Ocean Engineering 145 (2017) 268–276

Contents lists available at ScienceDirect

Ocean Engineering

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

Optimal design of variable stiffness laminated composite truncated cones under lateral external pressure

Izzet U. Cagdas[1]

Civil Engineering Department, Faculty of Engineering, Akdeniz University, 07058, Antalya, Turkey

ARTICLE INFO

Keywords:
Cone
Buckling
Pressure stiffness
Finite elements
Design optimization

ABSTRACT

The purpose of this paper is to present optimal designs for variable stiffness laminated composite truncated cones under lateral external pressure. The objective is to maximize the failure load which is defined as the minimum of the buckling load and the first-ply failure (*FPF*) load. The numerical results are obtained using a semi-analytical degenerated shell element based on a refined first-order shear deformable shell theory and the influences of the pressure stiffness (*PS*) and the thickness/radius ratio are taken into account. A 2D degenerated shell element is also used for verification purposes. Results are presented for the related verification problems solved and the semi-analytical shell element is validated. Optimal designs, where *FPF* and buckling are imposed as design constraints, are presented for laminated composite thin and relatively thick cones having variable thickness and ply-angle. A simple graphical optimization technique and a modified Micro-Genetic Algorithm are employed. It is shown that, *FPF* constraint may be active for thicker cones having lower cone angles, *PS* slightly decreases the buckling pressures, and the stacking sequence has considerable influence on the failure load. The numerical results presented show that restraining the large end against rotation significantly increases the failure load.

1. Introduction

In this study, optimal designs for variable stiffness laminated composite truncated cones under external pressure are presented. The influence of pressure stiffness (*PS*) on buckling is considered and the first-ply failure (*FPF*) pressure is also taken as a design constraint.

Buckling behavior of truncated cones has been studied extensively and there is a vast literature on this subject. One of the most comprehensive studies was performed by Weingarten and Seide (1968) who prepared the NASA-SP8019 monograph in 1968, which includes analytical formulas for orthotropic cones under external pressure. A correlation coefficient of 0.75, which is relatively larger than the coefficients for cylinders, has been proposed. This monograph was later improved by Nemeth and Starnes (1998), who considered the effect of imperfections. In more recent related studies, Naj et al. (2008) studied thermal and mechanical instability of functionally graded truncated conical shells and Ajdar et al. (2012) derived analytical expressions for truncated composite cones under combined external pressure and axial compression. Jalili et al. (2014) conducted experiments and investigated the buckling behavior of constant thickness composite conical shells under dynamic hydrostatic pressure.

The above cited theoretical and experimental studies provide valuable information on the problem. However, in practice, cone thickness and ply angles are not uniform as filament winding technique is generally used for manufacturing, which further complicates the design problem. As stated by Goldfeld and Arbocz (2004), Goldfeld et al. (2005), Patel et al. (2008), Blom et al. (2009), and Goldfeld (2009) for the continuous fiber wound angle-ply laminated conical shells, the ply angles and the thickness vary along the axial direction. Considering this complicating factor, Goldfeld (2007) and Goldfeld et al. (2003) studied the imperfection sensitivity of laminated conical shells under axial compression and external pressure and stated that there is a need to use accurate shell theories in order to calculate lower buckling loads and to eventually have less sensitivity to imperfections. In a related study, Naderi et al. (2014) studied the influence of fiber paths on buckling loads of laminated cones under axial compression. Maleki and Tahani (2013) considered variable thickness conical shell panels under thermo-mechanical loads and concluded that the constant thickness assumption is not correct and causes significant errors.

A limited number of design/optimization studies are also found in the literature. One of the earliest optimization studies on laminated composite cones was conducted by Brown and Nachlas (1985), who

E-mail address: izzetufuk@gmail.com.
[1] Honorary Researcher: School of Mechanical Engineering, University of KwaZulu-Natal, Durban, South Africa.

http://dx.doi.org/10.1016/j.oceaneng.2017.09.011
Received 10 November 2016; Received in revised form 27 August 2017; Accepted 11 September 2017
Available online 9 October 2017

obtained the optimal ply angles maximizing strength. Goldfeld et al. (2005) obtained optimal lamination angles for variable thickness laminated cones using response surface method and revealed that the assumption of nominal stiffness properties in the calculation of the buckling load is not valid. Goldfeld et al. (2005) studied optimization of variable stiffness cones against buckling. Kabir and Shirazi (2008) obtained optimal laminate configurations for filament wound laminated cones under axial compression using the penalty function method. Blom et al. (2008) optimized laminated cones for maximum fundamental frequency considering manufacturing constraints. In a recent study, Cagdas (2017) studied optimal design of filament wound conical adapters under axial compression. As can be seen from this survey so far, *FPF* and the influence of *PS* have, in general, not been taken into account in the related design/optimization studies.

In the present study, it is aimed to improve the above cited optimization studies by using *FPF* as a constraint and by using an accurate semi-analytical shell element including *PS*. Also, a relatively new optimization technique called Micro-Genetic Algorithms (MicroGA) is employed and the optimization results are compared with the results obtained using a simple graphical optimization strategy based on engineering intuition. Genetic Algorithms, first developed by Holland (1975) have been successfully applied to optimal structural design; see Gürdal et al. (1999). However, the technique is computationally costly and therefore a semi-analytical element is used in this study and a 2D shell element is used for verification purposes.

