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Thermoelastic analysis of functionally graded carbon nanotube reinforced composite cylindrical panel embedded in piezoelectric sensor and actuator layers

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A R T I C L E I N F O

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Based on theory of piezo-elasticity, bending behavior of functionally graded carbon nanotube reinforced composite (FG-CNTRC) cylindrical panel attached to thin piezoelectric layers subjected to thermal, mechanical loads and or electric field is investigated. It is assumed that thermo-elastic constants of the structure are independent of temperature gradient. In this paper, uniformly and various cases of functionally graded CNT distribution along the radial direction of host layer are considered. Governing differential equations are solved analytically by using the Fourier series expansion along axial and circumferential direction and state-space technique across the radial direction. Temperature, stress and displacement fields as well as induced electric voltage in sensor layer are obtained and used to study the thermo-piezoelastic behavior of hybrid FG-CNTRC cylindrical panel. Accuracy of present approach is validated by comparing the numerical results with the available reported results in literatures. Parametric studies are carried out to assess the effects of CNT volume fraction, case of CNT distribution along the radial direction, surface thermal/mechanical surface boundary conditions, applied voltage on the bending behavior of FG-CNTRC hybrid cylindrical panel.

1. Introduction

The exceptional mechanical, thermal and electrical properties of carbon nanotube (CNT) causes to be considered as significant reinforcement materials for high performance structural composites with much application potential [1,2]. Carbon nanotubes have high strength and stiffness to weight ratio in comparison to standard carbon-fibers used in fiber reinforced polymers [3,4]. Recently, the significant properties of CNT, motivates researchers to study on the behavior of CNTRC beam, plate and shell structures subjected to mechanical and or thermal load. Gou et al. [5] employed the molecular dynamics (MD) simulations and experimental method, to study on the interfacial bonding of single walled carbon nanotube (SWCNT) reinforced epoxy composites. Multiscale analysis of the deflection and stress behavior of CNT reinforced polymer composite beams has been performed by Wuite and Adali [6]. Bending and bending-induced local buckling of SWCNTRC beams was studied by Vodenitcharova and Zhang [7]. Based on modified Donnell theory of shell, Sofiyev [8] investigated thermal buckling behavior of simply supported FGM conical shells using Galerkin's method. Shen [9] analyzed nonlinear bending of simply supported, FG composite plates reinforced by SWCNTs under transverse uniform or sinusoidal load in thermal environments. Shen and Zhang [10] used multi-scale method to analysis of thermal buckling and post buckling of FG nanocomposite plates reinforced by SWCNTs under in-plane temperature gradient. Formica et al. [11] studied on vibrational behavior of CNT-reinforced composites using an equivalent continuum model based on the Eshelby–Mori–Tanaka technique. Based on higher order shear deformation theory and von Kármán-type of kinematic nonlinearity, postbuckling analysis of SWCNTRC cylindrical shells subjected to axial load was carried out by Shen [12]. Shen [13] used micromechanical model and multiscale technique to investigate post-buckling of FG-CNTRC cylindrical shells subjected to mechanical load in thermal environments. Based on a higher order shear deformation plate theory, Wang and Shen [14] studied on nonlinear vibration of FG-SWCNT plates resting on elastic foundation in thermal environments using an improved perturbation method. Thermal buckling analysis of simply supported FGM truncated conical shell rested on two

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Nomenclature

E_{11}^{CNT}, E_{22}^{CNT}, G_{12}^{CNT}, E_m, G_m	Young's modulus, shear modulus of carbon nanotube and matrix, respectively
C_{ij} $(\mathrm{i,j} = 1,2,...,6)$	material elastic constants
D_r, D_θ and D_z	electric displacement
E_r, E_θ and E_z	electric field in r-, θ- and z-direction, respectively
d_1	piezoelectric modulus
h_f, h_p	thicknesses of the FGM and piezoelectric layers, respectively
K	thermal conductivity coefficient of carbon nanotube reinforced composite
k_r, k_θ, k_z	thermal conductivity coefficient for FG-CNTRC cylindrical panel in$r$-, θ- z-direction, respectively
k_m	thermal conductivity coefficient for polymer matrix
k_{rs}, $\mathrm{k}_{\theta\mathrm{s}}$, k_zs	thermal conductivity coefficient for sensor layer in r-, θ- z-direction
k_{ra}, $\mathrm{k}_{\theta\mathrm{a}}$, k_za	thermal conductivity coefficient for actuator layer in r-, θ- z-direction
L, h	length and thickness of panel
n, m	number of half waves in θ- and z-direction
P	aspect ratio of CNTs, L/d, (length to diameter ratio of CNTs)
p_3	pyroelectric constant
T_s, T_a	temperature distribution for the sensor and actuator layers
T_{fi}, T_{fo}	temperature at the inner and outer surfaces respectively of UD layer
R_k	interface thermal resistance between CNT and matrix
r_i, r_o	inner and outer radius of cylindrical panel
u_r, u_θ, u_z	displacement components in r-, θ- z-directions, respectively
V_{CNT}, V_m	carbon nanotube and matrix volume fractions, respectively
W_{CN}, ρ_{CNT}	mass fraction and density fraction of CNT, respectively
α_i $(i = r, \theta, z)$	thermal conductivity coefficient for piezoelectric layers in r-, θ- z-direction, respectively
α_{ij}^{CNT}, k_{CNT}, α_m, k_m	thermal expansion coefficient and thermal conductivity coefficient of carbon nanotube and matrix respectively
β_i $(i = r, \theta, z)$	thermoelastic constants in r-, θ- z-direction, respectively
ρ_m, ν_m	density fraction and Poisson's ratio of matrix
θ_m	span angle of cylindrical panel
η_i $(\mathrm{i} = 1,2,3)$	CNT efficiency parameters accounting for the scale-dependent material properties
$\sigma_i (i = r, \theta, z)$	normal stresses
$\tau_{r\theta}$ $\tau_{\theta z}$ τ_{rz}	shear stresses
$\gamma_{z\theta}$, γ_{rz}, $\gamma_{r\theta}$	shear strains
ε_i $(i = r, \theta, z)$	normal strains
e,μ	piezoelectric constants and dielectric constants, respectively
δ, δ_p	state vectors of the FG-CNTRC plate and piezoelectric layers
ψ	electric voltage

