Composites Part B 79 (2015) 224–235

Contents lists available at ScienceDirect

Composites Part B

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

Hygrothermal deformation of orthotropic nanoplates based on the state-space concept

Mohammed Sobhy [a], [b], [*]

[a] Department of Mathematics and Statistics, Faculty of Science, King Faisal University, P.O. Box 400, Hofuf 31982, Saudi Arabia
[b] Department of Mathematics, Faculty of Science, Kafrelsheikh University, Kafrelsheikh 33516, Egypt

ARTICLE INFO

Article history:
Received 18 October 2014
Received in revised form
11 March 2015
Accepted 25 April 2015
Available online 5 May 2015

Keywords:
A. Nano-structures
B. Thermal properties
C. Analytical modeling
Levy type solution

ABSTRACT

This paper deals with the investigation of the effect of hygrothermal conditions on the bending of nanoplates using Levy type solution model employing the state-space concept. The nanoplates are assumed to be subjected to a hygrothermal environment. The two-unknown function plate theory is used to derive the governing differential equations on the basis of Eringen's nonlocal elasticity theory. The governing equations contain the small scale effect as well as hygrothermal and mechanical effects. These equations are converted into a set of first-order linear ordinary differential equations with constant coefficients. Analytical solution of bending response for nanoplates under combinations of simply supported, clamped and free boundary conditions is obtained. Comparison of the results with those being in the open literature is made. The influences played by small scale parameter, temperature rise, the degree of moisture concentration, boundary conditions, plate aspect ratio and side-to-thickness ratio are studied.

1. Introduction

Nanostructures have many advantages such as high stiffness, high strength to weight ratio, elastic modulus >1 TPa, superior thermal and electrical properties [1], etc. Therefore, they are widely used in several engineering applications such as fabrication of nano-electro-mechanical systems, which have low mass and high sensitivity to use in medicine, computers, biosensors, etc. These structures used in the above fields are more often exposed to high temperature as well as moisture. The varying environmental conditions due to moisture absorption and temperature seem to have an adverse effect on the stiffness and strength of the structural composites. The rise in moisture and temperature reduces the elastic moduli of the material and induces internal initial stresses, which may affect the stability as well as the safety of the structures [2]. Hence, the changes in deformations due to the hygrothermal effect seem to be an important consideration in composite analysis and design. Whitney and Ashton [3] studied the effect of hygrothermal conditions on the bending, buckling and vibration of simply supported composite laminated plates based on the classical laminated plate theory using Ritz method. The bending response of general cross-ply, symmetric and antisymmetric angle-ply laminates under thermal and hygroscopic loadings was investigated by Bahrami and Nosier [4]. Rao and Sinha [5] illustrated the influences of temperature and moisture on the bending characteristics of thick multidirectional fibrous composite plates. Ram and Sinha [6] investigated bending of laminated composite plates with a cutout subjected to moisture and temperature loads. Zenkour [7,8] studied the hygrothermal bending analysis for a functionally graded material plate and multilayered angle-ply composite plates resting on elastic foundations. The effect of hygrothermal ageing on mechanical properties and damage behavior of flax-fiber reinforced epoxy composite was studied by Scida et al. [9].

Despite the intensive investigations documented in the literature on the analysis of deformations of composite laminates, few publications focused on the study of nanostructures behavior under hygrothermal loading conditions. The effect of moisture on graphene sheets has been studied experimentally in some published papers (see, Refs. [10–13]). These studies show that the properties of graphene and its behavior are significantly affected by the moisture conditions due to adsorption of water molecules. The effects of temperature and moisture on the response of graphite/epoxy laminated composites to high strain rate

* Department of Mathematics, Faculty of Science, Kafrelsheikh University, Kafrelsheikh 33516, Egypt.
E-mail addresses: msobhy@kfu.edu.sa, msobhy2011@gmail.com.

http://dx.doi.org/10.1016/j.compositesb.2015.04.042
1359-8368/

penetration loading were experimentally investigated by Wosu et al. [11]. Alzahrani et al. [14] employed the sinusoidal shear deformation plate theory to investigate the hygrothermo-mechanical bending of single-layered graphene sheets embedded in an elastic medium.

