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Postbuckling behavior of shear deformable anisotropic laminated cylindrical shell under combined external pressure and axial compression

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ABSTRACT

Structural design of composite shells are more challenging than conventional metals due to the complex mechanical behavior and damage mechanisms which composite materials exhibit. Postbuckling analysis for a moderately thick anisotropic laminated cylindrical shell subjected to combined loadings of external pressure and axial compression is presented which extends the boundary layer theory of shell buckling. The governing equations are based on Reddy's higher order shear deformation shell theory with von Kármán-Donnell-type of kinematic nonlinearity. Both nonlinear prebuckling deformations and initial geometric imperfections of the shell are taken into account. A two-step singular perturbation method is used to determine interactive buckling loads and postbuckling equilibrium paths. A verification study is conducted, and the validity of the formulation is established through comparison with results of nonlinear finite element software such as ABAQUS®. The internal physical mechanism of the shell geometric parameters on the buckling load and the postbuckling equilibrium path is obtained. The numerical illustrations concern the postbuckling response of perfect and imperfect, moderately thick, anisotropic laminated cylindrical shells with different load-proportional parameters. The analytical model can provide an effective tool to investigate postbuckling of composite shell structures.

1. Introduction

Thin-walled shell structures of various types are very important structural elements. From the perspective of engineering application, it is necessary to predict different modes of behavior of plates and shells under applied loadings. Interest in the structural instability analysis of relatively thick composite-material shells has been led by a need for more accurate analysis especially in the case of thick-walled structures. As a kind of typical structure, shells are used in civil and mechanical engineering include slabs, vaults, chimneys, cooling towers, pipes, tanks, containers and pressure vessels; in shipbuilding-ship and submarine hulls (Mouritz et al. [1]). On the one hand, the challenge to the engineer and researcher is the discrepancy between the highly efficient load-carrying capacity of the perfect shell and the real, manufactured shell/tube. For the complex buckling behavior of composite cylindrical shell structures, it is very important to investigate how different initial imperfections influence the load-carrying capacity. Due to the inherent anisotropy, the buckling behavior of composite structures is more complicated than those of their metallic components. High performance composite materials, for example, graphite/epoxy, boron/epoxy, glass/epoxy etc. are currently being used in many engineering applications. Such beneficial properties as high stiffness-to-weight and strength-to-weight ratios, etc., make laminated panels/shells attractive for structural components in aerospace, marine, automobile and other application. On the other hand, many studies have observed buckling and many attempts have been made to predict buckling behavior for composite cylindrical shells. Leissa [2] summarized technical literatures dealing with buckling and postbuckling behavior of laminated composite plates and shell panels. In these analyses, only perfect initial configurations were assumed. Teng [3] provided a review of recent research advances and trends in the area of thin shell buckling. He emphasized and discussed imperfections in real structures and their influence, buckling of shells under local/non-uniform loads and localized compressive stresses, and the use of computerized buckling analysis in the stability design of complex thin shell structures. Dinkler and Pontow [4] introduced the perturbation energy concept and its application to stability of imperfection sensitive structures under time-dependent loads. In the first order shear deformation theory, the displacement field is assumed to vary linearly with respect to thickness (measured from the midsurface) and the rotations of the normal to the

