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Thermal buckling of double-layered graphene sheets embedded in an elastic medium with various boundary conditions using a nonlocal new first-order shear deformation theory

Nebojša Radić*, Dejan Jeremić

Faculty of Mechanical Engineering, University of East Sarajevo, Bosnia and Herzegovina

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ABSTRACT

In this paper, thermal buckling of double-layered graphene sheets (GSs) with various boundary conditions is analyzed. The new first-order shear deformation theory (NFSDT) is reformulated using nonlocal differential constitutive relations of Eringen. Unlike the conventional first-order shear deformation (FSDT), NFSDT contains only two unknowns. It is assumed that two GSs are bonded by an internal elastic medium and surrounded by external elastic foundations. The equations of equilibrium of the nonlocal model have been derived by using the virtual displacement method. Analytical solutions for the thermal buckling of double-layered GSs under various boundary conditions are presented. The analytical expression is given for the three types of temperature distribution as uniform, linear, and nonlinear temperatures rise through the thickness of the plate. Two comparison studies are carried out to demonstrate the high accuracy of the presented nonlocal NFSDT. The influences of nonlocal parameter, plate aspect ratio, elastic foundation parameters, boundary conditions on critical buckling temperature, and critical temperature ratio are investigated.

1. Introduction

Following the production of carbon nanotubes (CNTs) [1] and GSs [2] these two nanostructural elements, due to their extraordinary mechanical, chemical, electronic and thermal conductivity properties [3–8] have very often been used as components in micro electro-mechanical systems (MEMS) and nano electro-mechanical systems (NEMS). These superior properties have made GSs promising candidates in many applications such as transistors [9], mass sensors [10], strain sensors [11], organic solar cells [12], gas sensors [13] and magnetic and electric field sensors [14]. In recent times, researchers all over the world have participated in experimental, numerical and theoretical studies on GSs, which present a 2D nanostructural element. Due to their extraordinary and unique mechanical and physical properties, GSs can be used as an excellent reinforcement for the better performance of polymer composites [15]. Similarly to CNTs, GSs have recently been used in composites as an additional material which significantly improves the mechanical, thermal and electric properties in carbon-based composites [16]. When GSs are inserted into polymer matrices, the properties of the host materials demonstrate an extraordinary improvement. These graphene-based composite materials have a large potential for many applications, such as photocatalysis, lithium-ion batteries, fuel cells, and sensors [17]. Composite materials are one of the most significant applications of multilayer nanoplate structures. Nanoplates significantly increase the strength and thermal conductivity of composites. The double-nanoplate systems (DNPS) can be found in nanocomposites structures such as multiple GSs dispersed in a polymer matrix. DNPS consist of two GSs bonded by an elastic medium, e.g. polymer resin. The internal elastic medium between the two layers of GSs is modelled in the Winkler model. The surrounding elastic medium is modelled by the two-parameter Pasternak-type foundation. The first parameter presents normal pressure, while the other presents the influence of shear stress.

Every potential application of GSs requires very good knowledge of their mechanical behaviour. That is why, the analysis of mechanical behaviour of nanoplates has been the subject of interest for many researchers in recent years. Because of the very small dimensions of nanostructure elements, it is very difficult to perform experimental research. Also, molecular dynamic (MD)

* Corresponding author.
E-mail address: nesor67@yahoo.com (N. Radić).

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simulation is highly computationally expensive in the analysis of GSs with large numbers of atoms. Behfar and Naghdabadi [18]used classical elasticity theory to investigate the vibration behaviour of orthotropic multi-layered graphene sheets embedded in an elastic medium. Liew et al. [19] investigated the vibrations of isotropic multi-layered GSs embedded in an elastic matrix using a classical continuum model. Classical elasticity theory is a scale free theory and cannot handle such small effects. As a result, the mechanical behaviour of the nanostructures cannot be described by classical elasticity theory successfully. This made Eringen formulate nonlocal elasticity theory [20] as a modification of the classical elasticity theory. In Eringen's nonlocal elasticity theory the small scale effects have been taken into account assuming that the stress tensor in the observed point depends on the deformation tensor in all other points of the entire domain occupied by the material. In the classical elasticity theory, the state of stress in the observed point depends on the state of deformation in that point only. Peddiesson et al. [21] were the first to apply the theory of nonlocal elasticity to the analysis of static deformations of Euler-Bernoulli nanobeams. Sudak [22] applied nonlocal continuum mechanics to the buckling analysis of multiwalled CNTs. Duan and Wang [23] were the first to formulate the nonlocal continuum plate model while researching the influence of small scale parameter on the bending of circular nanoplates. Sakhaee-Pour et al. [24] applied the nonlocal continuum plate model for the vibration analysis of single-layered GSs.

