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Non-linear analysis of fiber-reinforced open conical shell panels considering variation of thickness and fiber orientation under thermo-mechanical loadings

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ABSTRACT

Non-linear bending analysis of moderately thick laminated conical panels under various thermo-mechanical loadings and boundary conditions is presented using the generalized differential quadrature (GDQ) method together with the Newton–Raphson iterative scheme. The stiffness coefficients are assumed to be functions of the meridional and circumferential coordinates in panels for the realistic applications. In the first case of orthotropic open conical shell panels, the orientation of fibers are assumed to be in the meridional and circumferential directions. The stiffness coefficients of this type of fiber-reinforced panel are usually assumed to be constant. It is shown that due to the geometry of the conical surface, thickness of laminate will be changed along the meridional direction. The effect of stiffness variation on the non-linear response of panel is considered for the first time. In the second type, open conical shell panel can be made by cutting from a filament wound circular conical shell. In this case, thickness and ply orientation are functions of the shell coordinates. In this paper, different path definitions for variable stiffness filament wound shells are considered. The inclusion of this geometric complicating effect in large deformation analysis will add considerably to the complication and cost of a solution scheme. Paper presents some results to show when these assumptions have a significant effect on the end result. Assuming the effects of shear deformation and initial curvature, based on the first-order shear deformation theory (FSDT) and von Kármán-type of geometric non-linearity, the governing system of equations is obtained. Comparisons of the predictions with those available in the literature and finite element analyses show very good agreement. More results for panels with particular boundary conditions and thermo-mechanical load are presented for future references. For the sake of brevity, numerical results which presented in this paper are limited to deflection responses only.

1. Introduction

Fiber reinforced shell panels are widely used in various engineering applications such as aeronautic, naval and civil engineering structures. Due to enhanced strength-to-weight ratio, in the past decades, much research has been done on problems of composite shells and panels. In recent years, large deformation and stress analysis of these composite plates and panels has been the subject of many researches. Several works about non-linear thermo-mechanical analysis of laminated panels can be seen in the literature.

It is well-known that analytical methods are only applicable to very specific group of issues. Thus, numerical techniques, as alternatives to analytical approaches, have been developed to obtain solutions for different structural components subjected to various types of loading and boundary conditions. Among these numerical methods, the finite element method (FEM) has been widely used for non-linear analysis of laminated plates and panels [1–7]. Kim and Lee [1] developed a solid element to model the behavior of laminated composite shells undergoing large deformation. Huang and Taucher [2] employed the finite element technique based on the first-order shear deformation theory to predict thermally-induced large-deflection behaviors of laminates, including flat plates and cylindrical and doubly-curved panels. Barut et al. [3] investigated the response of moderately thick laminated panels experiencing large displacements and rotations under non-uniform thermal loading through a non-linear finite element analysis. Naidu and Sinha [4] investigated large deflection bending behavior of composite cylindrical shell panels subjected to hygrothermal environments. Kreja and Schmidt [5] derived a finite element formulation of composite laminated shells undergoing large rotations based on the use of the Euler angles in the framework of the first-order transverse shear deformation hypothesis. Kundu et al.

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[6] presented geometrically non-linear analysis of laminated doubly-curved shells in a hygrothermal environment using the finite element method. Han et al. [7], using a modified first-order shear deformable element-based Lagrangian shell element, studied bending of geometrically non-linear thin plates and shells. Maleki and Tahani [8] employed the generalized differential quadrature as another numerical method for non-linear analysis of moderately thick laminated plates and cylindrical shell panels under thermomechanical loads.

In the case of fiber-reinforced conical shell panels, according to method of production, the thickness and material properties vary with the shell coordinates. The literature on the variable stiffness conical panels is scarce. This is mainly due to the inherent complexity of the basic equations in curvilinear conical coordinates.

In most researches published in the literature about conical shells and panels, it is assumed that fibers are laid out in the meridional and circumferential directions [9–26]. Maleki et al. [9] studied bending analysis of moderately thick laminated open conical shell panels with various boundary conditions. Srinivasan and Krishnan [10] investigated dynamic response of layered conical shell panel using integral equation technique. Bhaskar and Vardan [11] presented a higher order theory for bending analysis of laminated open conical shells. Also, Pinto Coriera et al. [12] analyzed conical shell panel structures using higher-order models. Thermal buckling analysis of laminated conical shell/panel embedded with and without piezoelectric layer subjected to uniform temperature rise based on a higher-order shear deformation theory was studied using the finite element method by Singh and Babu [13]. There are some other publications about circular conical shell [14–22]. Non-linear analysis of conical panels is considered by some investigators [23–26]. Roh et al. [23] used the finite element method to study thermal post buckling and vibration characteristics of composite open conical shell panels. Kundu and Han [24] also used the finite element method in non-linear buckling analysis of hygrothermoelastic composite shell panels. Non-linear static response of laminated conical panels subjected to mechanical and thermal loadings was presented by Joshi and Patel [25]. Gupta et al. [26] investigated static response and failure load of laminated composite shallow cylindrical and conical panels subjected to internal and external pressure. Fig. 1 shows that for a conical panel in the meridional fiber-reinforced layers the distance between the fibers changes along the meridional coordinate. Therefore, for this

