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Elastic buckling and free vibration analyses of porous-cellular plates with uniform and non-uniform porosity distributions

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ABSTRACT

The aim of this research paper is to present the elastic buckling and free vibration analyses of porous-cellular plates based on the first-order shear deformation theory (FSDT). In the porous-cellular plate model, porosities are dispersed by uniform and non-uniform (symmetric and asymmetric) distribution patterns. The material properties, such as Young's modulus and mass density of the porous-cellular plates are assumed to vary along the thickness direction in term of porosity coefficient. First, the dynamic version of Hamilton's principle is applied to derive the Euler–Lagrange equations. Then, in the case of simply supported boundary condition, the critical buckling load and natural frequency of the porous-cellular plates are obtained using the Navier procedure. Furthermore, the reliability of the current formulation is validated by several examples. Finally, a comprehensive examination into the influence of porosity coefficient, porosity distributions, and the geometric parameters on the buckling behavior and vibration response of the porous-cellular plates are performed. Numerical results indicate that the effect of porosity distributions on the structural performance and provide the useful insights into the porosity design to achieve appropriately natural frequency and buckling resistance.

1. Introduction

In the important development of material science, lightweight structures made of porous-cellular materials such as porous metal foam, are widely used in many applied sciences and applications such as in aerospace industry, automotive and civil engineering, etc. [1–4]. For the porous materials model, the variation of porosity through the thickness direction of the structures causes a smooth and continuous change in material properties. Therefore, the structures made of the porous-cellular materials have received a lot of attention from scientists and researchers in the recent years.

Up to date, the buckling and vibration analyses of porous beams have been investigated. For example, Wattanasakulpong and Ungbhakorn [5] presented an investigation on the vibration response of the functionally graded (FG) beams with porosity. They used a differential transformation method to obtain the frequency parameter and nonlinear response of the FG beams. The buckling and bending analyses of the FG porous beam based the first-order beam theory were reported by Chen et al. [6]. These authors assumed that Young's modulus and mass density of the beam are changed to be graded in the beam thickness direction. With the same approach, these authors also studied the vibration response of FG porous beams [7], in which the Ritz method and Newmark-β method were applied to solve the natural frequencies and deflection. Chen et al. [8] proposed a sandwich beam model with porous core to investigate the vibration problem. Barati and Zenkour [9] investigated the post-buckling behavior of an imperfect nanobeam made of metal foam with various porosity distribution. They found that porosities had a good impact on the nonlinear behavior of the nanobeam. A porosity-dependent vibration study of the magneto-electric-elastic nanobeam based on the third-order beam theory was carried out by Ebrahimi and Barati [10]. These authors used the Eringen's nonlocal elasticity model for the vibration problem of the nanobeam. Kitipornchai et al. [11] presented the vibration and buckling analyses of a FG porous beam. They assumed that the beam is reinforced by graphene platelets. The modeling of porous beam reinforced graphene platelets was also developed by Barati and Zenkour [12] for the post-buckling problem.

As background understanding buckling behavior of porous circular plate, a brief review of relevant studies is presented in this paragraph. A study on global and local buckling of the circular plates with metal foam core based on analytical and numerical

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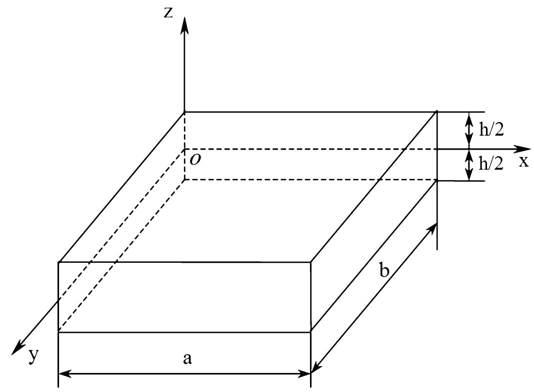

Fig. 1. Geometry and coordinate system of a porous-cellular plate.

approaches was presented by Jasion et al. [13]. They carried out experimental results to compare with the results of finite element method. Using the classical plate theory, Jabbari et al. [14,15] studied the mechanical and thermal buckling of the FG circular plate with of porous material. It should also be noted that, these authors just considered the plate with asymmetric distribution. Mojahedin et al. [16] used an analytical solution to investigate the buckling behavior of a porous circular plate under uniform compression load. Qinghua et al. [17] proposed an analytical model to analyze the dynamic response of a sandwich plate with the metal foam core under low-velocity load. An investigation on the free vibration response of a porous-cellular plate based Levy-type solution was also studied by Rezaei and Saidi [18]. In their investigation, they used the Carrera Unified Formulation (CUF) to derive the governing equations and these equations were solved by using the state space method. Moreover, a series paper regarding on buckling and vibration of functionally graded plates using the refined theory and the new shear deformation theory was presented [19–26].

