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New approach to investigate nonlinear dynamic response and vibration of imperfect functionally graded carbon nanotube reinforced composite double curved shallow shells subjected to blast load and temperature

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ABSTRACT

This paper presents a new approach – using analytical solution to investigate nonlinear dynamic response and vibration of imperfect functionally graded carbon nanotube reinforced composite (FG-CNTRC) double curved shallow shells. The double curved shallow shells are reinforced by single-walled carbon nanotubes (SWCNTs) which vary according to the linear functions of the shell thickness. The shells are resting on elastic foundations and subjected to blast load and temperature. The shell's effective material properties are assumed to depend on temperature and estimated through the rule of mixture. By applying higher order shear theory, Galerkin method and fourth-order Runge–Kutta method and the Airy stress function, nonlinear dynamic response and natural frequency for thick imperfect FG-CNTRC double curved shallow shells are determined. In numerical results, the influences of geometrical parameters, elastic foundations, initial imperfection, temperature increment and nanotube volume fraction on the nonlinear vibration of the FG-CNTRC double curved shallow shells are investigated. The proposed results are validated by comparing with those of other authors.

1. Introduction

Carbon nanotube-reinforced composites (CNTRCs) are an emerging class of new materials that are being developed to take advantage of the high tensile strength and electrical conductivity of carbon nanotube materials. Therefore, the problems of thermal-mechanical properties of CNTRCs have attracted increasing research effort. Zhang and Liew [1] presented post-buckling analysis of FG-CNTRC plates resting on Pasternak foundations. Shen [2] investigated thermal post-buckling analysis for nanocomposite cylindrical shells reinforced by SWCNTs subjected to a uniform temperature rise. Griebel and Hamaekers [3] examined the elastic moduli of polymer–carbon nanotube composites by molecular dynamics simulations of a SWCNT embedded in polyethylene. Kolahchi et al. [4] dealt with wave propagation of embedded viscoelastic FG-CNT-reinforced sandwich plates integrated with sensor and actuator based on refined zigzag theory. Zhang et al. [5] considered the problem of the free vibration of FG-CNT reinforced composite moderately thick rectangular plates with edges elastically restrained against transverse displacements and rotation of the plate cross section. Mirzaei and Kiani [6] studied free vibration characteristics of composite plates reinforced with single walled carbon nanotubes. The bending, vibration and buckling of embedded nano-sandwich plates based on refined zigzag theory, sinusoidal shear deformation theory, first order shear deformation theory and classical plate theory are investigated in work [7] of Kolahchi. Han and Elliott [8] analyzed molecular dynamics simulations of the elastic properties of polymer/carbon nanotube composites. Further, Song et al. [9] researched the vibration characteristics of CNT reinforced functionally graded composite cylindrical shells. Aragh et al. [10] considered natural frequencies characteristics of a continuously graded carbon nanotube-reinforced cylindrical panels based on the Eshelby–Mori–Tanaka approach. Lei et al. [11] studied buckling behavior of FG-CNTRC laminated plate using the first-order shear deformation theory. Shen and Xiang [12,13] introduced investigations on the nonlinear bending analysis and the large amplitude vibration behavior of CNTRC cylindrical panels resting on

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elastic foundations in thermal environments. Mirzaei et al. [14] investigated linear thermal buckling of a composite conical shell made from a polymeric matrix and reinforced with carbon nanotube fibers. Kolahchi et al. [15] investigated nonlinear dynamic stability analysis of embedded temperature-dependent viscoelastic plates reinforced by single-walled carbon nanotubes. Zhang et al. [16] presented a first known investigation on the geometrically nonlinear large deformation behavior of triangular FG-CNTRC plates under transversely distributed loads.

Noted that in all above mentioned references about FG-CNTRC plates and shells, the authors used finite element methods, analytical solution has not been yet considered.

The studies of the behaviors of composite structures under blast load have been taken much attention of researchers in the word. Zhu and Khanna [17] studied the dynamic response of a novel laminated glass panel using a transparent glass fiber-reinforced composite interlayer under blast loading. Analytical approaches to obtain maximum deformations (center) of the double skin façades panels subjected to blast pressures are presented by Ding et al. [18]. Zhang et al. [19] considered experimental investigations on the laser-welded triangular corrugated core sandwich panels and equivalent solid plates subjected to air blast loading; and Flores-Johnson et al. [20] introduced a multi-layered composite inspired by the hierarchical structure of nacre and made of layers of aluminum alloy AA 7075 bonded with toughened epoxy resin for blast resistant applications. Lam et al. [21] developed existing knowledge on the modeling of blast pressure for engineering applications. Micallef et al. [22] studied the dynamic performance of simply-supported rigid-plastic circular steel plates subjected to localized blast loading. Recently, Yao et al. [23] analyzed anti-blast performance and damage characteristics of reinforced concrete slab with different reinforcement ratios through both blast experiments and numerical simulations. Arablouei and Kodur [24] presented a fracture mechanics-based numerical approach for quantifying delamination of spray-applied fire-resistive material from a steel beam–column subjected to a blast loading. Based on Reddy's higher-order shear deformation plate theory, Duc et al. [25] investigated the nonlinear dynamic response and vibration of imperfect FGM thick plates subjected to blast and thermal loads resting on elastic foundations. Pickerd et al. [26] conducted a series of small-scale internal blast experiments to assess the structural response and failure mechanisms of metal containers subjected to internal blast loading, for the enhancement of Vulnerability/Lethality modeling. Phuong et al. [27] developed a finite element model to understand the deformation and failure mechanisms of a multi-layered elastomer/fibre-reinforced polymer composite panel under blast. Linz et al. [28] used the von Karman theory for large deflections of plates to simulate the effect of large explosions on laminated glazing.

