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# Numerical analysis of anisotropic elasto-plastic deformation of porous materials with arbitrarily shaped pores

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ABSTRACT

The objective of this work is to numerically investigate the anisotropic compressive behavior of porous materials with randomly distributed, arbitrarily shaped pores in various directions. The relative pore volume fraction, the anisotropic aspect ratio and the pore arrangement are taken into account. The direction and anisotropic aspect ratio dependences of Young's modulus and the initial yield stress are examined. Our results indicate that the anisotropic aspect ratio has a significant effect on the elasto-plastic behaviors of porous materials. Independent of pores distribution, Young's modulus and the yield stress are found to be symmetric with the transverse direction. However, with increasing the aspect ratio Young's modulus and the initial yield stress are greatly enlarged in the longitudinal direction of pores than those of other directions while the minimum variations are observed in transverse direction. Moreover, equations for arbitrary porous materials are developed by relating Young's modulus and the initial yield stress in various directions to those in the transverse direction, which provides a simple and effective method for predicting the deformation of porous materials in arbitrary directions based on that in the transverse direction.



## 1. Introduction

Porous materials, offering lightweight, high specific strength and good energy absorption property, are a relatively new and uncommon group of engineering materials [1,2]. Due to the manufacturing process, pores in porous materials are usually longer in the longitudinal direction (LD) than those of normal to it, which makes the porous materials substantially anisotropic [1,3,4–6]. The anisotropy occurs when foaming is performed in a mold, in which the volume expansion generated by gases cause pores to rise in one direction, and the pores become elongated in the direction of rising because they are subjected to viscous forces [1]. Variations of the sizes and shapes of pores or inclusions with direction can lead to the significant direction dependence of their prosperities [7–10]. As an example, the stiffness and the strength of anisotropic porous materials in LD are much larger than those in transverse direction (TD) [7,11].

The investigation of anisotropic behaviors of porous materials has been an essential problem and extensively analyzed. Gent and Thomas [12] developed a two dimensional (2D) anisotropic model and discussed the anisotropic behaviors of open-cell plastic foams. Huber and Gibson [7] proposed an orthotropic unit-cell model to describe the anisotropy in foams, which was a simple extension of the Gibson and Ashby model [13]. Equations for the ratios of the modulus, of the elastic, plastic and brittle collapse stresses and of the fracture toughness in LD to those of TD are given. Afterward, their model were extended and modified by many researchers [14,15].

Amsterdam et al. [16] studied the anisotropic mechanical properties of open-cell aluminum foams. Their results showed that the stiffness and the plastic collapse stress of the LD specimens are higher than those of the TD specimens, which was attributed to the cell shape anisotropy. Kitazono et al. [17] carried out the uniaxial compressive tests of closed-cell foams. Mu and Yao [15] experimentally investigated the anisotropic compressive behaviors of closed-cell alloy foams. They obtained linear relationships between Young's modulus ratio, yield strength ratio and anisotropy ratio, and compared their results with those obtained by the Gibson and Ashby model. However, in all of these studies, only the LD and the TD results of the foams were taken into consideration.

Pore morphology is another key parameter that affects the anisotropic behaviors of porous materials. Using the mean-field approximation, Kitazono et al. [14] derived the elasto-plastic properties of isotropic and anisotropic closed-cell foams with an aligned spheroidal pores model. They concluded that the yield stress of closed-cell foams was independent of the loading direction, which