Furthermore, as mentioned above, although the porous structures are known to have many interesting applications in engineering, however, studies on the behavior and stability of these structures are still limited. To the best of author's knowledge, a comprehensive investigation of the elastic buckling and free vibration problems that deals with three types of porosity distribution based on an analytical approach has not been reported. This paper attempts to fill this research gap. The approach [27] is extended in this paper to obtain approximate solutions for buckling and vibration problems of the porous-cellular plates. In [18], these authors just considered the asymmetric distribution type. In this paper, we expand these problems for all three distribution (uniform, symmetric and asymmetric distributions). Moreover, the FSDT is employed to establish the governing equations of the plate. Based on the Navier solution and FSDT, an approximate solution for buckling and vibration analysis is applied, from which the critical buckling load and natural frequency can be determined. The accuracy of the present formulation is also demonstrated by comparing the results with those available in the literature.

The research paper is organized as follows. Section 2 presents three types of material distribution for the porous-cellular plate model. Section 3 deals with developing the FSDT to establish the governing equations. Boundary condition and Navier solution are presented in Section 4. Section 5 provides the numerical results for buckling and vibration analyses. Finally, some main conclusions are drawn in Section 6.

2. Porous-cellular plate with various porosity distributions

Let us initially consider a porous-cellular plate of length a, width b, and thickness h. Assume that plate is rectangular thick plate. The porous-cellular plate is referred to rectangular Cartesian

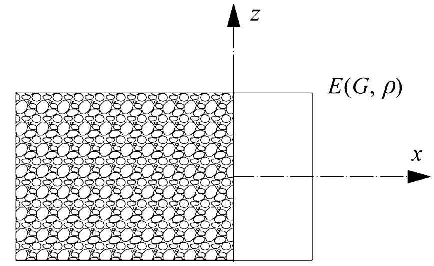

Fig. 2. Modeling of uniform porosity distribution through the plate thickness [6].

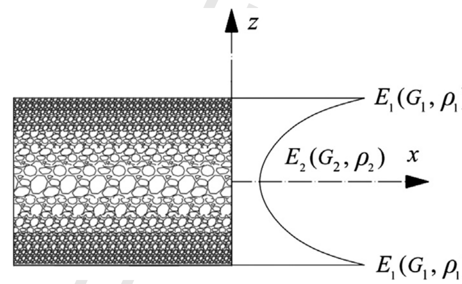

Fig. 3. Modeling of non-uniform symmetric porosity distribution through the plate thickness [6].

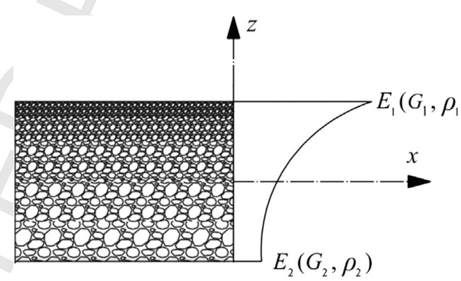

Fig. 4. Modeling of non-uniform asymmetric porosity distribution through the plate thickness [6].

coordinates (x, y, z), as shown in Fig. 1. We consider three different types of porosity distribution as [6,9]:

- Uniform porosity distribution (see Fig. 2)

$$E(z) = E_1(1 - e_0\chi) \tag{1a}$$

$$G(z) = G_1(1 - e_0\chi) \tag{1b}$$

$$\rho(z) = \rho_1\sqrt{(1 - e_0\chi)} \tag{1c}$$

where

$$\chi = \frac{1}{e_0} - \frac{1}{e_0}\left(\frac{2}{\pi}\sqrt{1 - e_0} - \frac{2}{\pi} + 1\right)^2 \tag{2}$$

- Non-uniform symmetric distribution (see Fig. 3)

$$E(z) = E_1\left[1 - e_0\cos\left(\frac{\pi z}{h}\right)\right] \tag{3a}$$

$$G(z) = G_1\left[1 - e_0\cos\left(\frac{\pi z}{h}\right)\right] \tag{3b}$$

$$\rho(z) = \rho_1\left[1 - e_m\cos\left(\frac{\pi z}{h}\right)\right] \tag{3c}$$

- Non-uniform asymmetric distribution (see Fig. 4)

$$E(z) = E_1\left[1 - e_0\cos\left(\frac{\pi z}{2h} + \frac{\pi}{4}\right)\right] \tag{4a}$$

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