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Test method

Characterizing the constitutive response and energy absorption of rigid polymeric foams subjected to intermediate-velocity impact

Behrad Koohbor [a], Addis Kidane [a,*], Wei-Yang Lu [b]

[a] Department of Mechanical Engineering, University of South Carolina, 300 Main St, Columbia, SC 29208, USA
[b] Sandia National Laboratories, Livermore, CA 94551-0969, USA

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ABSTRACT

As an optimum energy-absorbing material system, polymeric foams are needed to dissipate the kinetic energy of an impact, while maintaining the impact force transferred to the protected object at a low level. Therefore, it is crucial to accurately characterize the load bearing and energy dissipation performance of foams at high strain rate loading conditions. There are certain challenges faced in the accurate measurement of the deformation response of foams due to their low mechanical impedance. In the present work, a non-parametric method is successfully implemented to enable the accurate assessment of the compressive constitutive response of rigid polymeric foams subjected to impact loading conditions. The method is based on stereovision high speed photography in conjunction with 3D digital image correlation, and allows for accurate evaluation of inertia stresses developed within the specimen during deformation time. Full-field distributions of stress, strain and strain rate are used to extract the local constitutive response of the material at any given location along the specimen axis. In addition, the effective energy absorbed by the material is calculated. Finally, results obtained from the proposed non-parametric analysis are compared with data obtained from conventional test procedures.

1. Introduction

Owing to their superior energy absorption and acoustic characteristics, rigid polymeric foams are widely used in the aerospace and automotive industries. In addition to energy dissipation performance, advanced polymeric foams are also gaining attention in structural components, as well as the core material for strengthening hollow structures while maintaining the overall structural weight at low levels [1–3]. The enhanced energy dissipation properties of polymer foams are mainly due to their low mechanical impedance, whereas such low impedance is itself a direct result of the porous structure of these materials. Although the low impedance behavior makes polymeric foam the material of choice in applications where dynamic loading conditions are dominant, it makes characterization of the dynamic behavior of foams more challenging compared with solid non-porous structures. The main challenge is due to the relatively low elastic wave speed in these materials which results in a delayed state of stress equilibrium during loading [4]. There have been solutions proposed to compensate for the belated state of equilibrium in dynamic loading conditions, most of which are only applicable in studies utilizing split Hopkinson pressure bars (SHPB). Application of hollow and/or polymeric bars to reduce the impedance mismatch between bars and specimen [5–7], and pulse shaping techniques [8,9] are the most common solutions proposed to tackle the challenges in dynamic testing of foams in SHPB.

There have been several studies focusing on experimental characterization of direct impact response of polymeric foams [10–12]. In direct impact loading, none of the above-mentioned solutions are applicable since the basis of the experimental approach is on the direct measurement of the applied impact force. A more general solution to compensate for the non-equilibrium stress condition in direct impact experiments is the use of short specimens [13]. The main benefit in using short specimens in direct impact studies is due to the significant reduction of the elastic wave reverberation time in order to achieve the quasi-static equilibrium in a shorter time. However, in the case of cellular materials, there exists a lower bound on the dimensions of the specimen subjected to impact testing due to the representative volume element (RVE) size required to maintain the continuum response of the material

* Corresponding author. Department of Mechanical Engineering, University of South Carolina, 300 Main Street, Room A132, Columbia, SC 29208, USA.
E-mail address: kidanea@cec.sc.edu (A. Kidane).

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[14–16].

The challenges listed above call for a more general approach that (a) is independent of the specimen dimensions; (b) facilitates accurate assessment of the dynamic deformation response of the foam even where non-equilibrium stress conditions are present. Recent advances in high speed photography and full-field measurements have provided a path for more accurate study of the dynamic deformation of low impedance materials. In particular, recent advances in inverse identification of the constitutive response of materials have been established to be promising approaches providing accurate assessment of the high strain rate deformation response. The basic idea in the area of inverse identification from full-field measurement is the use of kinematics of the deformation (displacement and strain) to inversely identify the loads/stresses imposed on the object. The virtual fields method (VFM) is an example of such inverse analyses gaining extensive popularity in the experimental mechanics community [17].