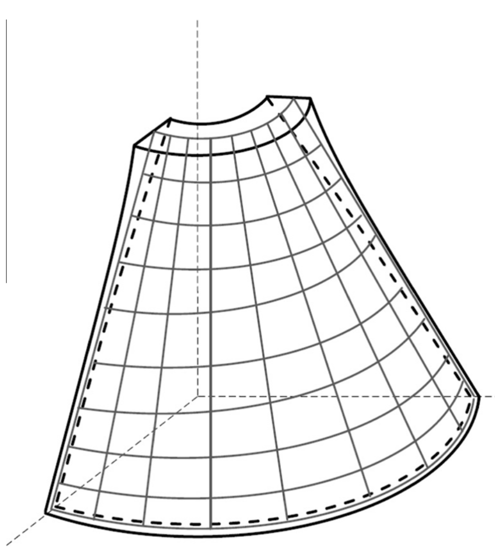

Fig. 1. Meridional and circumferential fiber-reinforced open conical shell panel.

type of lamina the material characteristics of macrostructure and hence the stiffness coefficients of lamina cannot be kept constant. It should be noted that in the mentioned papers variation of stiffness in the meridional direction was not considered. Therefore, the previous investigations which assumed constant stiffness for fiber-reinforced conical panels in the meridional direction are not applicable for all types of fiber-reinforced conical panels and may cover just some special cases.

As another case, an open conical shell panel can be a cut of filament wound circular conical shell. Filament winding is one of the most widely used methods for manufacturing tubular composite structures. In this method, fibers can be wound over a mandrel along different trajectories which have one requirement in common: they must be stable and hence slip free [27]. Geodesic paths which are shortest curve connecting two points on a surface are the best known fiber trajectories. In such a manner fiber will not tend to move or slip when being pulled. In the presence of friction, stable non-geodesic or semi-geodesic winding is possible. Baruch et al. [28] obtained variations of the stiffness coefficients of geodesic and semi-geodesic filament wound conical shells. Goldfeld and Arbocz [29], considered variation of the stiffness coefficients in buckling analysis of filament wound circular conical shell. Also, Goldfeld et al. [30–33] studied linear and non-linear buckling of circular conical shells given the variation of stiffness coefficients. Patel et al. [34] investigated postbuckling charactristics of angle-ply laminated composite circular conical shells subjected to thermo mechanical loadings. Blom et al. [35] optimized maximum fundamental frequency of fiber-reinforced composite conical shell. They presented four different geodesic and constant curvature paths for fibers. The shells are assumed to be built using an advanced tow-placement machine, which allows in-plane steering of the fibers, resulting in a variable-stiffness structure.

It is intended here to consider the practical forms of fiber-reinforced open conical shell panels. The non-linear governing equations are derived in conical curvilinear coordinate system (meridional, circumferential and normal directions). Three types of fiber-reinforced conical shell panel are considered. Variation of fiber angle and thickness of panel due to manufacturing constraints in all cases are considered. Therefore, the present work studies fiber-reinforced open conical shell panels by considering variation of the stiffness coefficients and their dependence on the shell's coordinate. Conical panels with different lay-ups and any combinations of clamped, simply supported and free boundary conditions are solved. In this study, the accuracy and convergence of the GDQ method together with the Newton–Raphson iterative scheme in large deformation analysis of variable stiffness thin/moderately thick open conical shell panels with various lay-ups subjected to different thermo-mechanical loadings and boundary conditions are investigated.

Both governing equations and solution domain are discretized based on the GDQ method. The GDQ discretization converts the system of non-linear partial differential equations to a system of non-linear algebraic equations. Efficiency of the GDQ in terms of accuracy and convergence of the method to provide solutions for various displacements and stress components of laminated cylindrical panels is shown by several examples. The results obtained from this method are compared with those available in the literature and finite element method.

2. Governing equations

A laminated composite conical panel with length a, minor radius R_t, major radius R_b, conic angle α, revolving angle β and total thickness h is considered as shown in Fig. 2. The curvilinear coordinate system is located on the mid-surface of the laminate in