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Material behaviour

Characterization of the compressive deformation behavior with strain rate effect of low-density polymeric foams

Akio Yonezu [a, *], Keita Hirayama [a], Hiroshi Kishida [a], Xi Chen [b, c, **]

[a] Department of Precision Mechanics, Chuo University, 1-13-27 Kasuga, Bunkyo, Tokyo 112-8551, Japan
[b] International Center for Applied Mechanics, SV Lab, School of Aerospace, Xi'an Jiaotong University, Xi'an 710049, China
[c] Department of Earth and Environmental Engineering, Columbia University 500 W 120th Street, New York, NY 10027, USA

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ABSTRACT

This study investigates the compressive deformation behavior of a low-density polymeric foam at different strain rates. The material tested has micron-sized pores with a closed cell structure. The porosity is about 94%. During a uni-axial compressive test, the macroscopic stress–strain curve indicates a plateau region during plastic deformation. Finite Element Method (FEM) simulation was carried out, in which the yield criterion considered both components of Mises stress and hydrostatic stress. By using the present FEM and experimental data, we established a computational model for the plastic deformation behavior of porous material. To verify our model, several indentation experiments with different indenters (spherical indentation and wedge indentation) were carried out to generate various tri-axial stress states. From the series of experiments and computations, we observed good agreement between the experimental data and that generated by the computational model. In addition, the strain rate effect is examined for a more reliable prediction of plastic deformation. Therefore, the present computational model can predict the plastic deformation behavior (including time-dependent properties) of porous material subjected to uni-axial compression and indentation loadings.

1. Introduction

Porous polymers with a low density are widely used for contact/impact absorption and heat/acoustic insulation because of their good energy absorbing properties, good vibration attenuation and thermal/acoustic insulation [1–5]. In use, compressive loadings, including indentation and low velocity impacts by foreign objects, are often applied [6], and quasi-static indentation tests have been used to understand the low velocity impact response of composites [7] and protective coatings [8,9]. Consequently, analytical and numerical modeling for porous polymer materials is necessary in order to predict their deformation behavior, especially large plastic deformation. In general, the mechanical response is strongly dependent on inherent porous structure, polymer type and loading conditions. Indentation loading usually induces a complicated stress state compared with that of uni-axial loading. Such a complicated tri-axial stress may make modeling of macroscopic deformation more difficult when using an analytical/theoretical approach. Several analytical models have been developed to predict indentation resistance during quasi-static indentation of aluminum foams [10–12] and for polymeric foams [2]. Olurin et al. used an indentation test on aluminum foams to obtain material properties, i.e. plateau stress and tear energy [10]. Flores-Johnson et al. investigated the indentation responses of polymeric foam (polymethacrylimide and polyetherimide) with an analytical model based on experimental observation [2]. The deformation behavior was described based on total resistance force (which consisted of a crushing force, tearing force and friction force) developed during indentation loading. The analytical model was successfully established in order to calculate a resistance force during an indentation test. They verified the proposed model by conducting several indentation tests with different indenter shapes [2].

On the other hand, numerical simulations of quasi-static loading, including indentation into metallic polymeric foams, have been explored based on a continuum model of plasticity (constitutive model of plastic deformation). In fact, plastic theory

* Corresponding author.
** Corresponding author. International Center for Applied Mechanics, SV Lab, School of Aerospace, Xi'an Jiaotong University, Xi'an 710049, China.
E-mail addresses: yonezu@mech.chuo-u.ac.jp (A. Yonezu), xichen@columbia.edu (X. Chen).

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for porous media based on continuum models has been investigated. Miller has proposed a continuum plasticity framework for metallic foams [13]. The Drucker-Prager yield criterion was modified and introduced three adjustable parameters to match the yield surface from experimental data. These data are the uniaxial tensile and compressive yield stresses, and the ratio of radial to axial plastic strain rate, i.e. the "plastic Poisson's ratio". An associated flow rule is also assumed to give a constitutive law of the plastic behavior. More simply, Deshpande and Fleck established a new yield criterion for porous media, which can be applied to both open cell and closed cell low density aluminum foam [14]. It is a very simple formula, which relies on only the plastic Poisson's ratio as the material parameter. These proposed criteria were verified based on the experimental data of yield surface for aluminum foam [15] and polymer foam [16]. Furthermore, the Deshpande and Fleck criterion was systematically investigated with regard to its applicability to plastic flow behavior with an assumption of associate flow [14,17,18]. Thus, this criterion may be readily employed to describe the plastic deformation of porous media with the aid of a numerical approach (e.g. FEM). As mentioned above, indentation loading (similar to low velocity impact) is critical for the use of porous materials, and it usually produces a strain rate effect in practice. Therefore, the modeling of plastic deformation, including indentation and rate-dependent behavior, is necessary for material design with a cellular structure.

