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Nonlocal postbuckling analysis of graphene sheets in a nonlinear polymer medium

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ABSTRACT

This article studies nonlocal postbuckling behavior of both uniaxially and biaxially loaded graphene sheets (GSs) in a polymer environment based on an orthotropic nano-plate model. The van der Waals interaction force between the graphene sheets and the polymer medium is considered as a nonlinear function of the graphene's deflection. Considering the small scale effect and using the thin plate theory, postbuckling equilibrium equations are derived with the von Karman-type geometrical nonlinearity. These equations are solved using the Galerkin method for GSs with different boundary conditions. Finally, postbuckling equilibrium path is plotted and the effects of nonlocal parameter, polymer medium, linear and nonlinear coefficients of the vdW interaction, boundary and loading conditions and geometric properties are studied in detail.

1. Introduction

Graphene, a single atomic layer of carbon atoms arranged in a honeycomb structure, has capacity for applications in a number of different fields because of its superior electrical, thermal, chemical, mechanical, and optical properties (Geim, 2009; Novoselov, 2011). For example, it can be used in optical devices as solar cells, liquid crystal displays and touch screens as a transparent conductive coating material (Novoselov, 2011). Also, based on its electrical properties it can be used in transistors and sensitive gas detectors (Schedin et al., 2007). Additionally, its unprecedented mechanical strength and high crystallographic quality allow one to use graphene to provide the perfect gas barrier (Bunch et al., 2008), strain gauges (Kim et al., 2009) and mass sensors (Jensen, Kim, & Zettl, 2008).

Graphene is the strongest and simultaneously is one of the stiffest known materials (Gong et al., 2010). Generally, there is a huge advantage in its being exactly one atom thick so it cannot cleave, giving it the maximum possible strength in the out-of plane direction (Novoselov, 2011). The unique combination of its electronic, chemical, optical properties along with its superior mechanical properties can be utilized in full in polymer composite materials (Novoselov, 2011). Generally, polymer nanocomposites need much lower filler loadings than polymer composites with conventional micron-scale fillers (such as glass or carbon fibers) to show substantial property enhancements, which ultimately results in lower component weight and can simplify processing (Potts, Dreyer, Bielawski, & Ruoff, 2011; Young, Kinloch, Gong, & Novoselov, 2012). In view of its mechanical properties, graphene not only fortify the polymer composites also acts as an ideal stopper for crack propagation in those materials because of its high aspect ratio. As for interaction with the matrix, chemical modification of the

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surface or edges may significantly strengthen the interface between the graphene and the polymer (Novoselov, 2011). It is also relatively easy to prepare nano graphene sheets for such an application (Novoselov, 2011).

Generally, graphene has good prospects for applications in tomorrow's ultrasmall technology considering its superior characteristics. However, in each application it may be subjected to various mechanical loading conditions for example, it may be under high in-plane loads.

At micro/nanoscale structures such as graphene sheets (GSs), interatomic large cohesive forces affect the mechanical behavior of the structure extensively. The classical elasticity theory, not accounting for the small scale effect, is generally inappropriate for mechanical analysis of these structures. Some continuum-based theories considering the small scale effect include couple stress elasticity theory (Mohammad-Abadi & Daneshmehr, 2014), strain gradient theory (Kahrobaiyan, Asghari, Rahaeifard, & Ahmadian, 2011), nonlocal theory (Eringen, 1983; Eringen, 2002), etc. However, the most widely reported theory applied for mechanical analysis of nanostructures is the nonlocal elasticity theory, introduced by Eringen (2002). This theory assumes that the stress at a point depends on the strain at all points of the body.