Recently, by applying the nonlocal continuum plate model, a number of papers concerned with the analysis of the mechanical behaviour of double-nanoplates systems have been published. Murmu and Adhikari [25] studied the nonlocal vibration of bonded double-nanoplate systems. Murmu et al. [26] investigated nonlocal buckling of double-nanoplate-systems under biaxial compression. Pouresmaeeli et al. [27] presented the vibration of double-orthotropic nanoplates embedded in an elastic medium. The external medium was modelled as Winkler type foundation. Recently, Radić et al. [28] studied the buckling of double-orthotropic nanoplates embedded in Pasternak elastic medium using nonlocal elasticity theory. Their work drew from Kirchhoff's nonlocal plate theory. Equations of equilibrium were being solved by applying Navier's method for the case of simply supported nanoplates.

All the research shows that thermal effects have a significant influence on the mechanical behaviour of nanostructural elements. It is necessary to pay special attention to the influence of thermal effects on the thermal vibration and buckling properties of nanoplates. A review of the literature reveals a number of papers published that have dealt with the research of thermomechanical vibration and thermal buckling of single-layered and double-layered nanoplates. Wang et al. [29] analyzed the thermal effects on vibration properties of double-layered nanoplates by considering small scale effects. The authors obtained exact expressions for natural frequencies of the system. Prasanna Kumar et al. [30] studied thermal effects in the vibration analysis of monolayer GSs embedded in an elastic medium. Exact expressions for natural frequencies were obtained by introducing Navier's solution for all edges simply supported. Fazelzadeh et al. [31] studied the thermo-mechanical vibration of double-orthotropic nanoplates surrounded by an elastic medium by using nonlocal theory. In the work by Sobhy [32] thermo-mechanical bending and the free vibration of single-layered GSs embedded in an elastic medium were considered. In this paper, sinusoidal shear deformation theory was reformulated using the nonlocal differential constitutive relations of Eringen. Small scale effect on the thermal buckling arbitrary straight − sided quadrilateral nanoplates was performed by Malekzadeh et al. [33]. The authors proposed the differential quadrature method (DQM) as an accurate numerical tool. Wang et al. [34] investigated the thermal buckling properties of a nanoplate with small scale effects. The authors applied nonlocal theory to modify Kirchhoff's and Mindline's plate theories. Zenkour and Sobhy [35] analyzed the thermal buckling behaviour of nanoplates lying on a Winkler-Pasternak elastic substrate medium. In this work closed form solutions were formulated for three types of thermal loadings. In the paper presented by Mohammadi et al. [36] the shear buckling of orthotropic graphene sheet embedded in an elastic medium in the thermal environment was considered. They obtained a critical shear buckling load for six boundary conditions. Karličić et al. [37] considered temperature effects on the vibration and stability behaviour of multi-layered graphene sheets embedded in an elastic medium.

Pradhan and Phadikar [38] reformulated the classical plate theory (CLPT) and first-order shear deformation theory (FSDT) of plates by using Eringen's nonlocal differential constitutive relation. The derived equations were solved for the case of simply supported boundary conditions by applying Navier's approach. Pradhan [39] analyzed the buckling behaviour of graphene by using the reformulated higher-order shear deformation theory (HSDT). Recently, Hashemi and Samaei [40] have analysed the buckling behaviour of micro/nanoscale plates based on nonlocal first-order shear deformation theory (FSDT). Samaei et al. [41] also used nonlocal FSDT to analyse the buckling behaviour of a single-layered graphene sheet embedded in an elastic medium. Thai et al. [42] investigated the bending, buckling and free vibration of functionally graded sandwich plates under various boundary conditions using a new first-order shear deformation theory (NFSDT). A verification study demonstrated that the NFSDT was more accurate in relation to FSDT and comparable to higher-order shear deformation theory (HSDT). Besides that, NFSDT is significantly simpler compared to FSDT and HSDT because of its lower number of unknown parameters.

In this paper, using Eringen's nonlocal differential constitutive relation local NFSDT has been reformulated and used for the analysis of the thermal buckling of double-layered GSs under various boundary conditions. The application of nonlocal NFSDT is especially useful in the analysis of multilayered nanoplates. In this paper, where double-layered GSs are discussed, the number of unknown parameters is four, while within the application of FSDT the number of unknown parameters is six. Four different boundary conditions have been discussed in the analysis of the thermal buckling of double-layered GSs. The results obtained by the application of nonlocal NFSDT have been compared to the results obtained by applying the molecular dynamics simulation and nonlocal FSDT at the analysis of thermal buckling behaviour of nanoplates.

To the best of authors' knowledge thermal buckling analysis of double-nanoplates embedded in a Pasternak elastic medium under various boundary conditions has not been investigated in the available literature. Also, this is the first time that NFSDT has been applied successfully in the analysis of the mechanical behaviour of nanostructures. In the literature, there is no accurate analytical solution for the thermal buckling load of double-nanoplates under various boundary conditions. There are only solutions for the case when double-nanoplates are simply supported at all four edges. The effects of nonlocal parameter and surrounding elastic medium based on the Pasternak foundation at DNPS with different boundary conditions have been discussed separately in this paper.

2. Mathematical modelling and formulations

Under consideration is one double-nanoplates system consisting of two layers of GSs. These GSs are coupled by an elastic