The change of the temperature in the structural and non-structural member causes thermal stress is defined as the effect of thermal load with temperature dependent properties. In the recent years, many investigations have been carried out on the nonlinear static and dynamic responses of composite structures. Eshraghi et al. [29] introduce solution methods capable of treating static bending and free vibration problems involving thermally loaded functionally graded annular and circular micro-plates. Duc [30] presented an analytical investigation on nonlinear thermal dynamic behavior of imperfect functionally graded circular cylindrical shells eccentrically reinforced by outside stiffeners and surrounded on elastic foundations using the Reddy's third order shear deformation shell theory in thermal environment. Mirsalehi et al. [31] evaluated the buckling of a thin FGM microplate subjected to mechanical and thermal loading using the spline finite strip method, based on modified couple stress theory. Buckling behaviors of shear deformable grid-stiffened functionally graded cylindrical shells under the combined compressive and thermal loads are investigated by Sun et al. [32]. Bich et al. [33] presented an analytical approach to investigate the nonlinear dynamic response and vibration of imperfect eccentrically stiffened FGM thick double curved shallow shells on elastic foundations using both of the first order shear deformation theory. Guo et al. [34] developed an interaction energy integral method is developed for the finite element evaluation of the T-stress in non-homogeneous materials under thermal loading. Warminska et al. [35] focused on dynamics of a composite beam subjected to thermal and mechanical loadings.

Up to date, to best of the authors' knowledge, there has been recently no publication using analytical approach to investigate the static and dynamic behaviors of imperfect FG-CNTRC double curved shallow shells. A novelty of this study is that the using analytical solution and Reddy's third order shear deformation theory to study the nonlinear vibration of imperfect thick FG-CNTRC double curved shallow shells subjected to the combination of blast load and temperature. The advantage of the present analytical method is that dynamic response and frequencies are presented explicitly by the geometric parameters and material properties of the structure, as well as the extrinsic force and temperature, so we can design and modify these parameters properly to actively control the dynamic behavior of the shells. In this work, the shell's effective material properties are assumed to depend on temperature and estimated through the rule of mixture. Numerical results for dynamic response of the FG-CNTRC double curved shallow shells are obtained by Galerkin method fourth-order Runge–Kutta method.

2. Determination of the elastic modules and the thermal expansion coefficients of CNTRCs

In this study, the FG-CNTRC material is made of Poly (methyl methacrylate), referred to as PMMA, reinforced by (10, 10) SWCNTs. The effective Young's and shear modulus of the FG-CNTRC material are determined as [1,2,12–14,16]

$$\begin{aligned}
&E_{11} = \eta_1 V_{CNT} E_{11}^{CNT} + V_m E_m \\
&\frac{\eta_2}{E_{22}} = \frac{V_{CNT}}{E_{22}^{CNT}} + \frac{V_m}{E_m} \\
&\frac{\eta_3}{G_{12}} = \frac{V_{CNT}}{G_{12}^{CNT}} + \frac{V_m}{G_m}
\end{aligned} \tag{1}$$

where $E_{11}^{CNT}, E_{11}^{CNT}, G_{12}^{CNT}$ are Young's and shear modulus of the CNT; E_m, G_m are mechanical properties of the matrix. V_{CNT} and V_m are the volume fractions of the CNT and the matrix, respectively and η_i $(i = \overline{1,3})$ are the CNT efficiency parameters.

The volume fractions of the CNT and the matrix are assumed to change according to the linear functions of the shell thickness. Three types of FG-CNTRCs, i.e. FG-V, FG-O and FG-X, are considered. Specifically, the volume fractions of the three distribution types are expressed as follows [6,14,16]

$$\begin{aligned}
&V_{CNT}(z) = \begin{cases} 2V_{VCT}^{*}\left(1 - 2\frac{|z|}{h}\right) & \text{(FG-O)} \\ 4V_{VCT}^{*}\frac{|z|}{h} & \text{(FG-X)} \\ V_{VCT}^{*}\left(1 + 2\frac{z}{h}\right) & \text{(FG-V)} \end{cases} \\
&V_m(z) = 1 - V_{CNT}(z)
\end{aligned} \tag{2}$$

where

$$V_{CNT}^{*} = \frac{w_{CNT}}{w_{CNT} + (\rho_{CNT}/\rho_m) - (\rho_{CNT}/\rho_m) w_{CNT}} \tag{3}$$

in which w_{CNT} is the mass fraction of CNTs, and ρ_{CNT} and ρ_m are the densities of CNT and matrix, respectively.

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