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Free flexural vibration of geometrically imperfect functionally graded microbeams

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ABSTRACT

Free flexural vibration characteristics of functionally graded (FG) microbeams with geometric imperfection are explored numerically, taking into account the size effect phenomenon based on modified couple stress theory. This theory employs only one material length scale parameter to interpret the size-dependent mechanical behavior of microstructures. The mechanical and physical properties of FG microbeam are assumed to vary smoothly and continuously through the thickness direction according to a power-law distribution. Hamilton's principle in conjunction with Euler-Bernoulli beam theory is used to establish the coupled longitudinal-transverse equations of motion and associated boundary conditions. A weighted-residual method is utilized to evaluate the size-dependent free flexural vibration behavior of FG microbeams with clamped-clamped, clamped-pinned, and pinned-pinned boundary conditions. The influences of different dimensionless parameters i.e., maximum imperfection amplitude-to-length ratio, length-to-thickness ratio, flexural rigidity ratio, and power-law index on the flexural frequencies and mode shapes of FG microbeams are investigated. The mode veering phenomenon is also explored. Finally, the role of longitudinal displacement in the free flexural vibration of the geometrically imperfect FG microbeams is examined.

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1. Introduction

The experimental tests (Lam, Yang, Chong, Wang, & Tong, 2003; Liebold & Müller, 2016; Liu et al., 2013; Motz, Schöberl, & Pippan, 2005; Son, Jeong, & Kwon, 2003) on microstructures proved that the behavior of these components is different from that predicted by the classical continuum theories. Hence, various higher-order elasticity theories have been developed to interpret the size-dependent behavior of microstructures. (Yang, Chong, Lam, & Tong, 2002) proposed a modified version of couple stress theory by introducing one additional equilibrium relation to govern the behavior of the couples. The relation requires that the deviatoric part of couple stress tensor must be symmetric and also that the strain tensor and symmetric curvature tensor are the deformation measures conjugate to the symmetric stress tensor and the deviatoric couple stress tensor, respectively. Based on modified couple stress theory, there is only one independent material length scale parameter for linear isotropic elastic materials.

