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Nonlinear bending analysis of a 3D braided composite cylindrical panel subjected to transverse loads in thermal environments

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Abstract The aim of this study is to investigate nonlinear bending for a 3-Dimensional (3D) braided composite cylindrical panel which has transverse loads on its finite length. By refining a micro-macro-mechanical model, the 3D braided composite can be treated as a representative average cell system. The geometric structural properties of its components deeply depend on their positions in the section of the cylindrical panel. The embedded elastic medium of the panel can be described by a Pasternak elastic foundation. Via using the shell theory of the von Kármán-Donnell type of kinematic nonlinearity, governing equations can be established to get higher-order shear deformation. The mixed Galerkin-perturbation method is applied to get the nonlinear bending behavior of the 3D braided cylindrical panel with a simply supported boundary condition. Based on the analysis of the braided composite cylindrical panel with variable initial stress, geometric parameter, fiber volume fraction, and elastic foundation, serial numerical illustrations are archived to represent the appropriate nonlinear bending responses.

1. Introduction

Composite materials are widely used to take place of metal structures in engineering for the aims of light weight and high resistance to chemical corrosion. The ability to design, analyze, optimize, and select proper materials for these structures is a necessity for structural designers, analysts, and researchers. It puts more and more important issues, like nonlinear mechanical behaviors of plate and panel structures, back on the front burner. Fabrication methods derived from the textile industry are used to manufacture textile composites for eliminating the delamination due to texture in-homogeneity. There are also numerous investigations into the physical and mechanical properties of composite plate structures, and minute analyses are available in the literature.[1–4]

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Plates and panels are primary components in many structures including space vehicles, aircraft, automobiles, buildings, bridge decks, ships, and submarines. During the expansion of their usage, the physical characteristics of these composite plates/shells, like stability, bending, and vibration, attract much more interests of engineers. Large numbers of previous studies on the large deflection and/or nonlinear bending problem of thin plates are available. Reddy and Wang 5 carried out bending analysis to study the effect of transverse shear deformation on deflections and stresses of laminated composite plates subjected to uniformly distributed load using the finite element method. Based on the first-order shear deformation theory, Xing and Xiang 6 studied linear buckling behavior of symmetric cross-ply rectangular composite laminates with a pair of parallel edges simply supported and the remaining two edges arbitrarily constrained. Brischetto et al. 7 investigated bending analysis of sandwich flat panels by applying the zig-zag function to the known higher-order theories. Considering the effect of transverse normal deformation of the core of a sandwich plate, Di Sciuva et al. proposed linear[8] and cubic[9–11] zig-zag theories that are able to compute transverse shear stresses directly from constitutive equations based on the cubic zig-zag theory, which leads to piecewise parabolic shear stress vanishes on top and bottom surfaces, and in most cases, exhibits a good accuracy. Dawe and Wang 12 developed a spline finite strip method to predict the postbuckling response of composite laminated panels, with the nonlinearity introduced in enhanced strain–displacement equations for panels in a total Lagrange approach. On the other hand, analysis of structures and structural elements, supported on an elastic foundation, e.g., soil, often requires the knowledge of the properties of the structures, as well as the properties of the soil. While properties of structural materials of a foundation and superstructure are usually well known, obtaining the soil's properties and, especially, evaluating the soil's behavior under applied loads, is very difficult. Various soils react differently to applied loads and, like any bearing material, produce under the same loads different settlements and different stresses. Analysis of beams, plates, panels, and other structures supported on elastic foundations is usually performed by modeling the soil; in other words, by replacing the soil with a material that behaves under applied loads like the given real soil. The most popular soil models used by practicing engineers are Winkler's soil model or Winkler foundation proposed by Winkler 13. Some scientists trying to improve the soil models mentioned above have recommended the use of new soil models. For example, Pasternak 14 proposed a soil model with two coefficients of subgrade reaction. The modulus of subgrade reaction represents a load that, being applied to one square unit of the soil surface, produces a settlement equal to one unit, and is the only parameter needed to obtain the settlement of the soil. The Winkler foundation is based on the following three assumptions:

(1) The load applied to the soil surface produces settlements of the soil only under the applied load and does not produce any settlements and stresses outside the loaded area.
(2) The soil can resist compression as well as tension stresses.
(3) The shape and size of the foundation do not affect the settlement of the soil.

These assumptions are not always accurate because it is well known that, in many cases, a load applied to the soil produces settlements not only under the applied load, but also outside the loaded area.

Based on a refined plate theory, Jiang et al. 15 studied the thermal bending behavior for a High-Strength Low-Alloy (HSLA) steel plate under a 3D temperature field, and the method of separation of variables[16,17] is used to provide geometrically nonlinear bending solutions for homogeneous isotropic and composite laminated plates subjected to mechanical and/or thermal loading and resting on an elastic foundation. In these studies, material properties were considered to be independent of temperature. Teo and Liew 18 presented a 3D analysis of rectangular orthotropic plates by employing the Differential Quadrature (DQ) method. They pointed out that the DQ method yields accurate results for the plate problems under investigation. Theoretical, numerical, and experimental studies which focus on the nonlinear problems involving bending, stability, and non-stationary vibrations are also addressed. It is noted that if the panels or plates in a structure are treated as 2D laminates, analyzed results will be some accidental non-linear distortions like inferior delamination resistance, redundant impact damage tolerance, and excessive notch sensitivity. In reality, in the case of the stress distribution analysis of a braided cylindrical plate/-panel with a moderate thickness, the loaded braiding cells play the major role due to the through-thickness-direction reinforcement.[19,20] However, it remains unclear whether 3D braided cylindrical panels still display a strong or weak nonlinearity under a low fiber volume fraction, and this motivates the current investigation. The present work focuses on the nonlinear bending response of a 3D braided composite cylindrical panel resting on an elastic foundation. A representative unit is established, which contains four interior cells and two surface cells in different regions by using a simple rule of mixtures idea. The algorithms are based upon Reddy's higher-order shear deformation shell theory with a von Kármán type of kinematic nonlinearity. A mixed Galerkin-perturbation technique is employed to determine transverse load-deflection and load-bending moment curves with initial in-plane loadings. Numerical results are presented in a graphical form to illustrate the nonlinearity of the bending responses of 3D braided composite cylindrical panels resting on elastic foundations.

The paper is organized in the following manner. Section 2 is focused on the analytical material mathematical modeling, the displacement field, the elastic stress-strain relations, and the principle of virtual work. In Section 3, the analytical method and asymptotic solutions are presented. Section 4 presents numerical results and conclusions.

2. Theoretical development

Based on the carrier movement and using the method of material volume control and surface limitation, yarn traces can be analyzed to describe 3D tubular braided composite plate preforms systematically. Similar studies have also been reported by Wang Y Q and Wang A 2.

We developed a micro-macro-mechanical model, in which a macro-cell is further decomposed into simpler elements, called unit cells, as shown in Fig. 1, in which $\bar{K}_1$ and $\bar{K}_2$ are the elastic

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