Nanostructures have attracted worldwide attention for their wide range of applications. Local continuum elasticity, which is a scale free theory, cannot predict the size effects. While, nonlocal continuum theory accounts for the small length scale effect that becomes significant when dealing with micro- or nano-structures. Eringen [15,16] represented the integral constitutive relations of nanostructures in an equivalent differential form. Eringen developed a nonlocal elasticity theory to account for the small scale effect by specifying the stress at a reference point is a functional of the strain field at every point in the body. Since then, many investigations on bending, vibration and buckling of nanostructures have been carried out using Eringen's nonlocal elasticity theory. Based on nonlocal third-order shear deformation plate theory, Aghababaei and Reddy [17] studied the effect of the nonlocal behavior on deflections and natural frequencies of nanoplates. Free vibration of simply supported multi-walled carbon nanotubes was investigated by Aydogdu [18] using the generalized shear deformation theory. Xiaohu and Qiang [19] illustrated the buckling of a multi-walled carbon nanotube under temperature field. Murmu and Pradhan [20,21] employed the nonlocal elasticity theory for the elastic buckling behavior and vibration analysis of rectangular single-layered graphene sheets (SLGSs) embedded in an elastic medium. The vibration of embedded multi-layered graphene sheets (MLGS) based on nonlocal continuum models was investigated by Pradhan and Phadikar [22]. Wang et al. [23] investigated the vibration of double-layered nanoplate with isotropic mechanical properties under thermal load. The thermal effects on the ultrasonic wave propagation characteristics of a nanoplate were studied by Narendar and Gopalakrishnan [24] based on the nonlocal continuum theory. Zenkour and Sobhy [25] studied the thermal buckling of SLGSs embedded in an elastic medium. Based on the nonlocal continuum theory, free vibration and buckling of the double-orthotropic nanoplates were studied by Pouresmaeeli et al. [26] Radic et al. [27], respectively. Sobhy [28] employed the sinusoidal shear deformation plate theory to analyze the thermo-mechanical bending and free vibration of the SLGSs embedded in two-parameter elastic medium. While, in Sobhy [29], the free vibration, mechanical buckling and thermal buckling responses of MLGSs were investigated using new two-variable plate theories accounting for the small scale effects. Radebe and Adali [30] employed an ellipsoidal convex model to study the biaxial buckling of a rectangular orthotropic nanoplate with uncertain material properties. The shear buckling of orthotropic SLGSs in thermal environment was investigated by Mohammadi et al. [31] using the differential quadrature method.

In addition, the modified couple stress theory [32] is also employed to capture the size effect in micro/nano-structures. Ma et al. [33,34] illustrated the static bending and free vibration of Timoshenko microbeam and Mindlin microplate based on a modified couple stress theory. Based on this theory also, the effect of the nonlocality on the bending, vibration and buckling of functionally graded microbeams has been studied by Reddy [35] using Euler-Bernoulli and Timoshenko beam theories, and Simsek and Reddy [36,37] using various higher order beam theories. Roque et al. [38] investigated the bending of Mindlin microplates using a modified couple stress theory and a meshless method. A new modified couple stress theory has been developed by Chen et al. [39] to study the bending of composite laminated Reddy microplate. Moreover, Chen and his colleagues [40–43] employed the modified couple stress theory to investigate the bending and vibration analyses of composite laminated microbeams using various beam theories. A size-dependent model for bending and free vibration of functionally graded microplate is developed by Thai and Kim [44] using Reddy's theory and Thai and Vo [45] using sinusoidal shear deformation theory.

Most of the above previous studies that analyzed the nanostructures behavior have been carried out based on Navier solution method, because of the ease of its calculations. Therefore, the studies concerned with Levy type solution are very rare in literature. On the basis of the classical plate theory (CLPT), Aksencer and Aydogdu [46] proposed Levy type solution for vibration and buckling of nanoplate with isotropic property. Jomehzadeh and Saidi [47] employed the first-order shear deformation plate theory to study the free vibration of an isotropic nanoplate using Levy type method. Recently, Mohammadi et al. [48] studied the effect of the temperature change on the vibration frequency of SLGSs embedded in an elastic medium using Levy type solution based on CLPT.

Levy type solution [46–48] can be arisen for plates with two simply supported opposite edges and the remaining ones have a possible combination of boundary condition: free, simple support, or fixed support. The idea of Levy type method can be applied with respect to the various boundary conditions to reduce the governing partial differential equations to a system of ordinary differential equations which can be then solved. However, Navier solution [14,20,22,23,25] can be developed for plates when all four edges of them are simply supported. In this method the midplane displacements are expanded in a double trigonometric series in terms of unknown parameters. The load is also expanded in double trigonometric series. The trigonometric functions in these series are chosen to satisfy the boundary conditions of the problem. By substituting the displacements and load expansions into the governing equations, a set of algebraic equations is resulted among the parameters of the displacements expansion.

In the present study, Levy type solution model is employed to demonstrate the bending response of orthotropic SLGSs subjected to a hygrothermal environment. The traditional shear deformation plate theories (see, e.g., [49–52]) contains five unknown functions, and consequently five governing equations are outcome. While, the present theory that called two-variable plate theory (TVPT) has only two unknown functions, and so, it gives two governing equations. This theory is developed by Shimpi [53] for isotropic plates by utilizing two components for representing transverse displacement (bending component and shear component). On the basis of Eringen's nonlocal elasticity theory incorporated in the two-variable plate theory, the governing differential equations are derived by using the principle of virtual displacement. The Levy type solution is employed for solving the governing equations of rectangular plates with two opposite edges simply supported and the other two edges having arbitrary boundary conditions. To illustrate the accuracy of the present theory, the obtained results are compared with those being in published papers. Numerical results are presented for rectangular orthotropic nanoplates with different edge conditions, moisture concentration, temperature, side-to-thickness, plate aspect ratios and small scale parameter.

2. Mathematical formulations

Consider an orthotropic nanoplate with length a, width b and thickness h. Let u, v and w be the plate displacements parallel to a right-hand set of axes (x, y, z), where x is the longitudinal axis and z is perpendicular to the plate. The origin of the coordinate system is located at the corner of the middle plane of the plate (see, Fig. 1).