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Modified couple stress theory has become a popular higher-order elasticity theory. Many researchers have used this theory to derive governing equations of microstructures and to study the influence of size-dependency on their mechanical behavior. Some of these works can be outlined as: an Euler-Bernoulli beam model for static bending analysis and comparison with experimental data by (Park & Gao, 2006), a microstructure-dependent Timoshenko beam model for static bending and free vibration analysis by (Ma, Gao, & Reddy, 2008), a nonlinear Euler-Bernoulli beam model for static bending, free oscillation and post buckling analysis by (Xia, Wang, & Yin, 2010), functionally graded Euler-Bernoulli and Timoshenko beam models for static and free vibration analysis by (Asghari, Ahmadian, Kahrobaiyan, & Rahaeifard, 2010; Asghari, Rahaeifard, Kahrobaiyan, & Ahmadian, 2011), buckling analysis of axially loaded micro-scaled beams with different boundary conditions based on Euler-Bernoulli beam theory by (Akgöz & Civalek, 2011), dynamic stability of microbeams made of functionally graded materials based on Timoshenko beam theory by (Ke & Wang, 2011), wave propagation characteristics of a twisted micro scale beam by (Mustapha & Zhong, 2012), static bending and dynamic analysis of third-order shear deformation functionally graded microbeams by (Salamat-talab, Nateghi, & Torabi, 2012), a model of composite laminated Reddy plate for static bending by (Chen, Xu, & Li, 2012), nonlinear free vibration analysis of extensible functionally graded microbeams by (Ke, Wang, Yang, & Kitipornchai, 2012), dynamic stability analysis of functionally graded higher-order shear deformable microshells by (Sahmani, Ansari, Gholami, & Darvizeh, 2013), three-dimensional nonlinear size-dependent behaviour of Timoshenko microbeams by (Ghayesh, Amabili, & Farokhi, 2013), a Mindlin plate finite element for static bending, buckling and dynamic analysis by (Zhang, He, Liu, Gan, & Shen, 2013), nonlinear analysis of functionally graded microstructure-dependent beams using finite element method by (Arbind & Reddy, 2013), on stability and fundamental frequency of a fully clamped capacitive circular microplate by (Rashvand, Rezazadeh, Mobki, & Ghayesh, 2013), static and dynamic stability analyses of a functionally graded microbeam under electrostatic force by (Abbasnejad, Rezazadeh, & Shabani, 2013), static bending and free vibration analysis of functionally graded microbeams using a new higher order beam theory by (Şimşek & Reddy, 2013), free flexural vibration analysis of axially functionally graded tapered Bernoulli–Euler microbeams by (Akgöz & Civalek, 2013), static and dynamic stability modeling of a capacitive FGM microbeam in presence of temperature changes by (Zamanzadeh, Rezazadeh, Jafarsadeghi-poornaki, & Shabani, 2013), thermo-mechanical buckling behavior of functionally graded microbeams embedded in elastic medium based on sinusoidal shear deformation beam theory by (Akgöz & Civalek, 2014), nonlinear vibrational behavior of functionally graded rectangular microplates including geometrical nonlinearity based on Mindlin plate theory by (Ansari, Faghih Shojaei, Mohammadi, Gholami, & Darabi, 2014), modeling of a functionally graded micro-ring segment for analysis of coupled extensional–flexural waves by (Mustapha, 2014), axisymmetric postbuckling analysis of functionally graded annular microplates using physical neutral plane by (Ke, Yang, Kitipornchai, & Wang, 2014), a thin conical shell model for free vibration by (Zeighampour & Tadi Beni, 2014), finite plate element for composite laminated plates by (Wanji, Shengqi, & Xiaopeng, 2014), dynamic pull-in instability of geometrically nonlinear actuated microbeams by (Sedighi, Chan-Gizian, & Noghreha-Badi, 2014), nonlinear static and free vibration analysis of microbeams based on the nonlinear elastic foundation using He's variational method by (Şimşek, 2014), nonlinear-electrostatic analysis of micro-actuated beams incorporating surface elasticity by (Shaat & Mohamed, 2014), nonlinear thermal stability and vibration of pre/post-buckled temperature- and microstructure-dependent functionally graded beams resting on elastic foundation by (Komijani, Esfahani, Reddy, Liu, & Eslami, 2014), three-dimensional vibration analysis of curved microbeams under fluid force induced by external flow by (Tang, Ni, Wang, Luo, & Wang, 2014), a functionally graded sandwich microbeam model for static bending, free vibration and buckling by (Thai, Vo, Nguyen, & Lee, 2015), out-of-plane free vibration of rotating microbeam based on classical and first shear deformation beam theories by (Dehrouyeh-Semnani, 2015), free vibration and instability of fluid-conveying functionally graded microshells by (Ansari, Gholami, Norouzzadeh, & Sahmani, 2015), developing a nonlinear model for cantilevered microbeams and also exploring the nonlinear dynamics i.e., frequency–response curves, phase portraits and time histories by (Dai, Wang, & Wang, 2015), a discussion on incorporating the Poisson effect in Euler-Bernoulli and Timoshenko microbeam models by (Dehrouyeh-Semnani, Dehrouyeh, Torabi-Kafshgari, & Nikkhah-Bahrami, 2015b), stability analysis of thin functionally graded microplate subjected to mechanical and thermal loading by using spline finite strip method by (Mirsalehi, Azhari, & Amoushahi, 2015), nonlinear bending and postbuckling of functionally graded Mindlin rectangular microplates considering the physical neutral plane position by (Ansari, Gholami, Faghih Shojaei, Mohammadi, & Darabi, 2015), a parametric investigation of influence of size-dependent shear deformation on static deformation, critical buckling load, and natural frequencies of microbeam using finite element method by (Dehrouyeh-Semnani, Dehrouyeh, Torabi-Kafshgari, & Nikkhah-Bahrami, 2015a), a parametric study on nonlinear dynamics of microbeams by considering different parameters due to time-dependent longitudinal excitation load by (Ghayesh, Farokhi, & Alici, 2015), static and dynamic analysis of functionally graded annular and circular microplates by consideration of spatial variation of length scale parameter by (Eshraghi, Dag, & Soltani, 2015), new models for viscoelastically 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2015a), nonlinear free vibration of an axially functionally graded (AFG) microbeam using

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