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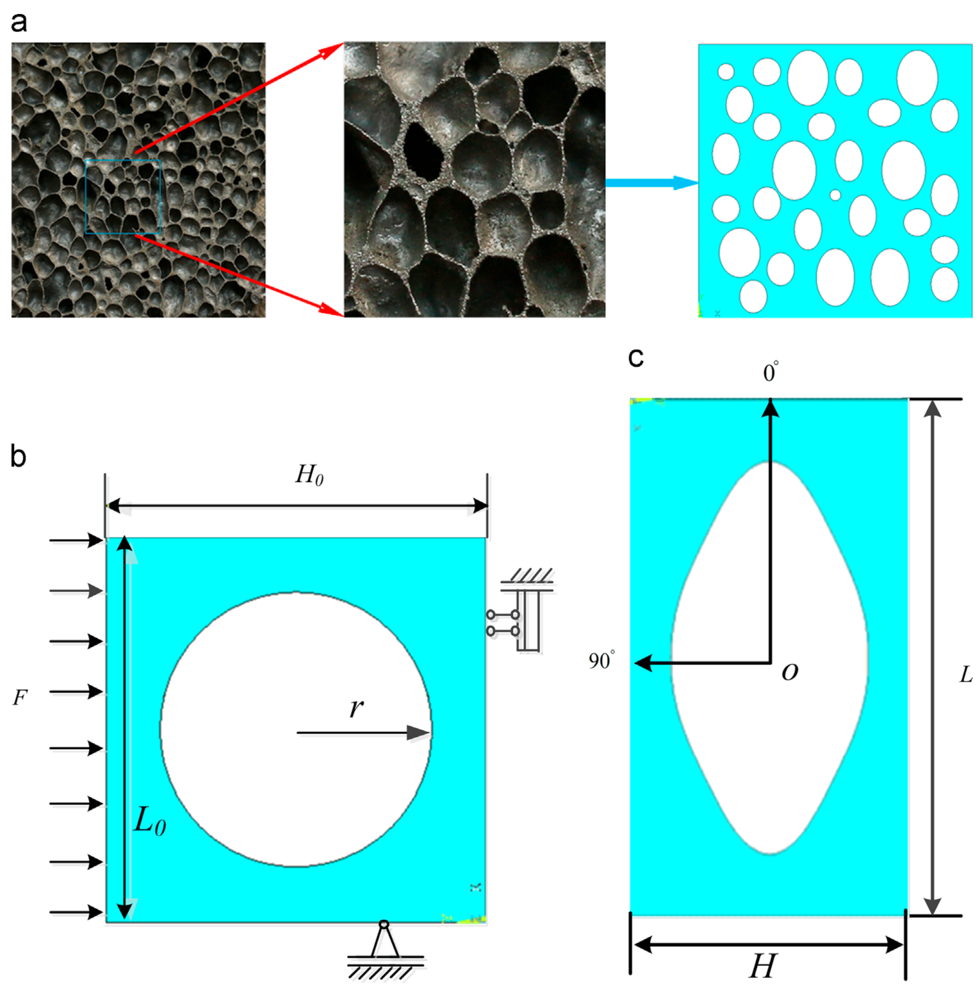


**Fig. 1.** The modeling process of unit cell models: (a) porous materials with arbitrary pore distributions; (b) the initial model with spherical pore; and (c) the arbitrarily shaped pore model. *F* denotes the compressive loading.

was not consistent with the previous results of Huber and Gibson [7]. Tane et al. [18] extended the mean-field method for predicting yield behaviors of porous materials. Their calculations revealed that the yield stress was virtually independent of the elastic anisotropy of the matrix, but strongly depended on the plastic anisotropy and also on the pore morphology.

In the aforementioned investigations, two simplifications were basically adopted: (1) Only the materials behaviors of two directions, LD and TD, were considered for the anisotropic porous materials; (2) The pores in the porous materials were usually simplified to have an ellipsoid shape. However, understanding of the proprieties of the porous materials in arbitrary directions, which is still an open problem, is essential for the extensive application of anisotropic porous materials. Moreover, the pore shape is complex after fabrication and cannot be accurately described by ellipsoids. In this paper, unit cell models with periodic boundary condition are developed and adopted to address the anisotropic compressive behaviors of porous materials. The major concerns are (1) the macroscopic anisotropic compressive behaviors of porous materials in arbitrary direction, and (2) the relations of the modulus and the initial yield stress in arbitrary directions to those of TD. The organization of this paper is as follows: In Section 2, the material models and the numerical process are presented. Then, results of the elasto-plastic deformation in various directions are presented in Section 3 for porous materials with various pore shapes. Section 4 outlines some major conclusions.

## 2. Formulation of the problem

### 2.1. Material models

Pore distributions vary in anisotropic porous materials. To well describe the features of material microstructures, it is essential to characterize the macroscopic anisotropic behaviors of the porous materials in arbitrary direction. Thus, models with different pore arrangements and sufficiently large representative volume element (RVE) are necessary, as shown in Fig. 1(a). However, large amounts of computation are involved in this modeling process [19,20]. Therefore, 2D unit cell models are often adopted to study the macroscopic anisotropic behaviors of porous materials. It is necessary to mention that the real microstructure of porous material plotted in Fig. 1(a) is only a diagrammatic sketch that aims to illustrate the complex pore distributions. The RVE applied in this work is not simplified from the real microstructure of the material.

Herein we take the rectangular unit cell model shown in Fig. 1(b) as an example to briefly demonstrate the modeling process. In order to investigate the anisotropy deformation behavior of porous, arbitrary pore shape shown in Fig. 1(c) is modeled to mimic the complex microstructures of anisotropic porous material, which is obtained by applying a compressive load to the spherical pore model with the same pore arrangement as plotted in Fig. 1(b). Firstly, compress the unit cell model with spherical pore, as shown in Fig. 1(b). Then, the node coordinates of