Thin-Walled Structures 132 (2018) 604–615

Contents lists available at ScienceDirect

Thin-Walled Structures

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

Full length article

On the stability of spinning thin-walled porous beams

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ARTICLE INFO

Keywords:
Flutter and divergence instabilities
Porosity
Graphene platelets
Spinning thin-walled beam
Vibration

ABSTRACT

In the current study, the stability analysis of functionally graded (FG) thin-walled porous beams reinforced by nanocomposite graphene platelets (GPLs) under compressive axial load is investigated. It is assumed that the thin-walled porous beam is spinning along its longitudinal axis and both symmetric and asymmetric distributions of porosity are considered. Furthermore, the GPLs are distributed thorough the thickness direction both uniformly and non-uniformly. The effective material properties such as Young's modulus, mass density and Poisson's ratio of the porous beams are computed based on the Halpin-Tsai micromechanics model and the rule of mixture. The extended Hamilton's principle is utilized to establish the governing equations and they are discretized by the extended Galerkin method (EGM). The effects of various parameters such as GPL porous distribution patterns, GPL weight fraction, geometry of GPL nanofillers and porosity coefficient on the frequencies as well as flutter and divergence instabilities of the thin-walled porous beams have been studied. Numerical results demonstrate that the best efficient way to increase the stability region is considering GPL pattern A, with dispersing more GPL fillers near the top and bottom surfaces of the thin-walled porous beam along with symmetric porosity distribution.

1. Introduction

Porosities and micro-voids can be observed inside the materials in some production operation for fabricating the functionally graded materials (FGMs) due to the technical problems. The most potential applications of the FG porous material are dependent on our understanding of their mechanical behavior. Therefore, the mechanical analysis of the FG porous structure has become a subject of primary interest in recent years. In the sense of vibration analysis of FG porous structure, Wattanasakulpong and Ungbhakorn [1] found linear and nonlinear vibration responses of the porous beams made of FGMs. The effects of volume fraction of material constituents and volume fraction of porosity were the remarkable points of their study. Later, Wattanasakulpong and Chaikittiratana [2] examined the flexural vibration analysis of imperfect FGM beams with porosities based on Timoshenko beam theory. Leclaire et al. [3] studied the vibration behavior of thin rectangular porous plate saturated by a fluid. The buckling and bending behaviors of beams made of two different porosity distributions were performed by Chen et al. [4] to illustrate the influence of porosity coefficient on the maximum deflection, critical buckling load and related stress distribution. Chen et al. [5] investigated free and forced vibration of the porous beams with FG behavior along the thickness direction. They discussed the effects of varying porosity distribution, porosity coefficient, different loading conditions and boundary conditions on the frequency and dynamic deflection. The effects of porosity volume fraction, various thermal loadings, material property, gradient index and boundary conditions on the frequencies of FGM porous beams were examined by Ebrahimi et al. [6]. Askari et al. [7] investigated the free vibration of the porous-cellular plates with piezoelectric layers based on third-order shear deformation plate theory. Using Euler-Bernoulli beam theory, Ebrahimi and Hashemi [8] considered thermal vibration characteristics of the FG porous beams subjected to different thermal loadings. They expressed the dependency of porosities on power-law exponent, porosities distribution and temperature changes. Rjoub and Hamad [9] presented an analytical method to investigate the dynamic behavior of FG porous beams with different boundary conditions. Forced vibration analysis of the FG porous deep beams under dynamically load were studied by Akbaş [10]. There are other studies on the FG porous structures as well such as (Rezaei and Saidi [11–15], Rezaei et al. [16], Ebrahimi et al. [17], Wang and Zu [18] and Wang et al. [19]).

