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Nonlinear bending analysis of FG-CNT reinforced composite thick plates resting on Pasternak foundations using the element-free IMLS-Ritz method

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Abstract

With very limited literature being available on the nonlinear bending behaviors of functionally graded carbon nanotube (FG-CNT) reinforced composite thick plates, this paper fills the apparent void by providing solutions to this problem based on the first-order shear deformation theory (FSDT). The plate considered rests on elastic foundations under transversely distributed loads. The analysis is carried out using the element-free IMLS-Ritz method. The arc-length iterative algorithm and the modified Newton–Raphson method are employed to obtain the nonlinear responses of FG-CNT reinforced composite plates. Convergence and comparison studies on a few example problems are performed to validate the numerical stability and accuracy of the IMLS-Ritz method. In this study, the characteristics of nonlinear bending influenced by foundation stiffness, transverse shear deformation, CNT distribution, CNT volume fraction and boundary conditions are examined.

Introduction

For decades, composite materials have been tailor-made with fiber reinforcement

specific strength and stiffness in order to serve weight sensitive structural applications such as marine vehicles, civil, mechanical, automotive and aircraft structures. This was the trend until the recent discovery of carbon nanotubes (CNTs) which are now being used as the fibers in such reinforcement. It was found that the addition of CNTs into the matrix enhances the thermal and mechanical properties of composites. This has led to a new type of CNT-reinforced composite material being proposed which has attracted increasing attention [1]. Inspired by the concept of functionally graded (FG) materials, the CNT-reinforced composites can follow a functionally graded pattern of reinforcement, i.e. the CNTs are reinforced uniaxially, aligned in the axial direction, with their material properties graded in the thickness direction, forming the FG-CNT reinforced composite [2]. This FG-CNT reinforced composite is an advanced material that can be embedded in beams, plates or shells, forming structural components. The main purpose of this paper is to present the nonlinear bending solution of FG-CNT reinforced composite plates resting on Pasternak foundations.

A number of investigators have examined the influences of FG-CNT reinforced composites on the mechanical behaviors of beams, plates and shells. The static analysis of a CNT reinforced composite rectangular host plate attached to thin piezoelectric layers subjected to thermal load and/or electric fields was conducted by Alibeigloo [3]. The kp-Ritz method was employed by Lei et al. [4] to study the free vibration of FG-CNT reinforced composite rectangular plates in a thermal environment. The same method was used by Zhang et al. [5] to carry out static and dynamic analyses of FG-CNT cylindrical panels. A two-step perturbation technique was proposed by Shen [2] to study the nonlinear bending of simply supported FG-CNT composite plates subjected to a transverse uniform or sinusoidal load in thermal environments. A unified formulation of finite prism methods based on Reissner's mixed variational theorem was developed by Wu and Li [6] for analysis of the three-dimensional free vibration of FG-CNT reinforced composite plates and laminated fiber-reinforced composite plates. The thermal buckling and post-buckling behaviors of FG-CNT reinforced composite plates subjected to in-plane temperature variation was studied by Shen and Zhang [7]. The same methodology was extended by Shen [8] to study shell problems. The large deflection analysis of FG-CNT reinforced composite plates under different boundary conditions was conducted by Lei et al. [9]. The finite element method was employed by Zhu et al. [10] to study the static and free vibration of FG-CNT reinforced composite plates. Postbuckling [11] and large deformation analyses [12] of FG-CNT cylindrical shell panels were performed based on the element-free FSDT method. The element-free IMLS-Ritz method was employed by Zhang et al. [13], [14], [15] to study the free vibration of FG-CNT reinforced composite plate problems.

In [1], it is revealed that FG-CNT reinforced composites can considerably improve mechanical structural behaviors through the functionally graded distribution of CNTs in the matrix. It is also revealed that only a limited volume of work has been reported on the nonlinear analysis of FG-CNT reinforced composite plates. Due to the shortage of literature in this area, this paper provides a geometrical nonlinear analysis of FG-CNT reinforced composite plates of moderate thickness resting on Pasternak foundations using the element-free IMLS-Ritz method. Unlike the finite element method, the element-free method furnishes a solution in terms of nodes rather than meshes [16]. In recent decades, a number of element/mesh-free methods have been developed based on different sets of trail functions [17], [18], [19], [20], [21], [22], [23], [24], [25], [26], [27]. In this study, the IMLS is used as the trail function for development of the element-free

computational framework [20], [27]. Since plates with moderate thicknesses are considered, the theoretical formulation incorporates the FSDT and the Von Kármán assumption, accounting for transverse shear strains, rotary inertia and moderate rotations. The nonlinear governing equation for the large deformation of plates is derived based on the IMLS approximation via the Ritz procedure. The nonlinear responses of the FG-CNT reinforced composite plates are obtained through the arc-length iterative algorithm and the modified Newton–Raphson method. In this study, the effects of CNT distributions, CNT volume ratios, thickness-to-width ratios, aspect ratios, elastic parameters and boundary conditions on the nonlinear deflection of the plates are studied. These data could be a useful benchmark for future references.

Section snippets

Problem definition

As shown in Fig. 1, four types of FG-CNT reinforced composite plates with length a, width b and thickness t are considered. The CNTs are assumed uniaxially aligned, that is UD represents uniform distribution and FG-V, FG-O and FG-X denote the other three types of functionally graded distributions of CNTs. According to the distributions of uniaxially aligned SWCNTs, CNT content by volume V_{CNT} is expressed as $V_{\mathrm{CNT}}(z)=\begin{cases} V^*_{\mathrm{CNT}} & (\mathrm{UD}) \\ \left(1+\frac{2z}{t}\right)V^*_{\mathrm{CNT}} & (\mathrm{FG\text{-}V}) \\ 2\left(1-\frac{2|z|}{t}\right)V^*_{\mathrm{CNT}} & (\mathrm{FG\text{-}O}) \\ 2\left(\frac{2|z|}{t}\right)V^*_{\mathrm{CNT}} & (\mathrm{FG\text{-}X}) \end{cases}$, where UD represents the …

Total potential energy functional

Considered is a rectangular FG-CNT reinforced composite plate resting on elastic foundations under uniformly distributed loads, as shown in Fig. 2. The stain energy due to the two-parameter foundations is given by $V=\frac{1}{2}\int_\Omega\left\{K_f w^2+K_s\left[\left(\frac{\partial w}{\partial x}\right)^2+\left(\frac{\partial w}{\partial y}\right)^2\right]\right\}d\Omega$, in which w is the transverse deflection of the plate, and K_f and K_s are the Winkler and shearing modulus of the elastic medium.

The formulation for the large deflection analysis of this plate is derived here based on the FSDT. The displacement field of this…

Numerical results and discussion

In this section, the examples of FG-CNT reinforced composite plates resting on elastic foundations with loads large enough to cause significant geometric nonlinearity are numerically investigated using the IMLS-Ritz method. Detailed parametric studies are carried out to present the effect of elastic parameters, CNT distributions, CNT volume ratios, thickness-to-width ratios, aspect ratios and boundary conditions on the central deflection of the studied plates.

The effective material properties…

Conclusions

Large deflection behavior is investigated for FG-CNT reinforced composite plates resting on elastic foundations under transversely distributed loads using the element free IMLS-Ritz method. Beyond the comparison study, the effect of Winkler and shear layer parameters on the load–deflection curves of UD, FG-O, FG-V and FG-X CNT reinforced composite plates is studied in detail. From the numerical results, it is concluded that the characteristics of nonlinear bending are influenced by foundation…

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