For the specific case of impact loading of low impedance materials, direct identification of the constitutive response based on full-field measurements was proposed by Othman et al. [18], in which the contribution of inertia was also included in the analysis by computing the full-field acceleration developed in the impacted specimen. The same approach was implemented to study the direct impact response of various polymer foams at strain rates of up to 2500 s^{-1} [19,20]. Our objective in the present work is to extend the previous idea by adopting the same non-parametric analysis to study the energy absorption characteristics of closed-cell polymeric foams subjected to intermediate-velocity direct impact. The term “intermediate-velocity” indicates that the impactor velocity is sufficiently high so that a static analysis may not be justified. In this range, the initial inertia forces are of considerable magnitude [21]. On the other hand, the impactor velocity is not high enough to significantly increase the influence of elastic wave and shock wave propagations in the material, therefore the term “intermediate-velocity” is adopted. The novel contribution in the present study is the consideration of dynamic deformation of the foam during loading and unloading in the analysis. Accordingly, impact experiments were designed in a way that a relatively large magnitude of plastic strain (>20%) is imposed on the specimens without causing total failure. Full-field displacement is used to determine the distribution of acceleration over the entire length of the specimen. Inertia stresses are computed from the acceleration, and then superimposed with the boundary-measured stress to determine the total axial stress magnitudes. A complete stress-strain hysteresis loop is acquired, enabling the study of energy dissipation characteristics of the utilized material.

2. Experimental

2.1. Material and specimen geometry

High density closed-cell polyurethane foam under the commercial name TufFoam35 was examined in this work [22]. Nominal bulk density of the as-received foam was measured in-house by measuring the mass and volume, and found to be 560 kg/m^3 (35 pcf). Cellular structure of the material is presented in Fig. 1, exhibiting circular cells with a 150 μm average diameter and 150 μm cell-wall thickness. Elastic modulus of the foam at quasi-static conditions was measured in-house as 780 MPa. Cylindrical specimens of 28.8 mm in length and 25.3 mm in diameter were extracted from the as-received foam billet by the use of a hole saw. The application of a hole saw results in a smooth lateral surface finish with ±0.1 mm dimensional accuracy. For image correlation purposes, a high contrast speckle pattern comprised of a black substrate with 80 μm white particles was applied on the lateral surface of the specimen. Speckling was carried out using normal flat spray paints.

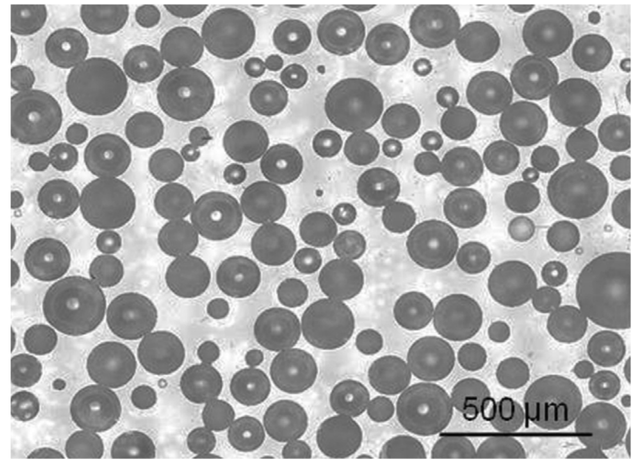

Fig. 1. Cellular structure of the examined foam.

2.2. Direct impact experiments

Controlled direct impact was applied to the specimen using a shock tube apparatus. Details on the design aspects of the shock tube are beyond the scope of this work, but can be found elsewhere [19,23]. A schematic representation of the utilized shock tube is depicted in Fig. 2. The speckled specimen was inserted on a custom fabricated fixture close to the muzzle of the shock tube. The custom fixture incorporates a piezoelectric load-cell, facilitating measurement of the reaction force at the rear side of the specimen. The load-cell used in this work was an 88.8 kN capacity PCB piezotronics® load-cell, designed primarily for impact force measurements. The specimen was placed in its position on the fixture with the use of lithium grease, which also serves as a lubricant to diminish the effect of friction.

To increase the momentum transfer to the specimen and achieve higher strain rates, a 0.07 kg aluminum projectile was placed inside the tube and shot directly at the foam. Velocity of the projectile at the tube exit can be manipulated by varying the number and/or thickness of the plastic diaphragms used to separate the driver and the driven sections of the shock tube (see Fig. 2). In the present work, projectile velocity of 40.4 m/s was achieved by using a plastic diaphragm with 0.1 mm total thickness. The impactor velocity was measured by tracking the aluminum projectile after release from the muzzle of the tube, just before contact with the specimen. The velocity of the projectile is highly repeatable, with uncertainty level in this work of about ±5%, which corresponds to ±2 m/s. More details on the projectile velocity measurement can be found in Ref. [20]. The projectile velocity regarded here falls well within the range of intermediate velocity impact for the case of the foam studied in this work. Impact experiments were designed in such a way that the material will deform up to a global strain at which surface cracks are visibly formed on the lateral surface of the specimen. Reproducibility of the results was confirmed by conducting at least three independent experiments following the same experimental procedure. Once the repeatability was confirmed, typical results were extracted and presented in this work.

2.3. High speed imaging and digital image correlation

High speed stereovision imaging in conjunction with digital image correlation was used in order to analyze and quantify the