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# Stability of carbon nanotube-reinforced composite plates with surface-bonded piezoelectric layers and under bi-axial compression

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ABSTRACT

Based on Reissner's mixed variational theorem (RMVT), we develop a unified formulation of finite layer methods (FLMs) for the three-dimensional (3D) buckling analysis of simply-supported, functionally graded (FG) carbon nanotube-reinforced composite (CNTRC) plates with surface-bonded piezoelectric actuator and sensor layers and under bi-axial compressive loads. In this work, a set of membrane stresses is assumed to exist just before instability occurs, and determined using the predefined 3D deformations for the prebuckling state. The carbon nanotubes (CNTs) are considered to be uniformly distributed (UD), and FG rhombus- and X-type variations through the thickness coordinate, and the effective material properties of the FG CNTRC layer are evaluated using the rule of mixtures, and two different surface conditions, open- and closed-circuit, are considered. In the formulation, the plate is divided into a number of finite rectangular layers, in which the trigonometric functions and Lagrange polynomials are used to interpolate the in- and out-of-plane variations for the field variables of each individual layer, respectively. The accuracy and convergence of the FLMs with various orders used for the expansion of each field variable in the thickness are assessed by comparing their solutions with the exact 3D ones available in the literature.

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## 1. Introduction

In recent years, nano-scaled carbon nanotubes (CNTs), instead of micro-scaled continuous fibers (i.e., graphite, boron and glass ones), have been mixed with elastic polymer matrices to produce a variety of beam-, plate- and shell-like structures. CNTs have been applied in a number of advanced technologies [1–5] due to their excellent mechanical and electric properties of CNTs, and it is possible to modify CNT distributions through the thickness of the related materials in order to achieve certain functions. CNTs have also been mixed with some piezoelectric polymers that are currently used as low-cost sensors and actuators, such as poly-(vinylidene fluoride) (PVDF) to improve their electro-mechanical responses [6,7]. Various coupled thermo-electro-mechanical analyses of functionally graded (FG) carbon nanotube-reinforced composite (CNTRC) elastic/piezoelectric structures and laminated fiber-reinforced composite (FRC) ones have thus been carried out. Comprehensive literature surveys have also been undertaken with regard to such analyses by means of analytical and numerical approaches using finite element, boundary element and meshless methods [8–14]. The survey presented in the current work will focus on the buckling of laminated hybrid elastic and piezoelectric plates/shells, single-layered FG CNTRC plates/shells, and sandwiched hybrid FG CNTRC and piezoelectric ones subjected to thermo-mechanical loads.

Some two- and three-dimensional (2D and 3D) plate/shell theories have been applied to the buckling of laminated hybrid elastic and piezoelectric plates and shells, such as the classical plate/shell theories (CPTs/CSTs), first- and higher-order shear deformation theories (FSDTs and HSDTs), layerwise theories (LWTs), and zigzag theories (ZZTs). Shen [15] studied the compressive buckling and postbuckling of anisotropic laminated FRC cylindrical shells with surface-bonded piezoelectric actuator layers in thermal environments using CST combined with von Karman's kinematic nonlinearity (VKKN). In conjunction with the FSDT and VKKN, Jadhav and Bajoria [16] investigated the stability of an FG plate integrated with a piezoelectric sensor and actuator at the top and bottom faces, subjected to electrical and mechanical loads, in which the material properties of FG plates were assumed to be graded along the thickness coordinate according to a simple power law distribution in terms of the volume fractions of the constituent materials. Shen and Zhu [17] and Shen [18] presented the compressive and thermal postbuckling behaviors of FG plates with fiber-reinforced

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piezoelectric actuators, in which a two-step perturbation technique was used to obtain the critical loads (or temperature rises) and postbuckling equilibrium paths. A coupled third-order ZZT with VKKN was developed by Kapuria and Achary [19,20] for the electro-thermo-mechanical buckling analysis of laminated hybrid elastic and piezoelectric plates. The analytical solutions of the critical load, temperature rise and voltage of this third-order ZZT were obtained and demonstrated to be in excellent agreement with the exact 3D solutions available in the literature. This ZZT was also used by Dumir et al. [21] to obtain the solutions for forced harmonic response, buckling and free vibration of flat angle-ply hybrid piezoelectric panels under initial electro-thermo-mechanical loads. Kapuria and Achary [22] presented the exact 3D piezoelectric solutions for buckling of hybrid cross-ply plates using the state space method combined with the transfer matrix one, in which the effects of the thickness parameters, aspect ratios and electric surface conditions on the critical load parameters were examined. Based on the 3D theory of piezoelectricity, Santos et al. [23,24] developed a finite element model for the static behaviors and dynamic responses of 3D axisymmetric laminated shells with surface-bonded piezoelectric sensors and actuators, in which the coupling between symmetric and anti-symmetric terms for laminated materials with piezoelectric rings was emphasized.

