Polymer Testing 67 (2018) 441–449

Contents lists available at ScienceDirect

Polymer Testing

journal homepage: www.elsevier.com/locate/polytest

Multiaxial experiments with radial loading paths on a polymeric foam

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ARTICLE INFO

Keywords:
Cellular materials
Multiaxial experiments
Analyzing shape and volume changes

ABSTRACT

Cellular materials such as polymeric foams in particular have been widely studied under uniaxial loading conditions. Many experimental studies have been focusing recently, however, on the responses of these foams to multiaxial loads. In the present study, a novel experimental hexapod device was used to perform combined uniaxial compression and simple shear tests. Using a post-processing method of analysis which can be used to study elementary mechanical behavior, the authors show the occurrence of non-proportional stress paths in the material under investigation although proportional kinematic paths were imposed. A failure limit criterion is presented for use with the foam of interest. The results of the present analysis yield useful information for meeting our future objective, namely to develop a numerical model for simulating multiaxial loading conditions.

1. Introduction

Cellular materials have been widely used for many years for manufacturing safety equipment and protective applications. Because of their considerable dissipative capacity and their weak force transmission properties, they are good candidates for protecting both goods and persons. The choice of cellular materials, which range from soft polymer foam to rigid aluminum foam, depends on the damping power required. Mills et al. [1], for instance, have studied the use of polymer foams for producing several types of personal protection, such as cushions, shoes and helmets. Fernandes and Alves de Sousa [2] recently published a review focusing on motorcycle helmets and showed the importance of including polymeric foam liners in the helmet design. The authors of the previous study [2] have also briefly addressed the topic of Finite Element models, citing several studies in which impact tests were simulated with a view to optimizing helmet design. In the present context of engineering applications, Yang and Shim [3] have recommended using a macroscopic description of the responses observed, taking elastomer foams to constitute a homogeneous continuum. Foam behavior can therefore be decomposed into elementary behavior such as hyperelasticity, viscosity and irreversible transformations.

When drawing up numerical models simulating foams subjected to mechanical loads, it is necessary to characterize the material. In most previous studies, foams have been characterized experimentally by performing uniaxial compression tests, which are easy to apply. The influence of the strain rate or the impact speed has often been studied to account for the normal conditions of use, as in Refs. [4–7]. However, the validity of these characterizations and models is questionable when the mechanical loads are no longer uniaxial loads. Some models such as Ogden's model [8] have taken several loading conditions into account. This model, which was developed for rubber-like materials, has been extended to compressible materials by including the changes of volume in addition to the shape change behavior. This distinction is a natural way of describing the hyperelastic behavior of rubber-like and cellular materials, and has been adopted in several models such as the Mooney-Rivlin [9,10] model, which is based on tensor invariants, and the Ogden model, which is based on principal stretches.

Several authors have naturally performed multiaxial experiments to provide numerical models with data. Volume change behavior has been studied by performing hydrostatic tests [4,11–14] and shape change behavior, by performing simple shear tests [4, 15, 16]. In both cases, the question of finding suitable methods for the post-processing analysis multiaxial data arises. In the case of large transformations, Criscione et al. [17] used an invariant basis for natural strains consisting of the *amount-of-dilatation*, the *magnitude-of-distortion* and the *mode-of-distortion*. These authors recommended using natural or Hencky strain and Cauchy stress tensors to study and compare the results of multiaxial loading tests. Combaz et al. [18,19] recently used these post-processing tools to analyze the results of tests on aluminum and polymeric foams subjected to multiaxial loads.

In the present study, quasi-static multiaxial experiments were performed with radial loading paths on a polymeric foam. This Polypropylene foam has been studied in detail by Viot et al. [5,7,12] by

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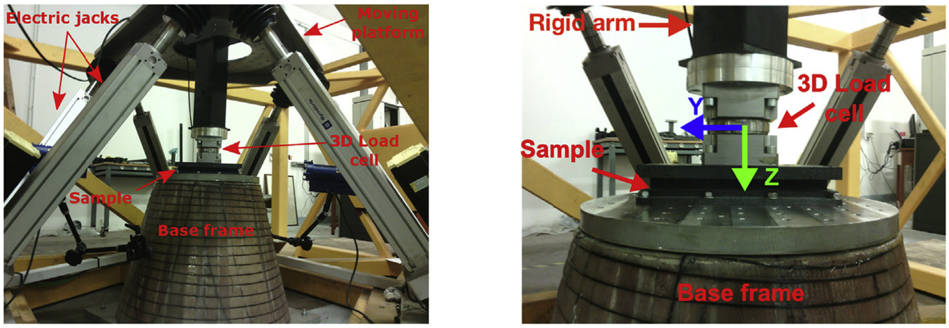
https://doi.org/10.1016/j.polymertesting.2018.03.003
Received 30 October 2017; Received in revised form 1 February 2018; Accepted 3 March 2018
Available online 16 March 2018
0142-9418/



(a) Hexapod in its environment. (b) Zoom on the sample.

