Composite Structures 119 (2015) 709–726

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Buckling and postbuckling of anisotropic laminated cylindrical shells under combined external pressure and axial compression in thermal environments

Zhi-Min Li [a,c,*], Pizhong Qiao [b,c]

[a] State Key Laboratory of Mechanical System and Vibration, Shanghai Key Lab of Digital Manufacture for Thin-Walled Structures, School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai 200240, PR China
[b] State Key Laboratory of Ocean Engineering and School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University, Shanghai 200240, PR China
[c] Department of Civil and Environmental Engineering, Washington State University, Pullman, WA 99164-2910, USA

ARTICLE INFO

Article history:
Available online 14 October 2014

Keywords:
Postbuckling
Anisotropic laminated cylindrical shell
Classical shell theory
Boundary layer theory of shell buckling
Singular perturbation technique

ABSTRACT

The buckling and postbuckling analysis for an anisotropic laminated thin cylindrical shell of finite length subjected to combined loading of external pressure and axial compression using the boundary layer theory is presented. The material of each layer in the shell is assumed to be linearly elastic, anisotropic and fiber-reinforced. The governing equations are obtained utilizing classical shell theory and von Kármán–Donnell strain displacement relations. The nonlinear prebuckling deformations and initial geometric imperfections of the shell are both taken into account. A boundary layer theory of shell buckling, which includes the effects of nonlinear prebuckling deformations, large deflections in the postbuckling range, and initial geometric imperfection of the shell, is extended to the case of anisotropic laminated thin cylindrical shells under combined loading cases. A singular perturbation technique is employed to determine interactive buckling loads and postbuckling equilibrium paths. Postbuckling response of perfect and imperfect, anisotropic laminated cylindrical shells with respect to the material and geometric properties and load-proportional parameters under different sets of thermal environmental conditions is numerically illustrated. The analytical model developed can be used as a versatile and accurate tool to study the buckling and postbuckling behavior of composite structures.

© 2014 Elsevier Ltd. All rights reserved.

1. Introduction

Thin shells as structural elements are broadly used in civil, mechanical, architectural, aeronautical, and marine engineering. In mechanical engineering, shell forms are used in piping systems and pressure vessels. Aircrafts, missiles, rockets, ships, and submarines are examples of the use of shells in aeronautical and marine engineering. Accurate structural analysis of composite cylindrical shells is of great importance in aerospace industry as it closely relates to aircraft fuselage design. Since the load-carrying capability of thin shells is mostly determined by the buckling load, it is very important to determine a reliable and accurate value of this load for design purposes, especially in the case of thin-walled structures subjected to mechanical loadings.

Buckling of circular cylindrical shells has posed baffling problems to engineering for many years. Early tests by Robertson [1], Lundquist [2] and Wilson and Newmark [3] indicated that real cylinders buckle at loads much lower than the classical buckling load, which is the linear bifurcation load based on the assumptions of simple supports and a membrane state of prebuckling stress distribution. Experimental buckling loads as low as 30% of the classical loads are not uncommon. This is due to the fact that large discrepancies between theoretical prediction and experimental results had been focus of long debate in the case of compressive buckling of cylindrical shells. Among the studies by Donnell [4], Kármán and Tsien [5], Koiter [6], Donnell and Wan [7], Budiansky and Hutchinson [8], Tennyson and Muggeridge [9], Esslinger and Geier [10], Calladine [11] and Yamaki [12], Kármán and Tsien [5] particularly carried out the pioneering work on the large deflection analysis of cylindrical shells under axial compression which revealed for the first time the highly unstable postbuckling behavior of such shells. This unstable behavior indicated that the load which can be sustained in a slightly deformed configuration is well below the classical buckling load; but their study did not explain why

---

* Corresponding author at: State Key Laboratory of Mechanical System and Vibration, Shanghai Key Lab of Digital Manufacture for Thin-Walled Structures, School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai 200240, PR China. Tel.: +86 21 34206542; fax: +86 21 34204542.

E-mail address: zmli@sjtu.edu.cn (Z.-M. Li).

http://dx.doi.org/10.1016/j.compstruct.2014.09.039
0263-8223/© 2014 Elsevier Ltd. All rights reserved.

the applied load cannot reach the classical buckling. The next step in the study of the stability of cylindrical shells was made when Donnell and Wan [7] introduced in 1950 an initial imperfection into the buckling analysis. They showed that the initial imperfections can reduce appreciably the maximum load that an axially compressed cylinder can support. The next investigations supported the view that the discrepancy between the linear stability theory and test results was mainly due to the presence of initial geometric and loading imperfections. Another approach was developed by Koiter [6] for studying the effect of imperfections on shell buckling. This study represented the general initial postbuckling theory first developed by Koiter [6]. However, with the analytical means available at that time, these equations were no more accessible to computation than the well-established linearized buckling equations. As a consequence, applications of Koiter's general theory remained also restricted to problems with a linear prebuckling state. The aforementioned theories used in these analyses are mostly extensions of the various isotropic models.