In addition to the above-mentioned theories, most of which are based on the principle of virtual displacement (PVD), Reissner [25–27] proposed an alternative variational principle, known as Reissner's mixed variational theorem (RMVT), for the analysis of laminated elastic structures. The main difference between application of the PVD and RMVT to the analysis of piezoelectric structures is that, in the former, the elastic displacement and electric potential components are regarded as the primary field variables subject to variation, while in the latter the elastic transverse stress and normal electric displacement components are also included in these. Based on the PVD and RMVT, Carrera [28] developed the Carrera unified formulation (CUF) to assess the performance of a variety of plate theories for the bending [29] and buckling [30] analyses of laminated composite plates, and it has been concluded that the RMVT-based theories have better performance than the PVD-based ones for the analyses of multilayered composite structures. Subsequently, the CUF was extensively used to develop various advanced and refined 2D theories of laminated piezoelectric plates and FG piezoelectric ones [31,32], in which closed-form solutions for the coupled electro-thermo-mechanical analyses of these were presented, and the accuracy of these solutions was evaluated. Introducing the kinematic and kinetic models of PVD- and RMVT-based 2D theories in the CUF, Robaldo et al. [33] developed a unified formulation for assorted classical and mixed finite element methods (FEMs), and applied these FEMs to the static and dynamic analyses of laminated piezoelectric plates [34,35]. Kim and Reddy [36] presented analytical solutions for the bending, vibration and buckling of FG elastic plates using a couple stress-based third-order shear deformation theory, which was also extended to the nonlinear analysis of FG elastic plates by Reddy and Kim [37], in which the geometric nonlinearity, microstructure-dependent size effect, and two constituent-material variations through the thickness were considered. Na and Kim [38,39] developed a 3D finite element model for the thermo-mechanical buckling and postbuckling analyses of FG elastic plates/panels, in which the material properties were assumed to be temperature-dependent and continuously varying in the thickness coordinate according to a power-law distribution in terms of the volume fractions of constituent materials. In addition, the volume fraction optimization of FG panels was studied by considering reductions in stress and critical thermo-mechanical loads.

As mentioned above, CNTs have also being mixed with polymer matrices to produce FG CNTRC structures, because the resulting materials have better mechanical and electric characteristics than conventional laminated FRC ones. However, few related mechanical analyses of the FG CNTRC structures can be found in the public literature due to the variable material properties produced in these. Using the HSDT and VKKN, Shen [40] and Shen and Xiang [41] studied the nonlinear bending and free vibration of FG CNTRC plates and cylindrical shells in thermal environments, in which the material properties were assumed to be temperature-dependent and were obtained using either the Mori–Tanaka scheme [42] or the rule of mixtures [43]. The above-mentioned formulation was also extended to the nonlinear vibration and bending of sandwich homogeneous plates with CNTRC face sheets by Wang and Shen [44], in which a parametric study was conducted with regard to the effects of the CNT volume fraction and distribution, thickness ratio for each layer, temperature change and different boundary conditions on the nonlinear bending behaviors and vibration characteristics. Shen [45,46] and Shen and Xiang [47] also applied this formulation to the postbuckling analysis of FG CNTRC cylindrical shells in thermal environments and under axial compression, external pressure, and a combination of these loads, in which a singular perturbation technique was used to obtain the critical loads and postbuckling equilibrium paths. Based on the FSDT combined with either the element-free *kp*-Ritz method or differential quadrature (DQ) one, Lei et al. [48] and Zhu et al. [49] investigated the bending, free vibration and buckling of FG CNTRC plates, in which four different distributions of CNTs through the thickness were considered. Within the framework of 3D elasticity, Alibeigloo [50] and Yas et al. [51] presented the static and free vibration analyses of FG CNTRC plates and cylindrical panels, and these embedded in piezoelectric layers, in which the state space method combined with the transfer matrix one was used in the former and with the differential quadrature (DQ) one was applied in the latter. Finally, Brischetto and Carrera [52,53] extended the above-mentioned 2D refined and advanced theories for laminated composite plates and shells to the analysis of nano-reinforced layered plates and shells, in which the CST was concluded to be inadequate for the analysis of these, and the beneficial effect of the nano-scaled reinforcements in terms of displacements and stresses was quantified.

Based on the PVD, Cheung and Chakrabarti [54] and Zhou et al. [55] developed finite layer methods (FLMs) to study the 3D free vibration problems of thick, layered rectangular plates with full simple supports. Cheung and Jiang [56] and Akhras and Li [57–60] then extended the PVD-based FLMs to the 3D static, vibration, stability and thermal buckling analyses of simply-supported, piezoelectric composite plates. Considering the RMVT-based theories are superior to the PVD-based ones for the analysis of laminated elastic and piezoelectric structures [61–63], Wu and Li [64] and Wu and Chang [65] developed unified formulations of RMVT-based FLMs for the bending analysis of simply-supported, laminated composite plates/cylinders and FG elastic ones, in which the influence of related orders used to expand each field variable through the thickness coordinate on the static behaviors of the plates was discussed in detail. To take account of the effect of different edge conditions in the analysis of FLMs, Wu and Li [66,67] proposed RMVT-based finite prism methods (FPMs) for the analysis of laminated FG elastic plates and cylinders with various boundary conditions. Implementing these methods in the cases of laminated FRC plates/cylinders and FG elastic ones shows that the convergence rate is rapid, and the convergent solutions are in excellent agreement with the exact 3D ones available in the literature.

After a close literature survey, we found that there are relatively few articles dealing with the structural behaviors of single-layered FG CNTRC plates and shells compared with those that examine laminated FRC ones, and much fewer that consider the coupled analysis of FC CNTRC plates/shells with surface-bonded piezoelectric actuator and sensor layers. In this article, within the

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