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midsurface are independent variables. Iu and Chia [5] developed a first order shear deformation theory to study nonlinear vibration and postbuckling of imperfect, moderately thick, cross-ply laminated cylindrical shells. Fu and Waas [6] applied first order shear deformation theory to study the initial postbuckling behavior of thick rings under uniform, external hydrostatic pressure. Han and Simitses [7] investigated buckling behavior of symmetric laminates composite cylindrical shell subjected to lateral or hydrostatic pressure based on Sanders-type [8] of first order shear deformation theory. These studies show that first order shear deformation theories significantly improve the prediction accuracy of the buckling load compared to the thin shell Kirchhoff-Love assumption. However, the improvement offered by the higher order theories over the first order ones is much smaller, and in the first order shear deformation theory the conditions of zero shear stress on the top and bottom surfaces of the shell are not met, and this requires a shear correction to the transverse shear stiffnesses. Simitses and Anastasiadis [9,10] developed a higher order shear deformation theory, and studied buckling loads of moderately thick, symmetrically laminated cylindrical shells. Reddy and Savoia [11] investigated the postbuckling response of imperfect laminated cylindrical shells, which can produce much more accurate results but the boundary conditions cannot be imposed accurately in their solutions. Recently, research on composite pipes/shells over the last few decades has covered the buckling and postbuckling response due to bending, compression or combined axial-external pressure loadings and buckling failure can also be observed to occur when maximum compressive stress in the structure reaches the critical stress under pure compression or when the prebuckling load significantly contributes to the bifurcation load through ovalization (Sun et al., [12]). Corona and Rodrigues [13] carried out a study on the bending response of long and thin-walled cross-ply composite cylinders including three phases: pre-buckling response, material failure by Tsai-Wu criterion, and shell-type bifurcation buckling. Yang et al. [14] studied the buckling of cylindrical shells under external pressure with general axisymmetric thickness imperfections. Based on a system of linearized governing partial differential equations of perfect shells with variable thickness, the effects led by three patterns of thickness imperfections on the buckling of the laterally pressured cylindrical shells, which are uniform, axisymmetric modal and parabolic, are respectively analyzed. Papadakis [15] studied a set of stability equations for thick cylindrical shells under external pressure, analyzed and discussed differences between the benchmark solutions and the analytic expressions based on the refined high order theory and the classical shell theory, and estimated the stress and moment resultants of thick shell based on a higher order shell theory. Schillo et al. [16] carried out experimental and numerical study for geometrical imperfection measurements of a set of 12 CFRP cylinders with the specified manufacturing method. Loading imperfections are measured and implemented in the finite element analysis. Model uncertainties are quantified with respect to loading and geometric imperfections as well as level of detail of the as-built layup. They point out a general assessment of the sensitivity of unstiffened cylinders towards geometric and load imperfections should include a wider range of values and different manufacturing methods. In order to compare the accuracy of the predictions from the classical and the improved shell theories, Kardomateas [17,18] and Kardomateas and Philobos [19] studied the buckling of orthotropic cylindrical shells subjected to axial compression, external pressure and combined loadings by using the three-dimensional (3D) elasticity theory. Tornabene et al. [20] and Brischetto et al. [21] investigated the cylindrical bending conditions in the free frequency analysis of functionally graded material (FGM) plates and cylindrical shells for different geometries (plates, cylinders, and cylindrical shells), types of FGM law, lamination sequences, and thickness ratios. 2D numerical approaches (the Generalized Differential Quadrature (GDQ) and the finite element (FE) methods) are compared with an exact 3D shell solution in the case of free vibrations of FGM plates and shells. Based on the Koiter' theory (Koiter, [22]), Arciniega et al. [23] investigated the buckling and postbuckling behavior of laminated cylindrical shells subjected to axial compression and lateral pressure loading using Rayleigh-Ritz method. By the same method, Salahshour and Fallah [24] investigated local elastic buckling of thin long cylindrical shells under external pressure. Based on Donnell's and Sanders' theories of thin shells and von Kármán nonlinearity assumptions, the potential energy is derived. The buckling load and curves of the static equilibrium path are obtained. Wang et al. [25] studied the effect material of nonlinearity on buckling and postbuckling of fiber composite laminated plates and cylindrical shells and obtained a modified Riks solution scheme with updated Lagrangian formulation. Based on the Donnell-Mushtari-Vlasov theory of shells, Semenyuk and Trach [26,27] obtained solutions of buckling and postbuckling behavior of composite cylindrical shells subjected to fundamental loads. By using finite element method and experimental measure, Priyadarsini et al. [28] investigated buckling characteristics of fiber reinforced composite cylinders subjected to axial compressive loads. The effects of different types of loadings, geometric properties and lamina lay-up were involved. Mistry et al. [29] presented experimental and numerical investigationfor the $\pm$ 55° filament-wound glass/epoxy pipes subjected to combined external pressure and axial compression. Based on a layer-wise and higher order shear deformation theory, Eslami et al. [30] and Eslami and Shariyat [31] investigated postbuckling of laminated cylindrical shells. Imperfections from manufacturing process can cause a scattered reduction of the load-carrying capacity cylindrical shell structures. Wang et al. [32] predicted the load-carrying capacity or buckling load of axially compressed cylindrical shell structures. The influence of pure geometric imperfections including imperfection component and amplitude on the buckling behavior is discussed based on Fourier series method. Some guidance for the dimensional tolerance in manufacturing process relating to the load-carrying capacity of thin-walled structures is provided. Lindgaard and Lund [33] presented an approach to nonlinear buckling fiber angle optimization of laminated composite shell structures. The approach accounts for the geometrically nonlinear behavior of the structure by utilizing response analysis up until the critical point. Sensitivity information is obtained efficiently by an estimated critical load factor at a precritical state. Liguori et al. [34] presented a strategy completely based on stochastic simulations for optimizing the stacking sequence of slender composite shells undergoing buckling. They predicted and evaluated postbuckling behavior of composite shells by using random numerical experiments for detecting both the best layup and the worst shape of the geometrical imperfection. However, in the foregoing studies, the shell theories used in these analyses are mostly extensions of the various isotropic or orthotropic and symmetric laminates shell models in buckling analysis involving seldom anisotropic coupling effects.

It has been shown in Weaver et al. [35] that all anisotropic coupling effects reduce the buckling loads. Shen [36–38] developed a boundary-layer theory for the buckling and postbuckling of anisotropic laminated thin shells under mechanical loading of axial compression, external pressure and torsion. Based on the above studies, Li and Lin [39] obtained analytical results of the buckling and postbuckling behavior for shear-deformable anisotropic laminated cylindrical shells subjected to varying external pressure loads. Li and Shen [40,41] investigated shear-deformable anisotropic laminated cylindrical shells subjected to axial compression or torsion. They found that there exists a compressive stress along with an associate shear stress and twisting when the shear-deformable anisotropic laminated cylindrical shell is subjected to axial compression. In contrast, there exists a shear stress along with an associate compressive stress when the shear-deformable anisotropic shell is subjected to torsion (Shen and Xiang [42]). Accordingly, we believe that there exists a circumferential stress due to boundary constraints along with an associate shear stress when an anisotropic thin shell is subjected to external pressure loads combined with axial compression (Li and Qiao [43]). Due to accounting for transverse shear strains, the shear deformation theory yield improved global response over the