The structural elements made of the mixture of polymer matrices and carbonaceous nano-fillers such as graphene and carbon nanotubes (CNTs) are attracting considerable attention from both research and engineering communities. They are basic elements of many devices and systems in the biology, industrial, biotechnology and engineering fields

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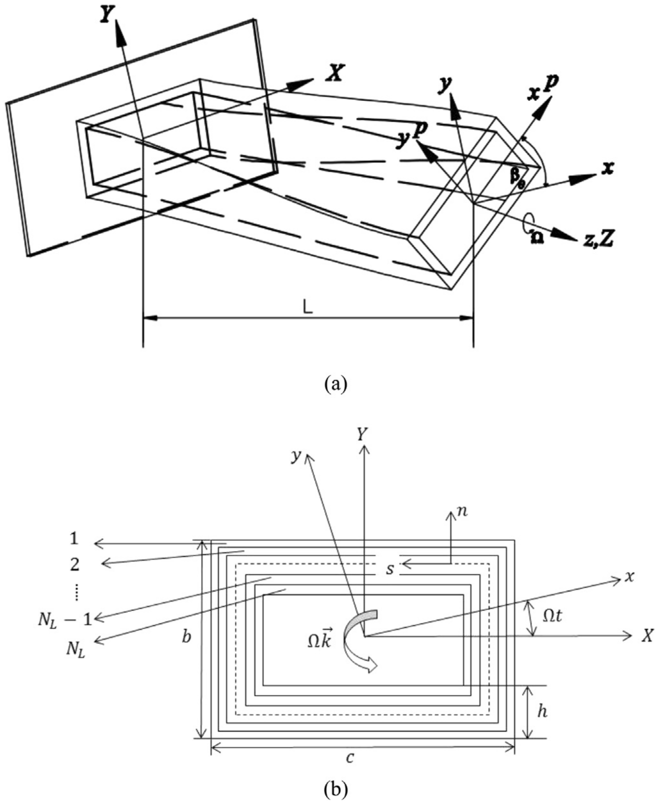
https://doi.org/10.1016/j.tws.2018.09.022
Received 20 March 2018; Received in revised form 28 August 2018; Accepted 5 September 2018
0263-8231/

[20,21]. Graphene is the lightest and strongest two-dimensional monolayer of carbon atoms. It has tensile strength and Young's modulus compared to CNTs, along with a much larger surface area [22,23]. Also, the extraordinary properties of nanocomposites reinforced by GPLs and CNTs convert them to effective nano-fillers for fabricating and manufacturing lightweight gasoline tanks, medical implants, sport equipment and strong wind turbines [24,25]. Nonlinear free vibration of a multilayer polymer nanocomposite beam reinforced by GPLs based on Timoshenko beam theory and von Kármán nonlinear strain-displacement relationship was studied by Feng et al. [26]. Feng et al. [27] also investigated nonlinear bending behavior of the multi-layer polymer nanocomposite beams reinforced by GPLs. Free and forced vibration of the FG polymer composite plates reinforced with GPLs using the first-order shear deformation plate theory were performed by Song et al. [28]. Wu et al. [29] studied thermal buckling and postbuckling of the FG multilayer nanocomposite plates reinforced with GPLs. Yang et al. [30] studied thermoelastic bending of the FG polymer nanocomposite plate reinforced with GPLs based on three dimensional elasticity theory. Buckling and postbuckling of the FG multilayer composite beam reinforced with GPL were studied by Yang et al. [31]. Besides, applying nano-fillers into porous materials is an important factor to enhance the mechanical properties of the lightweight structures. Such porous nanocomposites can provide the industrialization of high-tech smart materials, electromagnetic absorption components and superior fuel cells [32–34]. Wu et al. [35] performed the dynamic instability of reinforced beams with FG multilayer nanocomposite and subjected to axial force in thermal environment. In the frame work of Timoshenko beam theory, Chen et al. [36] studied the effects of weight fraction, dispersion patterns, geometry and size of GPL nano-fillers on the nonlinear vibration and post-buckling behaviors of the FG porous beams. The effects of GPL reinforcing nano-fillers and porosity distribution on the vibration and buckling of FG metal foam beams were investigated by Kitipornchai et al. [37]. Recently, Barati and Zenkour [38] have studied both ideal and imperfect nanocomposite beams for post-buckling behavior of the porous beams reinforced by GPLs resting on nonlinear foundation.

