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Investigation of the dynamic stress–strain response of compressible polymeric foam using a non-parametric analysis

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ABSTRACT

Dynamic stress–strain response of rigid closed-cell polymeric foams is investigated in this work by subjecting high toughness polyurethane foam specimens to direct impact with different projectile velocities and quantifying their deformation response with high speed stereo-photography together with 3D digital image correlation. The measured transient displacement field developed in the specimens during high stain rate loading is used to calculate the transient axial acceleration field throughout the specimen. A simple mathematical formulation based on conservation of mass is also proposed to determine the local change of density in the specimen during deformation. By obtaining the full-field acceleration and density distributions, the inertia stresses at each point in the specimen are determined through a non-parametric analysis and superimposed on the stress magnitudes measured at specimen ends to obtain the full-field stress distribution. The process outlined above overcomes a major challenge in high strain rate experiments with low impedance polymeric foam specimens, i.e. the delayed equilibrium conditions can be quantified.

1. Introduction

The determination of a material's constitutive behavior at intermediate to high strain rate ranges has been a subject of interest for quite a long time [1,2]. Historically, the importance of obtaining the equilibrium state has required special attention in the experimental setup, since configurations where equilibrium readily can be identified make it easier to study the dynamic stress–strain response of the materials. The issue is particularly significant in the case of engineering materials with low strength and low mechanical impedance [3], where conditions of stress/strain equilibrium oftentimes require a time duration that exceeds the time required for the material to undergo failure. In such cases, the determination of stress–strain response of the material based on the load and displacement measurement at specimen ends can introduce a significant degree of inaccuracy in the obtained constitutive response, with continued deterioration in accuracy at higher strain rates [4–6].

Polymeric foams, as a class of materials widely used in applications that require light weight structural design with superior energy dissipation characteristics, are among the materials possessing low wave propagation speed [7–10]. Their use in areas such as automotive industries, ships and packaging requires precise knowledge of the deformation response of the material at different loading rates. Dynamic deformation and failure behavior of these materials have been studied both experimentally and numerically in recent years [11–16]. In general, most polymeric foams possess remarkable strain rate sensitivity at strain rates above 500 s^{-1} [14]. However, owing to non-homogeneity in the stress and deformation states, particularly during the early stages of dynamic loading, quantifying the dynamic deformation of foams has been a major challenge. One of the most widely used methods in studying the dynamic deformation behavior of soft materials is the split Hopkinson pressure bar technique [3]. Different approaches have been practiced in recent years to increase the accuracy of the measurements in this technique, particularly in testing of low impedance materials. These approaches include pulse shaping techniques [3], use of polymeric bars [17] and long projectiles [18]. A recent study by Liu et al. [16] indicates that in addition to the solutions proposed above, full-field measurements must be incorporated in order to accurately measure the deformation response and reveal the active failure mechanisms in foam specimens subjected to high strain rate loading conditions.

The advent of full-field measurement techniques such as digital image correlation (DIC), in conjunction with different experimental techniques, has facilitated the study of deformation of materials over a wide range of time and length scales [16,19–23]. More importantly, the recent work by Pierron and his group [20,24,25] using virtual fields and inverse methods has identified a unique way of analyzing the dynamic deformation of materials by using

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D'Alembert's principle and incorporating "inertia forces" into the analysis. Though the inverse methods have already been demonstrated to be effective in calculating the stress–stress response of materials at high strain rate loading conditions, the effect of compressibility has not been addressed in previous studies.

The present work focuses on the study of rigid closed-cell polymeric foams subjected to direct impact loading by accounting for material compressibility and the effect of inertia. A shock tube apparatus is used to apply dynamic loading on the foam specimens, while high speed stereovision imaging together with 3D digital image correlation is used to study the full-field deformation of the material under high strain rate loading conditions. A simple mathematical model has also been proposed to account for both material compressibility and the local variation of density during deformation of the specimens. Also, based on the full-field displacement distribution captured by DIC and considering the instantaneous change of material density, a non-parametric analysis is developed to incorporate "inertia effects" into the analysis, following references 5 and 6. Using the proposed methodology, the full-field stress–strain response of the material has been determined during high strain rate loading and the global constitutive behavior of the foam has been quantified. The original contribution here is the inclusion of the material compressibility into the analysis. In addition, attempts have been made to generalize the methodology to study the dynamic deformation of any low-impedance compressible solid. To the authors' knowledge, this is the first time a thorough analysis of the dynamic deformation of compressible polymeric foams has been performed taking into account the concurrent effects of material compressibility and inertia loading to capture the full-field stress–strain response of the material.

