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Geometrically nonlinear large deformation analysis of functionally graded carbon nanotube reinforced composite straight-sided quadrilateral plates

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Abstract

An improved moving least-squares (IMLS) approximation for the field variables is proposed for geometrically nonlinear large deformation analysis of functionally graded carbon nanotube (FG-CNT) reinforced composite quadrilateral plates. The plate considered is of moderate thickness and, hence, the first-order shear deformation theory (FSDT) and Von Kármán assumption are adopted to incorporate the transverse shear strains, rotary inertia and moderate rotations. The CNTs are assumed to be uniaxially aligned in the axial direction and functionally graded in the plate thickness direction. The discrete nonlinear governing equation is derived based on the IMLS-Ritz method. The modified Newton–Raphson method combined with the arc-length iterative algorithm is employed to solve the nonlinear deformation of the FG-CNT reinforced composite quadrilateral plates. Improvements in computational efficiency and elimination of shear and membrane locking are achieved using a stabilized conforming nodal integration scheme to evaluate the system's bending stiffness. Through detailed parametric studies, CNT distribution, CNTs volume fraction, aspect ratio and thickness-to-width ratio and different boundary conditions are demonstrated to effect significantly on the large deflection behaviors of the quadrilateral FG-CNT reinforced composite plates.

Keywords: Geometrically nonlinear large deformation; Functionally graded carbon nanotube reinforced composite; Quadrilateral plates; The IMLS-Ritz method

1. Introduction

In view of their high specific strength and stiffness, and also their flexibility in tailoring the structural performance, composite materials have been used in many weight sensitive structural applications such as automotive structures,

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aircraft structures and bridge decks. Traditionally, composites are reinforced by glass, carbon, basalt or aramid fibers; these reinforcement materials have been used for decades but the recent discovery of CNTs has led to a new type of CNT-reinforced composite being considered. CNTs are found to have higher mechanical, electrical and thermal properties and are being used as reinforcement instead of traditional fibers. Trailed by the concept of functionally graded materials (FGMs), the FG-CNT reinforced composite that has been proposed follows the functionally graded pattern of reinforcement, which is uniaxially aligned in the axial direction with its material properties graded in the thickness direction [1]. The main objective of this paper is to study the geometrically nonlinear large deformation behavior of FG-CNT reinforced composite straight-sided quadrilateral thick plates.

Linear analysis considers displacements and rotations to be small, and material properties to be linear elastic. Linear analysis only provides acceptable results within these assumptions. In nonlinear analysis, if the geometry of structures is assumed to be unchanged during the loading process, with small strains and moderately large deflection and rotations, it leads to good results [2]. Linear and nonlinear analyses have been reported by Shen in relation to isotropic plates [3,4], laminated plates [5,6] and functionally graded plates [7,8]. The thermal bending of functionally graded plates has been conducted by Reddy and Chin [9]. The FSDT finite element method was employed by Praveen and Reddy [10] to study the nonlinear static and dynamic behaviors of functionally graded ceramic–metal plates subjected to transverse loads and temperature distribution. Linear and nonlinear analyses of functionally graded ceramic–metal plates were conducted by Reddy [11] based on the higher-order shear deformation theory. Aravinda Kumar et al. studied the nonlinear vibration [12] and design [13] of functionally graded composite plates integrated with piezoelectric actuators.

The influences of CNTs as reinforcement for composite structures have been reported by Liew et al. [1]. The FG-CNT reinforced composite is proposed as an advanced material to be embedded in beams, plates or shells, forming structural components. From Liew et al. [1], it is revealed that only limited studies have been conducted on these FG-CNT reinforced composite beams, plates and shells. The bending and free vibration behaviors of FG-CNT reinforced composite beams with thin piezoelectric layers were investigated by Alibeigloo and Liew [14]. Static analysis on a CNT reinforced composite rectangular host plate attached to thin piezoelectric layers subjected to thermal loading and/or an electric field was conducted by Alibeigloo [15]. Lei et al. [16] employed the kp-Ritz method to study the free vibration of FG-CNT reinforced composite rectangular plates in a thermal environment. Static and dynamic analyses of FG-CNT cylindrical panels were carried out by Zhang et al. [17] using the kp-Ritz method. The finite prism method was employed by Wu and Li [18] to analyze the three-dimensional free vibration of FG-CNT reinforced composite plates and laminated fiber-reinforced composite plates. Shen and Zhang [19] examined the thermal buckling behavior of FG-CNT reinforced composite plates subjected to in-plane temperature variation. Shen [8] extended the methodology in [20] to shell problems. The finite element method was employed by Zhu et al. [21] to study the static and free vibration of FG-CNT reinforced composite plates. The IMLS-Ritz method was employed by Zhang et al. [22–25] to study the free vibration and buckling of FG-CNT reinforced composite plate problems. The free vibration behavior of quadrilateral laminated thin-to-moderately thick plates with carbon nanotube reinforced composite (CNTRC) layers was studied by Malekzadeh and Zarel [26].

The aforementioned studies [14–26] have shown that the mechanical structural behaviors of FG-CNT reinforced composites can be considerably improved by the functionally graded distribution of CNTs in the matrix. Although some research on FG-CNT reinforced composite plates has been performed, the FG-CNT reinforced composite is a newly proposed composite material and more research efforts need to be made for a better understanding of this new material. For mechanical analysis, a critical challenge is to develop efficient and accurate numerical methods for the approximate solution of FG-CNT reinforced composite plates. It is found that only limited research has been conducted on the nonlinear analysis of FG-CNT reinforced composite plates [1]. This paper attempts to fill the apparent void by providing a geometrical nonlinear analysis of FG-CNT reinforced composite straight-sided quadrilateral plates of moderate thickness. The analysis employs the element-free IMLS-Ritz method. Apparently, solutions to the problem can be furnished by using any discretization techniques such as the finite element (FE) method [27], the NURBS-based FE method [28–30], the isogeometric approach [31,32] and other discrete solution methods [33,34]. Unlike the FE method, the element-free method furnishes solutions in terms of nodes instead of meshes [35]. Recently, a number of element-free methods have been proposed as numerical techniques based on different sets of trail functions such as the element-free Galerkin method [36], smooth particle hydrodynamics method [37], radial basis function method [38–41], meshless local Petrov–Galerkin method [42], reproducing kernel particle method [43] and improved element-free Galerkin (IEFG) method [44,45]. In particular, the IEFG method