parametric elastic foundation and subjected to nonlinear temperature along the thickness direction was presented by Sofiyev [15]. Wosu et al. [16] used Split Hopkinson pressure bar apparatus to investigate the influence of temperature and moisture on the response of graphite/epoxy laminated. Based on the first-order shear deformation (FSDT), Mehrabadi et al. [17] considered mechanical buckling of FG-SWCNTs plate using Mindlin plate theory. Bending and free vibration analyses of SWCNTRC plates was performed by Zhu et al. [18] using the finite element method based on the first order shear deformation plate theory. Shen [19] investigated postbucking of FG-CNTRC cylindrical panel in thermal environment by using higher order shear deformation theory and Von Karman type of kinematic nonlinearity. Shen and Xiang [20] used higher-order shear deformation theory with a Von Karman-type of kinematic nonlinearity to discus nonlinear vibration of FG-CNTRC cylindrical shell. Bending analysis of a substrate coated by nanomaterials with vacancies subjected to uniform extension load was carried out by Alizada et al. [21]. Effects of inclined carbon nanotubes on mechanical properties of nano-composites was studied by Joshi et al. [22] using 3-D hexagonal representative volume element (RVE) with short and straight CNTs. Sobhani Aragh [23] analyzed free vibration of CNTRC cylindrical panel by using Eshelby–Mori–Tanaka technique and two-dimensional differential quadrature method. Moradi-Dastjerdi et al. [24] employed mesh free method to investigate dynamic behavior of FG-CNTRC cylindrical shell subjected to impact load. Shen and Xiang [25] used higher order shear deformation shell theory formulation and a von Kármán-type of kinematic nonlinearity to analysis of postbuckling FG-CNTR cylindrical shell subjected to combined axial and radial loads in thermal environment. Nonlinear buckling behavior of polyvinylidene composite cylindrical shell was performed by Mosallaie Barzokie et al. [26] based on Donnell's theory and using Hamilton's principle as well as harmonic differential quadrature method (HDQM). Bhardwaj et al. [27] considered non-linear static and dynamic behavior of cross-ply CNTRC laminated plate using the double Chebyshev series. Alibeigloo and Liew [28] investigated thermoelasticity behavior of a simply supported FG-CNTRC rectangular plate using three dimensional theory of elasticity and state space technique.

Due to direct and inverse effects of piezoelectric materials they are widely used in various industries. The use of piezoelectric layers as distributed sensors and actuators in structures to control noise and deformations and suppress vibrations is quite common. Wu et al. [29] used linear through-the-thickness approximation of in-plane and transverse displacements and quadratic variation of the electric potential to analysis of FGM piezoelectric shells subjected to static electro-mechanical loads. Liew et al. [30] and He et al. [31] employed the classical shell theory to study active control of FGM shells by using piezoelectric sensors/actuators. Wu et al. [32] presented an analytical solution for thermo-electro-mechanical deformations of a laminated cylindrical shell with a FGM piezoelectric layer with material properties according to power law variation along the radial direction. Vibration analysis of FGM shell with piezoelectric sensor and actuator was carried out by Liew et al. [33] using FSDT and FEM. Based on HSDT and the von Karman–Donnell kinematic nonlinearity, Shen and Noda [34] investigated postbuckling of FGM cylindrical shell with piezoelectric actuators subjected to either lateral loads or hydrostatic pressure combined with electric loads in thermal environments. Based on three-dimensional theory of elasticity, Alibeigloo [35–37] employed three dimensional theory of elasticity to analysis of bending behavior of FG-CNTRC plate and cylindrical panel