Thin-walled structures spinning about their longitudinal axis are extensive in different branches of industry such as aviation, variety of aerospace structural systems, automobile, drilling tools, cutting tools used in boring and milling operations. Many studies have been investigated to examine the mechanical characteristics of composite and FG thin-walled structures due to their interesting features. In this sense, many researchers studied the vibration and instability analysis of thin-walled spinning blades [39–47]. Li et al. [48] studied vibration behavior of the thin-walled spinning beams made of composite materials in hygrothermal environment. They investigated the effects of spinning velocity, temperature, moisture, geometric parameters and fiber orientation angles on the natural frequency of system. Bahaadini et al. [49] studied stability analysis of the thin-walled pipe conveying fluid made of composite materials. Li et al. [50] also proposed coupled vibration analysis of a spinning and axially moving thin-walled beam made of composite materials. Shabanlou et al. [51] studied vibration of the spinning beams based on higher-order shear deformation beam theory. The stability of a pre-twisted spinning beam embedded in viscoelastic medium and subjected to non-conservative force were performed by Karimi-Nobandegani et al. [52]. Free vibration of the spinning beam made of an axially FGMs based on Timoshenko beam theory was reported by Huang et al. [53]. They observed that the axially FGM and boundary conditions have significant effects on the whirling frequency, critical velocity and mode shape. Recently, the effects of CNT distributions, volume fraction of CNT, fluid velocity, mass fluid ratio, spinning speed and thermal environment on the stability analysis of spinning thin-walled pipe reinforced by FG-CNT have been performed by Bahaadini and Saidi [54].

In view of the above mentioned literature review, the mechanical behaviors of polymer nanocomposite porous elements reinforced by GPLs have been investigated in a few works. As far as the authors are aware, no previous works have been done on the vibration and instability of the spinning FG thin-walled porous beams reinforced by GPLs under compressive axial load. The main objective of the present work is to develop a more comprehensive of various parameters such as GPL and porous distribution patterns, GPL weight fraction, geometry of GPL nanofillers and porosity coefficient on the natural frequency, divergence and flutter instabilities of the spinning FG nanocomposite thin-walled porous beams. The governing equations of the system are derived based on the thin-walled Timoshenko beam theory of Librescu et al. [55]. The EGM is used to determine the natural frequency, critical spinning speed and critical compressive axial load of the spinning thin-walled porous beams reinforced by GPLs. In order to demonstrate the accuracy of the proposed model, the numerical results are compared with those reported in the literature.



(a)

(b)

Fig. 1. The geometry of the spinning thin-walled beam: (a) pre-twisted thin-walled beam; (b) beam cross-section.

2. The basic formulations

The pre-twisted spinning thin-walled porous beams reinforced by GPLs have been demonstrated in Fig. 1. A pre-twisted beam has a length L, thickness h, angle of twist along the z-axis $\beta(z)$, and spinning speed Ω. The global and local coordinate systems are demonstrated by (x, y, z) and (x^p, y^p, z^p) in Fig. 1, respectively.

The transformation relationships between two coordinate systems can be assumed as [41]

$$\begin{aligned} x &= x^p\cos(\beta(z)+\gamma) - y^p\sin(\beta(z)+\gamma),\\ y &= x^p\sin(\beta(z)+\gamma) + y^p\cos(\beta(z)+\gamma),\\ z &= z^p,\\ \beta(z) &= \frac{\beta_0 z}{L}. \end{aligned} \tag{1}$$

where γ denotes the presetting angle. The displacement fields of thin-walled Timoshenko beam theory can be written as [41]