Composite Structures 162 (2017) 244–254

Contents lists available at ScienceDirect

Composite Structures

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

Dynamic instability of functionally graded multilayer graphene nanocomposite beams in thermal environment

Helong Wu [a], Jie Yang [b,*], Sritawat Kitipornchai [a]

[a] School of Civil Engineering, The University of Queensland, Brisbane, St Lucia 4072, Australia
[b] School of Engineering, RMIT University, PO Box 71, Bundoora, VIC 3083, Australia

ARTICLE INFO

Article history:
Received 10 November 2016
Revised 29 November 2016
Accepted 2 December 2016
Available online 5 December 2016

Keywords:
Graphene nanoplatelets
Functionally graded nanocomposites
Dynamic instability
Thermal buckling
Free vibration

ABSTRACT

This paper studies the dynamic instability of functionally graded multilayer nanocomposite beams reinforced with a low content of graphene nanoplatelets (GPLs) and subjected to a combined action of a periodic axial force and a temperature change. The weight fraction of GPL nanofillers is assumed to be constant in each individual GPL-reinforced composite (GPLRC) layer but follows a layerwise variation across the beam thickness. The Halpin-Tsai micromechanics model is used to estimate the effective Young's modulus of GPLRC layers. The differential quadrature method is employed to convert the partial differential governing equations into a linear system of Mathieu-Hill equations, from which the principle unstable region of functionally graded multilayer GPLRC beams is determined by Bolotin's method. Special attention is given to the effects of GPL distribution pattern, weight fraction, geometry and dimension on the dynamic instability behaviour. The thermal buckling and free vibration are also discussed as subset problems. Numerical results show that distributing more GPLs near the top and bottom surfaces can effectively increase the natural frequency and reduce the size of the unstable region. The influences of GPL geometry and dimension tend to be insignificant when the GPL width-to-thickness ratio is larger than 10^3.

1. Introduction

Polymer nanocomposites in which nanofillers such as carbon nanotubes (CNTs), graphene and its derivatives are dispersed in a polymer matrix have been attracting considerable attention from both research and engineering communities [1]. Compared with the conventional polymer composites, polymer nanocomposites exhibit significantly higher stiffness and strength due to the superiorly high moduli of nanofillers, together with the nanoscale effects and interface chemistry [2–4].

Since the first observations in the early 1990s [5,6], CNTs are considered promising reinforcement materials for high performance structural composites due to their exceptionally mechanical, thermal and electrical properties [7–9]. In order to make better use of a low content of CNTs, Shen [10] applied the functionally graded concept to polymer nanocomposites and found that the mechanical properties can be further improved through a nonuniform distribution of CNTs in the polymer matrix. Subsequently, the mechanical responses of functionally graded CNT-reinforced composite (FG-CNTRC) structures have been extensively investigated [11–14]. Among those, Ke et al. [15] examined the dynamic stability behaviour of FG-CNTRC beams under a periodic axial force. Yang et al. [16] studied the dynamic buckling of thermo-electro-mechanically loaded FG-CNTRC beams integrated with piezoelectric layers. Lei et al. [17] presented a dynamic stability analysis of FG-CNTRC cylindrical panels. These studies [15–17] revealed that the distribution pattern and volume fraction of CNTs have important influences on the dynamic stability behaviour of polymer nanocomposite structures. Although significant advances have been made in CNTs filled nanocomposites, agglomeration and relatively high production cost have hindered the further applications of CNTs as reinforcement materials in polymer nanocomposites [18].

Graphene [19] is a two-dimensional monolayer of carbon atoms with remarkable physical properties and chemical functionalisation capabilities [20–22]. Compared to CNTs, graphene has comparable tensile strength (130 GPa) and Young's modulus (~1 TPa) [20] but a much larger surface area of up to 2630 $m^2 g^{-1}$ [23]. More importantly, graphene and its derivatives are abundant in nature and less expensive when synthesized in large scale [24]. These merits make graphene and its derivatives excellent alternatives

* Corresponding author.
E-mail address: j.yang@rmit.edu.au (J. Yang).

http://dx.doi.org/10.1016/j.compstruct.2016.12.001
0263-8223/

to CNTs while improving the mechanical properties of polymeric materials. The superiority of graphene as a promising reinforcement material was further verified by recent studies [25] that demonstrated that the graphene nanocomposites exhibit significantly higher Young's modulus and tensile strength than the nanocomposites reinforced with the same amount of CNTs.

Rafiee et al. [25] measured and compared the mechanical properties of epoxy nanocomposites reinforced with 0.1 wt% of graphene nanoplatelets (GPLs) and CNTs, respectively. They found that the Young's modulus, tensile strength and fracture toughness of graphene nanocomposites are significantly higher than those of pristine epoxy and that GPLs dramatically outperform CNTs in terms of mechanical properties enhancement. Wang et al. [26] experimentally investigated the thermal properties of graphene nanocomposites. Their test results indicated that incorporation of graphene oxide sheets reduces the thermal expansion coefficients and considerably increases the thermal conductivity of the polymer matrix. By using Mori-Tanaka micromechanics method, Ji et al. [4] examined the stiffening effect of graphene sheets dispersed in polymer nanocomposites. Their results showed that the addition of a very low content of graphene sheets can remarkably increase the effective stiffness of the nanocomposite. Zhao et al. [27] reported that a loading of 1.8vol% graphene results in a 150% improvement in tensile strength and a nearly 10 times increase in Young's modulus of poly (vinyl alcohol) nanocomposites. Liu et al. [28] successfully fabricated GPL-reinforced alumina ceramic composites using Spark Plasma Sintering and observed that the resulting flexural strength and fracture toughness are significantly higher than those of monolithic ceramic samples. Rahman and Haque [29] studied the effects of GPL concentration, aspect ratio and dispersion on elastic constants and stress-strain responses of graphene/epoxy nanocomposites using molecular mechanics and molecular dynamics simulations. Liu et al. [30] used a stacking and folding method to generate aligned graphene/polycarbonate composites that considerably enhances effective elastic modulus and strength of the primitive polycarbonate even at an exceptionally low loading of graphene.