This study is motivated by the lack of a computational framework for the indentation mechanics with strain rate effect of low-density polymeric foams. In order to establish computational modeling for indentation responses subjected to various indenters with different loading rates, the yield criterion and plastic flow behavior proposed by Deshpande and Fleck [14] is used in the FEM computation. Note that strain rate effect is not included in the previous model [14]. Based on this, we will explore a computational framework, including the strain rate effect. In the experiment, a uniaxial compression test was first carried out to obtain the macroscopic stress–strain curve and the plastic Poisson's ratio. This leads to yield strength, work-hardening rate and the material parameter for the Deshpande-Fleck criterion. Subsequently, indentation tests were carried out on the porous polymer. Here, we used two indenters with different shapes (i.e. spherical type and wedge type) and different loading rates, to induce various indentation responses. Finally, we investigated the feasibility of our computational modeling, i.e., whether it can predict the indentation response obtained by the experiments. Our phenomenological approach may be more useful for explaining the indentation response (heterogeneous deformation) of low-density foam compared with the above analytical model based on the crush and fracture energy model.

In Section 2, the material properties of the present polymer foam will be presented. Section 3 investigates the response to the uni-axial compression test. Section 4 describes the theory of yield criterion and plastic flow in order to establish the computational model for plastic deformation. Subsequently, the verification of our computational modeling through several indentation experiments is described.

2. Material and experimental procedure

The material used in this study was commercial porous polymer material for heat/thermal insulating and impact absorption, more specifically a board of Porous Polypropylene (PP) with a closed cell structure (Zetlon®, Sekisui Chemical Co. Ltd) and thickness of 10 mm. Test specimens were taken from the board. The specimen size was different depending on the loading type (uni-axial compression and indentation), which will be described later. Fig. 1

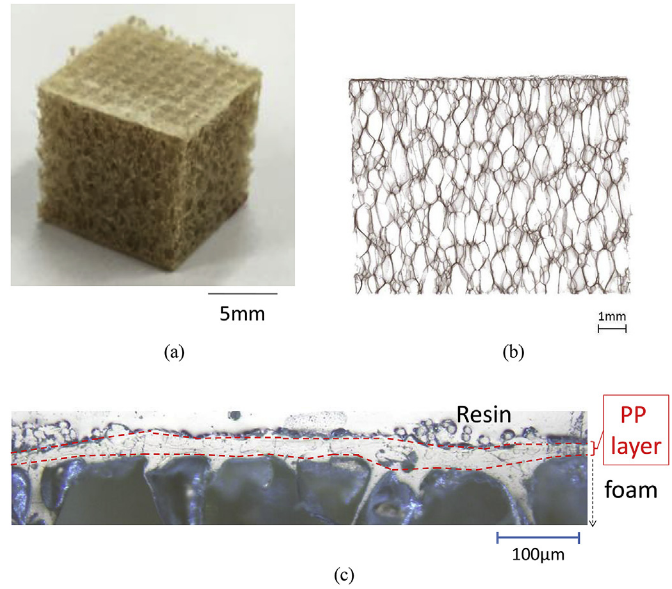

Fig. 1. Pictures of the present specimen: (a) macroscopic picture; (b) X-ray CT image; and (c) surface layer observed through an optical microscope.

(a) shows a macroscopic picture of the specimen. To observe the micro structure, the X-ray CT technique (micro-CT system, SkyScan 1172) was utilized. The specimens were scanned with the micro-CT system, whose scanning parameters were set as X-ray source voltage of 59 kV, image pixel size of 4.08 μm and rotation step of 0.2°. Fig. 1(b) shows the internal micro-CT cross-sectional images taken from the specimen. Many pores which seem to have elliptical geometry along the thickness direction were observed. A volume of 10 mm × 10 mm × 3 mm was used in order to measure the distribution of pore size. If the pore is assumed to be a spherical shape, its averaged diameter is 567 μm. Since the present specimen was of foam material, the structure was closed pore (closed-cell). The porosity was measured to be 94% based on the density measurement (the density of the PP material was 0.95 g/cm^3).

The foam had a surface layer of solid PP to protect the closed pore structure. To observe the cross section of a surface layer, the foam was potted in epoxy resin and the cross sectional surface was polished. Fig. 1 (c) shows the optical microscope image of the cross section. A surface layer of "solid" PP material was observed. Below the surface, a thin cell wall of PP ligament (to form the porous structure) was observed. This constitutes closed-cell PP foam. The thickness of the surface layer was measured in the range of about 5 mm length, resulting in an averaged thickness of 36 μm.

The uniaxial compression test was performed on a universal testing machine with a ball screw type (LSC-1/30: Tokyo Testing Machine Inc.) using a 10 mm cube specimen. A compression jig with a flat face was used for uni-axial loading under displacement control. The rate of loading displacement was set to 1.7 × 10^{-2} mm/s. For the measurement of displacement, two eddy current sensors (EX-305 and EX-201, Keyence) were used. These were mounted on the jigs so that they could directly measure the gap between the two compression jigs, which corresponds to the uniaxial deformation of the specimen.

Subsequently, concentrated loading was applied to the specimen in order to investigate different mechanical conditions. This is typical indentation testing to produce a tri-axial stress state in the material. The stress state due to indentation is quite different to that of the uni-axial compression test. This study used two types of indenter whose geometries are spherical and wedge type. The