Many researchers solved bending, buckling and free and forced vibration problems of nano graphene sheets as nanoplates based on the nonlocal elasticity theory (Aghababaei & Reddy, 2009; Aksencer & Aydogdu, 2011; Ansari, Arash, & Rouhi, 2011; Ansari & Rouhi, 2012; Assadi & Farshi, 2011; Farajpour, Danesh, & Mohammadi, 2011; Farajpour, Shahidi, Mohammadi, & Mahzoon, 2012; HosseiniHashemi & Tourki Samaei, 2011; Lu, Zhang, Lee, Wang, & Reddy, 2007; Murmu & Pradhan, 2009; Naderi & Baradaran, 2013; Naderi & Saidi, 2013; Narendar, 2011; Phadikar & Pradhan, 2010; Pradhan, 2009; Pradhan & Kumar, 2011; Pradhan & Murmu, 2010; Pradhan & Phadikar, 2009a; Pradhan & Phadikar, 2009b; Pradhan & Phadikar, 2010; Wang & Liew, 2007). However, unlike the linear analyses, nonlinear mechanical analyses of GSs based on the nonlocal elasticity theory are limited. For example, Jomehzadeh and Saidi, (2011) studied large amplitude vibration analysis of multilayered graphene sheets based on the nonlocal elasticity theory and von Karman geometrical nonlinearity. Jomehzadeh, Saidi, and Pugno (2012) solved nonlinear free and forced vibration of a bilayer graphene embedded in a polymer medium based on the nonlocal elasticity theory and von Karman nonlinear model. They considered the interaction force between the graphene layers and the polymer medium as a nonlinear function of graphene's deflection. Shen, Shen, and Zhang (2010) studied nonlinear vibration behavior for a simply supported, rectangular, single layer graphene sheet in thermal environments. They also used the nonlocal elasticity theory to account for the small scale effect and used the von Karman-type of nonlinearity. It is noticeable that in these three works, the in-plane boundary conditions were satisfied in the local form, which is not accurate.

Mahdavi, Jiang, and Sun (2012), based on the classical (local) elasticity theory, studied nonlinear free vibration and postbuckling analysis of single layer graphene sheets embedded in a polymer matrix. Although in their analysis, the nonlinear form of the polymer–graphene interaction force was used, the geometrical nonlinearity which should be considered in the postbuckling analyses was ignored. They solved the problem for simply supported graphene sheets and plotted the postbuckling equilibrium path for different mode numbers without specifying that which one is actually the correct path. Moreover, in that work the graphene sheets were modeled incorrectly as isotropic materials. Nevertheless, it can be said that ignoring the small scale effect and the geometrical nonlinearity effect are the main disadvantages of that analysis.

However, to the authors' best knowledge; there is no work on postbuckling behavior of graphene sheets embedded in a polymer matrix accounting for the small scale and the geometrical nonlinearity effects.

In this paper based on an orthotropic nano-plate model, postbuckling behavior of GSs subjected to both uniaxial and biaxial in-plane loadings is studied in three cases: as the GS is rested on a polymer substrate, as it is surrounded by a polymer matrix and as it is free-standing. The van der Waals (vdW) interaction force between the graphene sheets and the polymer medium is considered as a nonlinear function of the deflection. The small scale effect is captured through using the nonlocal elasticity theory. Nonlinear equilibrium equations are derived based on the Kirchhoff plate theory and the von Karman nonlinear model. The postbuckling equilibrium equations are solved using the Galerkin method for GSs with different boundary conditions. The approximation functions are chosen in such a way that the nonlocal form of the boundary conditions to be satisfied exactly for the described boundary conditions. To this end, the buckling mode shape function in deflection is initially obtained for each boundary condition afterwards the postbuckling deflection is approximated in the form of the buckling mode shape function. Finally, postbuckling equilibrium path is plotted and the effects of nonlocal parameter, polymer medium, linear and nonlinear coefficients of the vdW interaction, boundary and loading conditions, and geometric properties are studied in detail on postbuckling behavior of GSs.

2. Nonlocal postbuckling equilibrium equations

It is known that interatomic forces acting on an atom depends on the relative changes of atomic distances between this atom and neighboring atoms. So, it can be said that the interatomic forces on each atom depends not only on its own displacements but also on those of the neighboring atoms (Eringen, 2002). However, the latter dependency is considerably impressive as the body under consideration is a micro/nano structure, known as the small scale effect. This effect can be accounted for by the continuum-based nonlocal elasticity theory assuming that the stress at a point depends either on the strain at that point or at the strain values of all points on the body. The constitutive law based on the nonlocal elasticity theory is written as (Eringen, 2002).