Fig. 1. The hexapod device. A black 300 × 20 × 20 mm sample of EPP foam was glued between two steel plates.

performing uniaxial and hydrostatic compression tests at several strain rates. In the present study, simple shear tests and tests involving simple shear combined with uniaxial compression were conducted using a novel hexapod device [20] with which controlled shape changes and volume changes can be imposed. Using the method of analysis presented in Refs. [18,19], shape change and volume change processes were analyzed and compared between various imposed radial loading paths.

In the first part of this study (Section 2), the mechanical behavior of the Expanded Polypropylene foam under investigation is briefly described and the size of the specimens used is explained. The hexapod device and the post-processing method of analysis used are also presented. In the second part (Section 3), the results of basic experiments such as uniaxial compression and tension and simple shear tests are presented. The multiaxial loading experiments performed are described and the results are presented and discussed in Section 4. Lastly, the main results obtained are summarized in section 5.

2. Material and methods

2.1. Material

2.1.1. Polypropylene foam

This study was performed on a closed-cell expanded polypropylene (EPP) foam called Arpro supplied by the company JSP. This foam has been widely studied by the present authors, who have established that the strain rate and the density both affect the mechanical behavior of the material under uniaxial compression [5] and hydrostatic compression [12] loading conditions. To extend this database, a new specimen of the same material with a mean density of 85.3 kg m^{-3} (standard deviation 4.3 kg m^{-3}) was prepared.

2.1.2. Description of the samples

Two main characteristics have to be taken into consideration when performing mechanical tests. First, the specimen size has to be suitable for obtaining representative, fairly homogeneous elementary mechanical responses. Secondly, the shape of the specimen must correspond to the types of loading applied in the tests.

In the case of the present uniaxial tension tests, a dogbone specimen designed in line with standard NF EN ISO 1798 [21] was used in order to concentrate the strain in the thinnest part of the specimen.

In the case of simple shear tests, the shape of the specimen greatly affects the results [22,23]. Simple shear tests induce a tangential force and a normal force on the loaded faces. These two forces combined induce a compression load and a tensile load near the free edges [24,25], which could be regarded as a bending load. This process can be reduced by increasing the elongation ratio $\frac{l}{h}$ of the specimen, where l and h are the length and the height of the specimen, respectively. Bouvier et al. [25], for instance, used an elongation ratio of 10 on a metal sheet sample, G'Sell et al. [24] recommended a ratio of more than 15 in the case of polymers, and Mostafa et al. [26] used a ratio of 13 in that of a foam sample. Specimens measuring 300 mm long, 20 mm high and 20 mm wide, having an aspect ratio $\frac{l}{h}$ of 15 were chosen here for performing both simple shear and uniaxial compression tests.

2.2. Methods

2.2.1. Experimental devices

A classical electromechanical Zwick Z250 Roell device was used to perform quasi-static uniaxial tensile tests in line with the procedure defined in the French standard NF EN ISO 1798 [21]. A crosshead speed of 41.25 mm min^{-1} was imposed in order to obtain a strain rate of 0.0125 s^{-1}. Uniaxial stress was obtained using a 10 kN sensor and strain field with Digital Image Correlation (D.I.C.) VIC2D software from pictures recorded by a camera (CANON EOS 50D) at a frequency of 1 Hz.

Multiaxial experiments tests were performed using a hexapod facility. Fig. 1 shows the hexapod, which is a modified Gough-Stewart platform, a type of parallel robot constituted of a fixed and a moving platform. Thanks to 6 electromechanical jacks, the top plate can be moved independently in the six degrees of freedom, corresponding to three translation axes and three rotation axes. Its horizontal velocity can reach 1.4 m/s and the maximal vertical velocity is 1 m/s. For the multiaxial tests, a rigid arm is mounted perpendicular to the moving top platform. Specimens were glued between 2 steel plates, one of which was screwed onto a rigid arm and the other, onto a base frame. This arrangement made it possible to apply loads of all kinds to the sample, including even complex loads such as combinations of movements. The hexapod was able to reach speeds of up to 1 m/s in all directions. However, the present study focused simply on quasi-static loading performed at a speed of 0.25 mm/s. Strain rates of $\dot{\varepsilon}_{zz} = 0.0125\ s^{-1}$ and $\dot{\gamma}_{yz} = 0.0125\ s^{-1}$ were imposed at each test so as to be able to compare the results obtained without any involvement of the viscous contribution.

Forces were obtained using a piezoelectric 3D sensor (Kistler 9377C) mounted between the rigid arm and the sample. The local basis (X,Y,Z) of the sensor was defined as shown in Fig. 1b. The sensor was set at 2, 10, and 10 kN in the X, Y and Z directions, respectively. Electrical signals were then amplified and recorded at a frequency of 100 Hz, as can be seen in Fig. 2 in the particular case of a uniaxial compression applied on the Z-axis and a simple shear applied simultaneously on the YZ-plane.

As in the tensile tests, the displacements and strain fields were calculated using the D.I.C. technique. The region of interest in the D.I.C. was chosen so as to rule out the occurrence of boundary effects by excluding the areas on both sides of the specimen and those near the steel plates (see Fig. 3). A second camera was placed perpendicularly to