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Nonlinear bending of polymer nanocomposite beams reinforced with non-uniformly distributed graphene platelets (GPLs)

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ABSTRACT

This paper studies the nonlinear bending behavior of a novel class of multi-layer polymer nanocomposite beams reinforced with graphene platelets (GPLs) that are non-uniformly distributed along the thickness direction. Nonlinear governing equation is established based on Timoshenko beam theory and von Kármán nonlinear strain-displacement relationship. The effective Young's modulus of the nanocomposites is determined by modified Halpin-Tsai micromechanics model. Ritz method is employed to reduce the governing differential equation into an algebraic system from which the static bending solutions can be obtained. A comprehensive parametric study is then conducted, with a particular focus on the influences of distribution pattern, weight fraction, geometry and size of GPLs together with the total number of layers on the linear and nonlinear bending performances of the beams. Numerical results demonstrate the significantly improved bending performance through the addition of a very small amount of GPLs into polymer matrix as reinforcements. It is found that dispersing more GPLs that are in square shape with fewer single graphene layers near the top and bottom surfaces of the beam is the most effective way to reduce bending deflections. Beams with a higher weight fraction of GPLs that are symmetrically distributed in such a way are also less sensitive to the nonlinear deformation.

1. Introduction

Graphene and its derivatives have been widely used as reinforcing nanofillers in polymer to develop high performance nanocomposite materials. These composites possess significantly improved mechanical and physical properties by making use of the extraordinary properties of the graphene reinforcements while keeping the beneficial attributes of polymers such as large deformation, stretchability, sustainability and good chemical and biological compatibility [1–3]. The abundance of graphene's derivatives, e.g. graphene oxide (GO) and graphene platelet (GPL), makes their applications in real engineering structures more practical. Extensive studies on graphene based polymer nanocomposites have been reported [4–9]. Rafiee et al. [10] conducted an experimental investigation on graphene based epoxy nanocomposites and found that Young's modulus of the nanocomposite increases by 31% compared to that of the pristine epoxy when 0.1% weight fraction (w.t.%) of GPLs is added. Significant improvement in mechanical properties of graphene based nanocomposites was also observed in an experimental study by Liang et al. [11] who reported an increase of 76% in tensile strength and 62% in Young's modulus, respectively, when 0.7 w. t.% of graphene oxide is added into poly (vinyl alcohol) matrix. Park et al. [12] used an effective method to fabricate graphene based polyimide (PI) nanocomposites and demonstrated 170% and 64% increases in tensile modulus and strength, respectively, compared to those of pure PI. Significant enhancement in tensile modulus of multi-layer graphene reinforced poly (vinyl chloride) (PVC) films was also observed by Wang et al. [13]. Among the theoretical and numerical investigations on the mechanical behavior of graphene based composites, Spanos et al. [14] used a micromechanical finite element approach to obtain the mechanical properties of the composites reinforced by uniformly distributed graphene. Rahman and Haque [15] employed molecular mechanics (MM) and molecular dynamics (MD) simulations to study the GPL/epoxy nanocomposites. Their results showed that significant improvement in Young's and shear moduli can be achieved by incorporating GPLs into epoxy matrix. Li et al. [16] studied the mechanical responses of a graphene nanosandwich structure made of a single graphene sheet sandwiched between

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ultrathin polymer layers. The stress-strain behavior obtained showed that significant reinforcement is obtained in this novel graphene nanosandwich at small strains. It should be noted that so far, the majority of the existing studies are focused on the synthesis/fabrication and characterization of the material properties of graphene based composites. Research work on the mechanical behavior of structural elements made of such nanocomposite materials is very limited.

Functionally graded materials (FGMs) are characterized by continuous variations in both material composition and mechanical properties in one or more dimension(s). This provides an excellent solution to composite structures undergoing significant mismatch of mechanical and thermal behaviors across the interface between two dissimilar materials. Moreover, the gradual change of composition can be tailored to cater for various working environments and simultaneously meet different performance requirements [17]. Due to their unique advantages and great potentials in engineering applications, FGM structures have received extensive research efforts [18–28]. In particular, composite structures reinforced with carbon nanotubes (CNTs) that are non-uniformly distributed along the thickness direction have recently been developed [29,30] and successfully manufactured [31] in which greatly improved load transfer and interfacial bonding strength between the matrix and CNTs have been achieved through the continuous gradient in CNT volume fraction. Notably, among the studies available in open literature, Shen [29] studied the nonlinear bending behavior of simply supported, functionally graded nanocomposite plates reinforced by single-walled carbon nanotubes (SWCNTs) subjected to a transverse uniform or sinusoidal load in thermal environments. Ke et al. [30] investigated the nonlinear free vibration of functionally graded carbon nanotube-reinforced composite Timoshenko beam and discussed the effect of nanotube volume fraction on the nonlinear vibration frequencies. Shen and Zhang [32] analyzed the thermal buckling and postbuckling behavior of functionally graded carbon nanotube-reinforced composite plates. Ke et al. [33] presented a dynamic stability analysis of functionally graded nanocomposite beams reinforced by SWCNTs based on Timoshenko beam theory. Rafiee et al. [34] examined the large amplitude free vibration of functionally graded carbon nanotube reinforced composite beams with surface-bonded piezoelectric layers subjected to a temperature change and an applied voltage. Using meshless method, Zhu et al. [35] presented a finite element analysis on the static bending and vibration behavior of functionally graded carbon nanotube-reinforced composite plates. Lei et al. [36] discussed the dynamic stability of carbon nanotube-reinforced functionally graded cylindrical panels using the element-free kp-Ritz method. A comprehensive review on the mechanical analysis of functionally graded carbon nanotube reinforced composite structures was given by Liew et al. [37].