2. Experimental procedure

2.1. Material and specimen geometry

The material used in this study is a rigid closed-cell polyurethane foam of 560 kg/m^3 (35 pcf) nominal density supplied by Sandia National Laboratories [26]. The initial density of the foam specimens is measured in-house and confirmed to be consistent with density values reported in the literature [26]; the measured value is 95% of literature data. A cylindrical foam specimen with a high contrast speckle pattern is shown in Fig. 1a. The specimen is 25.4 mm in diameter and 25.4 mm in height. Each specimen is extracted from the as-received billets using a waterjet system, resulting in a relatively smooth lateral surface finish with ±0.1 mm dimensional variability. The high contrast speckle pattern shown in Fig. 1a consists of a thin white sub-layer with randomly-distributed black speckles; the black speckles are applied using an airbrush. A histogram of the speckle pattern is shown in Fig. 1b.

2.2. Impact loading

A shock tube apparatus is utilized to apply controlled dynamic loading to the specimens. The shock tube used in this work is shown in Fig. 2a. The apparatus has an overall length of 7.2 m, consisting of a 1.8 m driven section and a 5.4 m driver section. The inner diameter of the entire tube, except the last 0.9 m section near to the muzzle, is 75 mm. The inner diameter of the final 0.9 m end section of the tube is 50 mm, resulting in increasing shock velocity over the final stage.

To perform the experiment, the speckled cylindrical specimen shown in Fig. 1a is placed at the muzzle of the shock tube and affixed to a custom fabricated strong-back. As shown in Fig. 2b, three piezotronic load-cells are placed behind the specimen and mounted on a specially fabricated fixture. Use of three load-cells in this work assures the accuracy of the force measurements and compensates for any possible misalignment of the loading that might occur during high strain rate experiments. The specimen is held on the loading fixture by the use of lithium grease, which also acts as the lubricant. Further details on the shock tube used in this work can be found elsewhere [4,23,27,28].

As shown in Fig. 2b, direct impact loading is applied using a projectile placed inside the tube at the beginning of the reducing section. The projectile is made of high strength 7068 aluminum alloy with a diameter that is 2 mm smaller than the inside diameter of the reducing section. The projectile is fabricated as a cylinder hollowed from one end to reduce its mass, with an overall length of 72 mm and a 0.07 kg mass. Prior to performing the experiment, the high pressure driver section and the low pressure driven section are separated by a diaphragm, a 0.18 mm thick stretched polyester film, under

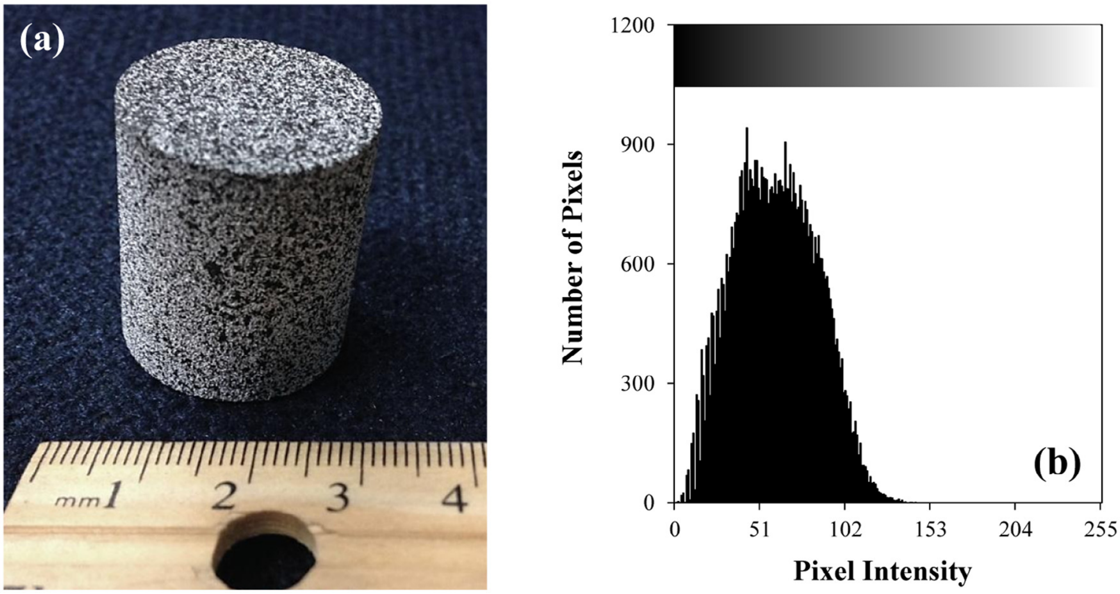

Fig. 1. (a) Typical speckled specimen with its corresponding grey scale histogram shown in (b).