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Modified strain gradient Reddy rectangular plate model for biaxial buckling and bending analysis of double-coupled piezoelectric polymeric nanocomposite reinforced by FG-SWNT

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In this paper, the modified strain gradient (MSG) Reddy rectangular plate theory is extended for biaxial buckling and bending analysis of double-coupled polymeric nanocomposite plates reinforced by functionally graded single-walled boron nitride nanotubes (FG-SWBNNTs) and functionally graded single-walled carbon nanotubes (FG-SWCNTs). Different distribution patterns of BNNTs and SWCNTs including uniform distribution (UD), FG-V, FG-X and FG-O are used. The micromechanical approach is employed to determine the elastic and piezoelectric material properties of the double-coupled nanocomposite rectangular plates. The equilibrium equations are obtained by Hamilton's principle. Then, the critical biaxial buckling load and deflection of the double-coupled nanocomposite plates are derived by Navier's method with simply supported boundary conditions for all edges. A good agreement is observed between the obtained and literature results. Inclusive parametric study is conducted to investigate the effects of material length scale parameters, applied voltage, elastic foundation coefficients, aspect ratio and van der Waals interaction on the dimensionless critical biaxial buckling load and deflection of the double-coupled nanocomposite rectangular plates. The results reveal that the elastic foundation and van der Waals interaction in contrast to applied voltage increase the dimensionless critical biaxial buckling load and vice versa decrease the dimensionless deflection of the double-coupled nanocomposite plates. Influence of the material length scale parameters on the dimensionless critical biaxial buckling load and deflection of the double-coupled nanocomposite plates are insignificant at $h/l \geq 10$ for modified couple stress theory (MCST) and MSGT. Also, the effects of volume fraction and various distributions of SWNTs on the shear stress of polymeric nanocomposite Reddy rectangular plates are studied. The obtained results can be useful for micro-electro-mechanical (MEMS) and nano-electro-mechanical (NEMS) systems.

1. Introduction

In recent year, the smart materials are used in nano and micro electromechanical systems (NEMS and MEMS). For highly durability and enhancement of them, the smart materials such as polymeric piezoelectric nanocomposite can be reinforced by single-walled or multi walled carbon nanotubes (SWCNTs and MWCNTs). Employing SWCNTs and MWCNTs in these materials result in wonderful properties (transparency, electrically and thermal conductive, light weight, tolerance of different magneto-electrostatic fields). Also these materials have been used in various applications particularly in wireless and powerless strain sensor, biosensors, nanogenerator, and harvesting devises [1–4].

Ansari et al. [5] studied the size-dependent bending, buckling and free vibration of functionally graded (FG) Timoshenko microbeams based on modified strain gradient theory (MSGT). Their results showed that the critical buckling loads obtained by MSGT and classical theory (CT) are the maximum and minimum values, respectively also the deflection of functionally graded materials (FGM) microbeam decreases with increasing of the material length scale parameter. Al-Basyouni et al. [6] carried out size dependent bending and vibration analysis of FG microbeams based on modified couple stress theory (MCST). They used first order shear

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deformation and sinusoidal beam theories and employed the Mori–Tanaka homogenization technique to define material property. They concluded that the microbeam becomes stiffer with considering the small scale parameter and the vertical displacement of it decreases in presence of the small scale parameter. Furthermore, employing the non-classical theories including MCST, MSGT, surface stress effect for precision investigation of mechanical response are necessary.