It is known that compared with CNTs, graphene and its derivatives are preferred reinforcing nanofillers due to their abundance in nature, relatively low fabrication cost, better dispersion, stronger bonding between the matrix and nanofillers due to graphene's large surface area and excellent mechanical properties [10]. To the best of the authors' knowledge, no work has been done on nanocomposites and structures with non-uniformly distributed graphene reinforcements. This paper proposes the development of functionally graded graphene based nanocomposites. Due to the constraint of current manufacturing technology, the fabrication of an FGM structure with GPL concentration varying continuously over thickness direction is very challenging and extremely difficult. Therefore, a multi-layer structure is used instead as an approximate alternative where the non-uniform distribution of GPLs is achieved by stacking up a number of individual layers. The GPL concentration shows a layer-wise change according to a prescribed distribution pattern while remains constant within each individual layer. A typical example of such functionally graded configuration is shown in Fig. 1. As the total number of layers stacked up is sufficiently large, the difference in GPL concentration and mechanical property mismatch between two neighbouring layers can be significantly reduced or minimized; the multi-layer structure will then represent an excellent approximation to the desired ideal FGM structure. Based on Timoshenko beam theory, von Kármán nonlinear strain-displacement relationship, and modified Halpin-Tsai micromechanics model for the prediction of effective Young's modulus, this paper investigates the linear and nonlinear bending behaviours of non-uniformly distributed GPL reinforced nanocomposite beams under transverse loading. Ritz method is used to obtain both deflection and normal bending stress. The influences of distribution pattern, concentration, geometry and size of GPLs, total number of layers and nonlinear deformation on the static bending behaviours of the functionally graded GPL/polymer nanocomposite beams are discussed in detail through a parametric study.

2. Theoretical formulation

Fig. 1 shows an N-layer GPL/polymer nanocomposite beam of length L, width b and total thickness h subjected to a transverse distributed load q. Each layer has the same thickness $\Delta h = h/N$ and is reinforced by GPLs uniformly dispersed in the polymer matrix within that layer. The GPL weight fraction (w.t.%) varies from layer to layer in the thickness direction according to a specified GPL distribution pattern to form a functionally graded structure. Shown in Fig. 2 are the three different GPL distribution patterns under current consideration in which the darker color represents a higher w. t.% of GPLs. As can be seen, Pattern 1 corresponds to an isotropic homogeneous beam in which GPLs are uniformly distributed at the same w. t.% across all layers. In contrast, Pattern 2 and Pattern 3 represent a functionally graded structure in which the w. t.% of GPLs shows a linear and symmetrical layer-wise change across the beam thickness. The GPL weight fraction is the highest in the neutral axis while the lowest on both top and bottom surfaces of the beam in Pattern 2, but in Pattern 3 the GPL weight fraction distribution is reversed with the maximum value on both top and bottom surfaces and the lowest in the neutral axis of the beam.

Denote the total w. t.% of GPLs in the beam by f_{GPL} and the maximum w. t.% among all layers by f_{max}, the w. t.% of GPLs in the i-th layer in Patterns 2 and 3 are expressed as

$$f_i = f_{max} + \left(\frac{N}{2} - i\right)\Delta f \quad \text{(Pattern 2)} \tag{1a}$$

$$f_i = f_{max} - (i-1)\Delta f \quad \text{(Pattern 3)} \tag{1b}$$

where $\triangle f = 4\,(f_{max} - f_{GPL})/(N-2)$ is the weight fraction increment of GPLs between neighbouring layers, and $i = 1, \ldots. N/2$.

2.1. Effective material properties

It is necessary that the effective material properties, i.e. Young's modulus and Poison's ratio, of the GPL/polymer nanocomposite in

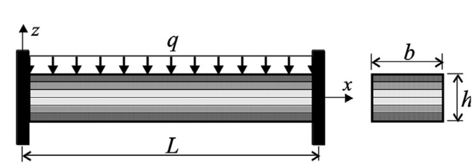

Fig. 1. Schematic configuration of GPL reinforced nanocomposite beam.