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On the thermally induced non-linear response of functionally graded beams

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ABSTRACT

The current paper presents an analytical investigation on the thermally induced non-linear response of shear-deformable slightly curved beams made of functionally graded materials. It is supposed that the temperature-dependent material properties of beam vary continuously along its thickness according to a power law. First-order shear deformation theory of beam in conjunction with neutral surface concept is implemented to establish the geometrically non-linear equilibrium equations of system under in-plane thermal loading. Subsequently, an analytical solution is presented to trace the equilibrium path of system with fully clamped boundary conditions. It is indicated that the system may undergo a perturbed pitchfork bifurcation at a critical temperature rise. Furthermore, it is shown that the initial configuration of system can't be considered as its equilibrium path before the onset of bifurcation. A comprehensive investigation is conducted to highlight the role of different parameters i.e., the length-to-thickness ratio, the amplitude of initial curvature, the power-law exponent, and the type of thermal loading in the non-linear response of system. Eventually, the influence of geometric nonlinearity on the thermally induced response of system is studied by comparing the results of linear and non-linear models.

1. Introduction

Functionally graded materials are defined as the materials composed of a mixture of two or more different materials with continuously gradient mechanical and physical properties. Considering the fact that the materials can be designed for specific usages, the functionally graded materials are extensively utilized in different industrial applications. In comparison with the isotropic and laminated materials, the functionally graded materials have reduced thermal stresses and stress concentrations and have the ability of withstanding high temperature gradient environments without losing structural reliability. These advantages, together with their high strength and light weight, have made the functionally graded materials an appropriate replacement for the conventional materials where the operating conditions are severe, including spacecraft heat shields, heat exchanger tubes, flywheels, reactor vessels, turbine rotors, and biomedical implants, etc. Owing to the wide applications of functionally graded materials in structures, analysis of thermal and mechanical responses of structures made of functionally materials has been made by many researchers

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(Alijani & Amabili, 2013, 2014; Barik, Kanoria, & Chaudhuri, 2008; Chen & Tan, 2007; Ciarletta, Sellitto, & Tibullo, 2017; Dehghan, Nejad, & Moosaie, 2016; Duc & Thang, 2015; Duc, Tuan, Tran, & Quan, 2017; Duc, Tran, & Nguyen (2017); Ersoy, Mercan, & Civalek, 2016; Eshraghi & Dag, 2018; Fung & Chen, 2006; Ghadimi, Dardel, Pashaei, & Barzegari, 2012; Ghayesh & Farokhi 2017a;Hosseini-Hashemi, Derakhshani, & Fadaee, 2013; Jabbari, Nejad, & Ghannad, 2015; Kandasamy, Dimitri, & Tornabene, 2016; Kiani & Eslami, 2012; Le, 2017; Li, Li, & Hu, 2017; Najibi & Talebitooti, 2017; She, Yuan, & Ren, 2017b; Sachdeva & Padhee, 2018; Şimşek & Reddy, 2013; Thang, Duc, & Nguyen-Thoi, 2017; Thang, Nguyen-Thoi, & Lee, 2016; Tornabene, Fantuzzi, Viola, & Batra, 2015; Tsiatas & Charalampakis, 2017; Wang & Mai, 2005). Not only in macro scale but also in micro and nano scales the functionally graded materials have been widely used in design of small scale structures as elements of micro/nano-electro-mechanical-systems (MEMS and NEMS). For instance, in micro scale (Akgöz & Civalek, 2014; Awrejcewicz, Krysko, Pavlov, Zhigalov, & Krysko, 2017; Azizi, Ghazavi, Esmaeilzadeh Khadem, Yang, & Rezazadeh, 2012; Dehrouyeh-Semnani, Dehrouyeh, Torabi-Kafshgari, & Nikkhah-Bahrami, 2015; Dehrouyeh-Semnani, Mostafaei, & Nikkhah-Bahrami, 2016; Eshraghi, Dag, & Soltani, 2016; Farokhi, Ghayesh, & Gholipour, 2017; Ghayesh, Farokhi, & Gholipour, 2017a; Komijani & Gracie, 2016; Li & Pan, 2015; Mohammadi, Eghtesad, & Mohammadi, 2017; Nguyen, Atroshchenko, Nguyen-Xuan, & Vo, 2017; Thai, Thai, Vo, & Patel, 2017) investigated thermal and mechanical responses of microstructures made of functionally graded materials. In addition, analysis of nanostructures out of functionally graded materials has been of interest of many researchers (Attia, 2017; Chen, Sun, & Li, 2017; Kiani, 2016; Li, Li, & Hu, 2016; Salehipour, Shahidi, & Nahvi, 2015; Sedighi, Daneshmand, & Abadyan, 2015a, b; Shahverdi & Barati, 2017; She, Yuan, Ren, & Xiao, 2017; Shen, Chen, & Li, 2016; Shojaeian & Zeighampour, 2016; Şimşek, 2016; Zeighampour & Shojaeian, 2017; Zhang et al., 2015; Zhu & Li, 2017).