Natarajan [7] studied approximation functions for gradient elasticity to investigate the response of Euler-Bernoulli and Timoshenko nanobeams and Mindlin nanoplates based on Eringen's nonlocal elasticity theory. Vibration and static analyses of plate based on strain gradient elasticity theory is presented by Mousavi and Paavola [8]. A microstructure-dependent sinusoidal plate model based on the strain gradient elasticity theory developed for bending, buckling and free vibration of microplate by Akgos and Civalek [9]. They showed that the shear deformation effect becomes more important for smaller values of length-to-thickness ratio. Movassagh and Mahmoodi [10] studied a micro-scale modeling of Kirchhoff plate based on MSGT. They found that the small scale parameter. Wang et al. [11] investigated the size-dependent Kirchhoff micro-plate model using strain gradient elasticity theory. They showed that these size effects on the buckling load are not noticeable if the plate thickness is about 15 times larger than the material length scale parameter. Murmu et al. [12] performed the nonlocal buckling of double-nanoplate-systems under biaxial compression using nonlocal elasticity theory. Their research showed that the small-scale effect on the biaxially buckling of double-nanoplate-systems of synchronous mode is higher than that of in the asynchronous mode. Zhang et al. [13] presented novel size-dependent plate model for the axisymmetric bending, buckling and free vibration analysis of FG circular/annular microplates based on the strain gradient elasticity theory. Analytical approach for size-dependent effect on the bending, buckling and vibration of FG Kirchhoff and Mindlin plate models based on a MCST is developed by Thai and Choi [14]. They revealed that there is considerable difference between CT and MCST results. Also it is concluded that the length scale effect on the buckling and bending of nanoplate is negligible when the thickness of plate becomes larger. The small scale effect on hygro-thermo-mechanical bending of nanoplates embedded in an elastic medium is studied by Zenkour et al. [15]. Temperature and moisture rises increases the bending of the nanoplate and their effects on the bending is remarkable in larger small scale parameter. Thai and Kim [16] developed bending and free vibration analysis of FG Reddy plate based on MCST. They proved that considering material length scale parameter increases plate stiffness and then this effect leads to reduce the deflection of FG Reddy plate. Zhang et al. [17] established the static, bending, free vibration and buckling analysis of Mindlin microplate based on MCST using finite element method (FEM). They demonstrated that with an increase in the material length scale parameter increases the buckling load and decreases the deflection of nanoplate. Vibration, bending and buckling analysis of sigmoid functionally graded materials (S-FGM) micro-scale plates based on the MCST are presented by Jung and Hun [18]. They exhibited that by considering the material length scale parameter, the critical buckling load increases whereas the displacement decreases. Thermal buckling analysis of FG rectangular nanoplates by considering the size effects using nonlocal elasticity theory and third order shear deformation theory (TSDT) is investigated by Rahim Nami et al. [19]. Their results indicated that the critical buckling temperature decreases with decreasing of voltage and nonlocal parameter. Based on MCST, buckling analysis of S-FGM nanoplates embedded in Pasternak medium is presented by Jung et al. [20]. They verified that the buckling load increases with an increase in the material length scale parameter and it more affected by the Pasternak's constant than the Winkler's constant. Shaat et al. [21] carried out the size-dependent bending analysis of Kirchhoff nano-plates based on MCST including surface stress effects. They showed that in very small thickness, the effect of material length scale parameter on bending of nanoplate is considerable. Moreover, nanoplate becomes stiffer with increasing of the material length scale parameter. Bending and buckling analysis of FG Mindlin nano-plate model based on strain gradient theory (SGT) are performed by Mohammadimehr and Salemi [22]. They found that the critical buckling load for SGT is larger than that of for CT and MCST and vice versa for deflection of nanoplate. Ansari et al. [23] extended bending, buckling and free vibration analysis of size-dependent FG circular/annular microplates based on MSGT. They concluded that the critical buckling load of microplate decreases with increasing of the value of h/l. Levy-type solution on the buckling and free vibration of rectangular nanoplates using nonlocal TSDT is developed by Hosseini-Hashemi et al. [24]. Their work illustrated that increasing the nonlocal parameter decreases the critical buckling load of the nanoplate and its effect is independent of the thickness to length ratio. Exact closed-form solution for non-local vibration and biaxial buckling of bonded multi-nanoplate system using nonlocal elasticity theory is done by Karličić et al. [25]. They concluded that both the natural frequency and the nonlocal parameter effects on the critical buckling load of bonded multi-nanoplate system are greater in higher modes than those of in lower modes. Analooei et al. [26] presented the elastic buckling and vibration characteristics of isotropic and orthotropic nanoplates subjected to biaxial compression and pure shear loading using finite strip method. They showed that the small scale parameter has an important role on the critical buckling load in small sizes plates. Biaxial buckling analysis of double-orthotropic microplate-systems including in-plane magnetic field based on strain gradient theory is investigated by Jamalpoora and Hosseini [27]. They illustrated that the in-phase dimensionless buckling load ratio is higher than those of out of phase and one fixed microplate. Natarajan et al. analyzed size-dependent free flexural vibration behavior of FG nanoplates [28]. They displayed that the natural frequency decreases with increasing of the length scale parameters. Nonlinear bending analysis of orthotropic nanoscale plates in an elastic matrix based on nonlocal continuum mechanics and first-order shear deformation theory (FSDT) is presented by Golmakani and Rezatalab [29]. They observed that the nonlocal parameter doesn't have more effect on deflection of orthotropic nanoscale plates. Buckling analysis of double-orthotropic nanoplates embedded in Pasternak medium using nonlocal elasticity theory is presented by Radic' et al. [30]. Their results revealed that increasing of Winkler and Pasternak parameter, increases the buckling load and the small scale effect on non-dimensional buckling load significantly decreases in external elastic medium. Furthermore, nonlocal effect on buckling loads in higher modes is greater than that of in lower modes. Buckling and sensitivity analysis of nonlocal orthotropic nanoplates with uncertain material properties using nonlocal theory are developed by Radebe and Adali [31]. They showed that as the uncertainty increases, the buckling load decreases.

A model of composite laminated beam based on the global-local theory is extended by Wanji and Junling [32]. They proposed the new MCST for an anisotropic constitutive relation. Wattanasakulpong and Ungbhakorn [33] presented analytical solutions for bending; buckling and vibration responses of carbon nanotube-reinforced composite beams resting on elastic foundation using various shear deformation theories and the extended rule of mixture approach. They found that FG-X and FG-O distribution of the nanotubes are strongest and weakest in resisting bending and buckling load, respectively. Lei et al. [34] investigated the buckling