Owing to the mechanical advantages of high strength and stiffness but low density, graphene nanocomposites show tremendous potentials for development of advanced lightweight engineering structures in the forms of beam, plate, as well as shell structural elements that are vital in aeronautical and space industries. However, all the aforementioned studies on graphene nanocomposites were focused on the synthesis and material property characterization only. Investigations on the mechanical behaviour of engineering structures made of such advanced nanocomposites are very limited. Most recently, Rafiee et al. [31] experimentally studied the buckling of graphene/epoxy nanocomposite beam structures. Significant increase (up to 52%) in critical buckling load was observed by adding only 0.1 wt% of GPLs into the epoxy matrix. Song et al. [32] carried out the free and forced vibration analysis of functionally graded multilayer GPL/polymer nanocomposite plates and suggested that the incorporation of a small amount of GPLs can significantly increase the natural frequencies and reduce the dynamic deflection of plates under pulse loading. As far as the authors are aware, no previous work has been done on the dynamic instability of graphene nanocomposite structures.

Hence, this paper is devoted to the investigation of the dynamic instability of functionally graded multilayer graphene nanoplatelet-reinforced composite (GPLRC) beams under a periodic axial force and a temperature change. A multilayer beam model with a layer-wise variation in GPL concentration is used since an ideal functionally graded nanocomposite structure with a continuous and smooth change in GPL content across the beam thickness is extremely difficult to fabricate due to the limitation of current manufacture technology. Obviously, such a multilayer structure with an adequate number of layers is an excellent approximation of the ideal functionally graded structure. It is assumed that each individual layer is made from a mixture of uniformly dispersed GPL nanofillers and polymer matrix and its effective Young's modulus is predicted by Halpin-Tsai micromechanics model. Governing equations are derived based on the first-order shear deformation beam theory (FSDT) and converted into a linear system of Mathieu-Hill equations by using differential quadrature method, after which the principle unstable region is obtained by using Bolotin's method. Parametric studies are conducted to examine the effects of GPL distribution pattern, weight fraction, geometry and dimension, the static axial force, as well as the temperature change on the dynamic instability behaviour of functionally graded multilayer GPLRC beams. Thermal buckling and free vibration are also discussed as subset problems.

2. Effective material properties of GPLRCs

Fig. 1(a) shows a multilayer beam composed of perfectly bonded GPLRC layers of same thickness h_L. It is assumed that the GPLRC layer is made from a mixture of an isotropic polymer matrix and rectangular shaped GPLs that are randomly oriented and uniformly dispersed. Hence, each individual GPLRC layer is isotropic homogeneous and its effective Young's modulus can be estimated by Halpin-Tsai micromechanics model [33–35]

$$E=\frac{3}{8}\frac{1+\xi_L\eta_L V_{GPL}}{1-\eta_L V_{GPL}}\times E_m+\frac{5}{8}\frac{1+\xi_T\eta_T V_{GPL}}{1-\eta_T V_{GPL}}\times E_m \tag{1}$$

where parameters η_L and η_T take the following forms:

$$\eta_L=\frac{(E_{GPL}/E_m)-1}{(E_{GPL}/E_m)+\xi_L},\quad \eta_T=\frac{(E_{GPL}/E_m)-1}{(E_{GPL}/E_m)+\xi_T}. \tag{2}$$

where E_{GPL} and E_m are Young's moduli of the GPL and matrix, respectively. V_{GPL} is the volume fraction of GPL nanofillers. Note that Eq. (1) does take into account GPL's geometry and dimension through geometry factors ξ_L and ξ_T which are defined by [33]

$$\xi_L=2(a_{GPL}/t_{GPL}),\quad \xi_T=2(b_{GPL}/t_{GPL}) \tag{3}$$

where a_{GPL}, b_{GPL} and t_{GPL} are the length, width and thickness of GPLs, respectively. Here, ξ_L can be rewritten as

$$\xi=2(\alpha_{GPL}/b_{GPL})\times(b_{GPL}/t_{GPL}) \tag{4}$$

in which a_{GPL}/b_{GPL} and b_{GPL}/t_{GPL} are GPL aspect ratio and width-to-thickness ratio, respectively.

According to the rule of mixture, the effective linear thermal expansion coefficient α, mass density ρ, and Poisson's ratio ν of the GPLRC are expressed as

$$\alpha=\alpha_m V_m+\alpha_{GPL}V_{GPL} \tag{5}$$

$$\rho=\rho_m V_m+\rho_{GPL}V_{GPL} \tag{6}$$

$$\nu=\nu_m V_m+\nu_{GPL}V_{GPL} \tag{7}$$

where α_{GPL} and α_m are thermal expansion coefficients, with the subscript "GPL" and "m" referring to the GPLs and matrix, respectively. ρ_{GPL} and ρ_m are mass densities; ν_{GPL} and ν_m are Poisson's ratios; the volume fractions V_{GPL} and V_m are related by $V_m+V_{GPL}=1$.

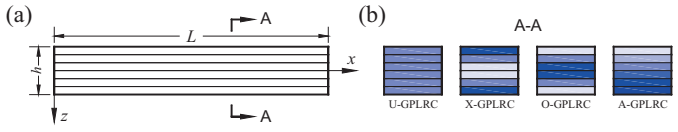

Fig. 1. Configuration and coordinate system of a multilayer GPLRC beam.