As stated above, the numerical results presented are obtained using two different degenerated, curved, and first order shear deformable shell finite elements; a semi-analytical element, developed by Cagdas and Adali (2011) and Cagdas (2011) and a 2D element, developed by Cagdas and Adali (2013), which is based on a refined shell element developed by Mallikarjuna and Kant (1992). The semi-analytical element has been developed by Cagdas (2011) specifically for stability analysis and generally yields slightly more accurate results than the 2D shell element while the computational time is much lower. The related refined first order shear deformable shell theory, where the thickness/radius ratio is taken into account, was developed by Leissa and Chang (1996) and Qatu (1999, 2004). The present study is the first application of the refined shell theory for stability analysis of laminated composite shells of revolution considering *PS* other than cylinders and for *FPF* analysis of laminated composite shells of revolution.

The literature on the influence of *PS* is not very extensive. *PS* was first considered for circular cylindrical isotropic shells under hydrostatic pressure by Koiter (1967) and Hibbitt (1979) described the pressure related stiffness terms as “pressure stiffness” terms. Loganathan et al. (1979) and Subbiah and Natarajan (1980), Kasagi and Srinivasan (1995), Schokker et al. (1996) Sridharan and Kasagi (1997) and Kardomateas (1997) have also considered this effect by using the work of Koiter (1967) and have reported substantial reductions in buckling loads due to *PS*. Jha and Inman (2004) investigated the influence of follower pressure load in the dynamic analysis of inflated structures by making use of Koiter's expression. In a more recent study, Cagdas and Adali (2011) investigated the influence of hydrostatic pressure on the stability of cross-ply laminated cylinders and obtained very accurate numerical results, which are in very good agreement with the analytical results found in the literature.

The inclusion of the *PS* effect in the finite element formulation, in general, results in non-symmetric matrices but, as stated by Koiter (1967), the resulting matrices are symmetric for shells of revolution and therefore no special solution procedure for the eigenvalue problem is required. However, a block iterative eigenvalue solver with Gram-Schmidt orthogonalization based on the Arnoldi Method developed by Arnoldi (1951) capable of solving non-symmetric eigenvalue problems is employed in computations.

Some of the important studies on *FPF* of thin shells were conducted by Prusty et al. (2001), who studied *FPF* of curved panels and Bakshi and Chakravorthy (2014), who considered *FPF* of conoidal shells. In the present study, first-ply failure (*FPF*) is taken into account and used as a constraint in the design problem. Note that, a frontal equation solver, defined by Hinton and Owen (1977), is employed for stress analysis using the 2D shell element.

An optimization study is performed and the optimal lamination parameters are determined for some selected cases. Also, the influence of the rotational boundary conditions is investigated.

2. Structural analysis procedure

As stated in the introduction section, the numerical results presented here are obtained using a degenerated, curved, and first order shear deformable semi-analytical shell finite element developed by Cagdas (2011). Also, a 2D element developed by Cagdas and Adali (2013) is used here to validate the semi-analytical element for *FPF* analysis and stability analysis considering *PS*. Brief formulation of the semi-analytical shell finite element used here is given next.

2.1. Static analysis

A linear static analysis is performed to obtain the stress distribution for *FPF* analysis and for linearized stability analysis.

2.1.1. Element geometry and the displacement field

The semi-analytical shell finite element is schematically shown in Fig. 1, where u_r, u_θ, and u_z denote the radial, circumferential, and axial displacement components, respectively and ψ_α, and ψ_θ are the rotations of the transverse normal about θ and α axes. Even though symmetrical loading is considered in the present study, the buckling mode shape is most probably not symmetrical and therefore the element has two rotational degrees of freedom. φ_{GP} is the angle between unit vectors $\mathbf{e}_r$ and $\mathbf{e}_{z'}$ at a Gauss point. A local coordinate system ($\alpha\theta z'$) is defined at a Gauss point on the mid-surface of the shell of revolution where u, v, and w denote the displacements parallel to α, θ, and z' coordinates and ψ_α, and ψ_θ are the rotations of the transverse normal about θ and α axes. The local coordinate system is obtained by interpolation from the element nodes. The lamination angle is taken as the angle between the fiber direction and the local α axis.

The element is based on the following displacement field;

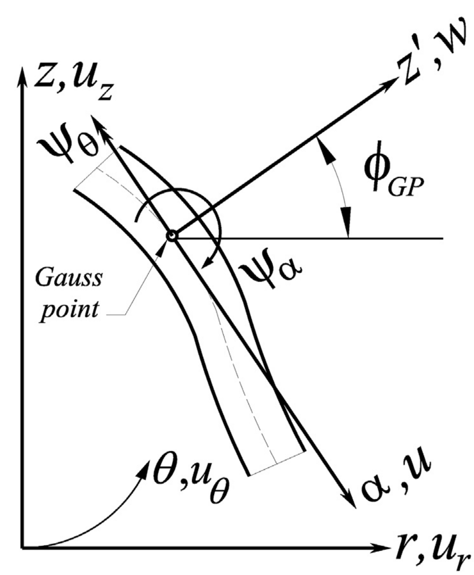

Fig. 1. Cross section of the curved semi-analytical shell element and the displacement components at a Gauss point.