Thermally induced non-linear responses of functionally graded beam with and without initial curvature in different scales have been investigated by some researchers. Zhao, Wang, and Liu (2007) analyzed the non-linear thermal stability characteristics of functionally graded Euler–Bernoulli beams under in-plane thermal loading and simply supported edges. Ma and Lee (2011) studied the non-linear stability and the linear free vibration of functionally graded beams under in-plane thermal loading based on both Euler–Bernoulli and Timoshenko beam theories. Ma and Lee (2012) presented closed-form solutions for the non-linear response of functionally graded Timoshenko beams to in-plane thermal loading for pinned-pinned and clamped-clamped boundary conditions. Esfahani, Kiani, and Eslami (2013) and Esfahani, Kiani, Komijani, and Eslami (2013) analyzed the non-linear thermal stability and free vibration characteristics of FG Timoshenko beams supported on non-linear hardening elastic foundations considering various boundary conditions and implementation of generalized differential quadrature method. Ghiasian, Kiani, and Eslami (2013) performed a numerical study on the non-linear dynamic buckling of suddenly heated or compressed functionally graded Euler–Bernoulli beams with and without initial curvature under clamped ends and resting on non-linear elastic foundation. Niknam, Fallah, and Aghdam (2014) examined the non-linear response of functionally graded tapered beam under in-plane thermal loading and different boundary conditions. Zhang (2014) analyzed the stability behavior of a third-order shear deformable FG beam under in-plane thermal load and pinned-pinned and clamped-clamped ends by using Ritz method. Komijani, Esfahani, Reddy, Liu, and Eslami (2014) performed a numerical investigation on the non-linear size-dependent thermal stability and linear free vibration of pre/post-buckled functionally graded beams resting on elastic foundation by implementation of modified couple stress theory as a higher-order continuum theory. Ghiasian, Kiani, and Eslami (2014) studied the non-linear thermally induced vibrations of functionally graded Euler–Bernoulli beams with and without initial curvature under rapid heating and different boundary conditions. Shen and Wang (2014) analyzed the non-linear bending and free vibration of simply-supported shear deformable functionally graded beams resting on elastic foundations in thermal environments. Ghiasian, Kiani, and Eslami (2015) performed a Ritz method-based numerical study on the dynamic buckling of functionally graded Timoshenko beams with and without initial curvature subjected to sudden uniform temperature rise and resting on non-linear elastic foundation. (Levyakov, 2013, 2015) carried out an analytical investigation on the non-linear thermal response of functionally graded with simply supported boundary conditions by considering the exact formulation of curvature based on Euler–Bernoulli and Timoshenko beam theories, respectively. Sun, Li, and Batra (2016) performed a numerical examination on the non-linear thermal equilibrium path of functionally graded beams on non-linear elastic foundation for pined-pinned and clamped-clamped boundary conditions. Paul and Das (2016a) performed a study on the non-linear equilibrium path of simply supported Timoshenko beam made of functionally graded material under in-plane thermal load by considering different materials. They verified successfully their results with those achieved by means of a commercial finite element software. Paul and Das (2016b) investigated the non-linear response of tapered Timoshenko beam made of functionally graded material under in-plane thermal loading. Dehrouyeh-Semnani, Mostafaei, Dehrouyeh, and Nikkhah-Bahrami (2017) examined the non-linear thermal pre- and post-snap-through buckling of functionally graded Euler–Bernoulli microbeams with and without initial curvature in framework of modified couple stress theory as a higher-order continuum theory. Malik and Kadoli (2017) investigated the non-linear vibrational response of functionally graded Euler–Bernoulli beams under various heat loads and different boundary conditions. Wu, Kitipornchai, and Yang (2017) carried out a numerical study on the non-linear response of functionally graded carbon nanotube-reinforced composite beams with initial curvature by use of differential quadrature method. Paul and Das (2017) analyzed the thermal free vibrational behavior of simply-supported functionally graded beams under large deflection using a tangent stiffness method. Dehrouyeh-Semnani (2017) analyzed the role of boundary conditions on the non-linear response of functionally graded Timoshenko beams under in-plane thermal loading by comparing results of simplified and original boundary conditions-based models. She, Yuan, and Ren (2017a,c) examined the non-linear thermal post-buckling of functionally graded tubes with clamped ends by employing Euler–Bernoulli and Timoshenko beam theories, higher order beam theories, and a refined beam theory. Based on best knowledge of author, there is no single work