wide range of strain rate conditions using a minimum number of impact tests. This was originally achieved by Avril et al. [32] to identify elasto-visco-plastic constitutive response using a single test at quasi-static loading conditions. Accordingly, the present work attempts to investigate the feasibility of extracting meaningful rate-dependent constitutive models from a single experiment carried out at very high strain rate conditions. The method is validated by comparing the results obtained from the proposed approach with those obtained from conventional SHPB tests.

2. Experimental procedure

2.1. Material and specimen geometry

The material examined in this work is a rigid closed-cell polyurethane foam supplied by Sandia National Laboratories, under the commercial name TufFoam35. Nominal density of the as-received stock was measured as 560 kg/m^3 (35 pcf). Cellular structure of the foam is presented in Fig. 1a, indicating average pore dimensions of 150 μm and 120 μm cell-wall thickness. Compressive elastic modulus of the material was determined as the initial slope of the quasi-static stress–strain curves averaged from three independent measurements and found to be (780 ± 20 MPa). Longitudinal wave speed of the examined foam, c_l, was calculated from the initial density and compressive elastic modulus and found to be 1180 m/s.

Cylindrical specimens with two different length-to-diameter ratios are extracted from the as-received billets, the dimensions of which are shown in Fig. 1b. Specimens are extracted from a single billet using a CNC waterjet, with a relatively smooth lateral surface finish and a ± 0.1 mm dimensional variability. For image correlation purposes, a high contrast speckle pattern is applied on the lateral surface of each specimen. The speckle pattern consists of random black and white particles applied using conventional airbrush. Average speckle size is 100 μm.

2.2. Impact loading

A modified shock tube apparatus is utilized to apply controlled direct impact on the specimens in the present work. Details on the design features of our shock tube can be found elsewhere [24,30]. The shock tube is schematically shown in Fig. 2a. Driver and driven sections of the tube are separated by stretched plastic diaphragms, under the commercial name "Mylar" sheets. The speckled specimen is fixed at the muzzle of the tube, inserted on a custom made load fixture. The specimen is simply supported by the load cell in one end and free on the projectile side. To keep the specimen intact with the load cell, a lithium grease is used, which also serves as a lubricant to minimize the effect of friction. The other end of the specimen along the impactor side is free, but the same lubricant is applied to reduce the effects of frictional stresses on the impacted end of the specimen. Further details on the load fixture utilized in this work can be found in Refs. [30, 31]. The applied dynamic load is measured on the back side of the specimen using a piezoelectric load-cell, as shown in Fig. 2b. The load-cell used in this work is 88.8 kN capacity PCB piezotronics® load-cell with 56 mV/kN sensitivity, designed primarily to measure compressive and impact forces. A polyimide film tap covering the cap surface of the load-cell reduces the effect of high frequency ringing associated with metal-to-metal contact.

To increase the momentum transferred to the specimen and achieve higher strain rates, a high strength 70 gr aluminum projectile

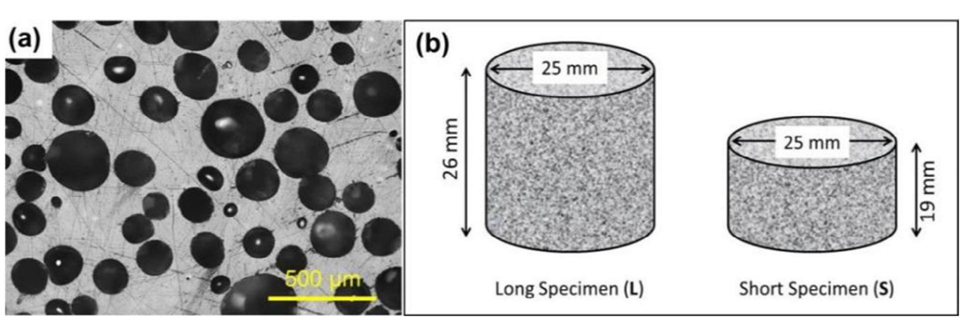

Fig. 1. (a) Cellular structure of the foam examined in this work. (b) Cylindrical specimens with different initial dimensions used for direct impact experiments.