Buckling of laminated composite structures is intensively studied as evidenced by a large number of articles being published in the recent years. These studies indicated that for composite structures the buckling analysis is more complex than that of their metallic counterparts due to the anisotropic nature of considered materials. Based on the Koiter's theory, Arciniega et al. [13] used the Rayleigh–Ritz method to investigate the buckling and postbuckling behavior of laminated cylindrical shells under axial compression and lateral pressure loading. Many works have focused on the default modeling related to real source of imperfections, such as the mean-line deviations, ply waviness and winding patterns, as studied, for example, in [14–18]. Messager [14] investigated numerically the influence of the winding-induced geometrical imperfection on the elastic buckling load of submersible composite hulls based on the linear Sanders-type buckling model of laminated shells. The effects of imperfection were taken into account by correcting the laminated stiffness coefficients. Han and Simitses [15] investigated the buckling behavior of symmetric laminated composite cylindrical shell subjected to lateral or hydrostatic pressure. Degenhardt et al. [16] focused on the experimental activities within these projects performed at the buckling test facility of the Institute of Composite Structures and Adaptive Systems (DLR) and gave an overview about the DLR buckling, postbuckling and collapse experimental results as well as the working of the buckling test facility and the advanced measurement systems. Hur et al. [17] investigated the buckling and postbuckling behavior and failure of composite cylinders subjected to external hydrostatic pressure using the finite element method and experiment. Tafreshi and Bailey [18] carried out investigation into the response of composite cylindrical shells subjected to combined loading by using the nonlinear finite element analysis. Their results showed that the buckling and nonlinear response of geometrically imperfect shell structures subjected to complex loading conditions might not be characterized correctly by an elastic linear bifurcation buckling analysis. Furthermore, Adali et al. [19] investigated the minimum sensitivity of buckling load for the laminated cylindrical shell of finite length under combined loads to variations in ply angles. The design variable was taken as the fiber orientation of individual layers. The general theory of laminated plates was employed to determine the buckling loads. The results showed that the minimum sensitivity design depends on the constraint on buckling load. Messager et al. [20] presented a design and analysis methodology for the optimal laminations of thin-walled laminated composite vessels for deep-water marine applications and carried out the experiments and nonlinear finite element analyses for stress and buckling of composite pressure vessels. Moreover, Teng [21] provided a review of research advances and trends in the area of thin shell buckling. Riks [22] pointed out that the perturbation method and the continuation method are the two most popular techniques for the solution of finite element equations that describe instability phenomena. He summarized the principle involved and described some trends in the development of these techniques. However, in the above studies, the shell theories used in these analyses are mostly the extensions of various isotropic shell models and these models are limited to orthotropic and/or symmetric laminates in their usage in buckling analysis without considering anisotropic coupling responses.

Since the laminated composite cylindrical shells generally exhibit the extension/twist and flexural/twist couplings when the fiber orientations do not lie parallel to the cylindrical axis or in a circumferential plane [23,24], the traditional double Fourier expansion of the transverse displacement [25,26], like $\bar{W} = A\sin(m\pi X/L)\sin(nY/R)$ or $\bar{W} = A\sin(m\pi X/L)\cos(nY/R)$ which is suitable for the cross-ply laminated cylindrical shells, is no longer capable of solving the asymmetric spiral buckling modes. On the other hand, Shen and Chen [27,28] found that in shell buckling there exists a boundary layer phenomenon where the prebuckling and buckling displacements vary rapidly. They developed a boundary layer theory of shell buckling, in contrast with the previous nonlinear shell buckling theory, for which the effects of nonlinear prebuckling deformations, large deflections in the postbuckling range, and initial geometric imperfections of the shell are accounted for. Based on this theory, postbuckling analyses for perfect and imperfect, isotropic and laminated cylindrical shells under various loading cases were performed by Shen [29–33] and Shen and Xiang [34]. To the best of the authors' knowledge, there is no literature covering the postbuckling response of anisotropic laminated thin cylindrical shells subjected to combined loading of external pressure and axial compression.

The present study extends the previous work to the case of anisotropic laminated thin cylindrical shells under combined external pressure and axial compression in thermal environments. The material of each layer of the shell is assumed to be linearly elastic, anisotropic and fiber-reinforced. The material properties of the composite are affected by the variation of temperature. The governing equations are based on the Donnell shell theory and strain–displacement relationship of von Kármán–Donnell type. The nonlinear prebuckling deformations and initial geometric imperfections of the shell including the extension/shear, extension/flexural and flexural/twist couplings are both taken into account, and for simplicity, the form of initial geometric imperfection is assumed to be the same as the initial buckling mode of the shell. A singular perturbation technique is employed to determine the buckling loads and postbuckling equilibrium paths. The numerical illustrations show the full nonlinear postbuckling response of anisotropic laminated composite cylindrical shells under combined axial compression and external pressure in thermal environments.

2. Theoretical development

The mean radius, length and total thickness of circular cylindrical shell studied in this paper are designated as R, L and h, which consists of N plies of any kind. The shell is referred to a coordinate system (X, Y, Z), in which X and Y are in the axial and circumferential directions of the shell and Z is in the direction of the inward normal to the middle surface (see Fig. 1). Let $\bar{U}$, $\bar{V}$ and $\bar{W}$ be the corresponding displacements. The origin of the coordinate system is located at the end of the shell. Denoting the initial deflection by $\bar{W}^*(X, Y)$, let $\bar{W}(X, Y)$ as the additional deflection and $\bar{F}(X, Y)$ as the stress function for the stress resultants defined by $\bar{N}_X = \bar{F}_{,YY}$, $\bar{N}_Y = \bar{F}_{,XX}$ and $\bar{N}_{XY} = -\bar{F}_{,XY}$, where a comma denotes the partial differentiation with respect to the corresponding coordinates.

Download English Version:

https://daneshyari.com/en/article/251512

Download Persian Version:

https://daneshyari.com/article/251512

Daneshyari.com