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Buckling optimization of laminated truncated conical shells subjected to external hydrostatic compression

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ABSTRACT

Buckling analyses of laminated truncated conical shells subjected to external hydrostatic compression are carried out by employing the Abaqus finite element program. The critical buckling loads of these truncated conical shells with a given material system are maximized with respect to fiber orientations by using the golden section method. Through parametric studies, the influences of the end condition, shell thickness, shell length, shell radius ratio and cutout size on the optimal buckling loads, the associated optimal fiber orientations and the associated buckling modes are demonstrated and discussed.

1. Introduction

The applications of fiber reinforced composite laminated materials in offshore and marine industries have increased rapidly in recent years. These composite structures are commonly subjected to compression in service, which may cause buckling problems [1–10]. The truncated conical shell structures are widely used in offshore platforms, pipelines, submarines and underwater vehicles, which may be subjected to hydrostatic compression. Hence, the buckling of laminated truncated conical shells under hydrostatic compression is of current interest to engineers engaged in offshore and marine engineering practices.

The buckling resistance of laminated truncated conical shells highly depends on end conditions, ply orientations [11–23], and geometric variables such as shell thicknesses, shell lengths, shell radius ratios, cutouts [11,12,14–30] and stiffeners [31–35]. Therefore, for laminated truncated conical shells with a given material system, geometric shape and end condition, the proper selection of appropriate lamination to realize the maximum buckling resistance of the truncated conical shells becomes a crucial problem [36–42]. However, up to present, most optimization works on conical shells have been focused on isotropic materials [43,44] and very few concentrated on laminated materials [41].

Structural optimizations have been popular research areas [45] and lots of them have been focused on laminated materials [46]. There are many optimization methods available today, such as sequential linear programming [37,38,40,42], nonlinear programming [47,48] and reliability-based optimization method [49–52]. Among them, the golden section method [47,48] is simple, efficient and has been successfully applied to many engineering problems. Hence, it is selected in this investigation to perform optimization analyses for the composite truncated conical shells.

In this investigation, optimization of fiber-reinforced laminated truncated conical shells to maximize their critical buckling loads with respect to fiber orientations is performed by using the golden section method. The critical buckling loads of the laminated truncated conical shells are calculated by the bifurcation buckling analysis implemented in the Abaqus finite element program [53]. In the paper, the constitutive equations for fiber-composite laminate, bifurcation buckling analysis and golden section method are briefly reviewed. Then the influences of the end condition, shell thickness, shell length, shell radius ratio and cutout on the optimal buckling loads, the associated optimal fiber orientations and the associated buckling modes of laminated truncated conical shells are presented. Finally, important conclusions obtained from this study are given.

2. Constitutive matrix for fiber-composite laminae

In the finite element analysis, the laminated truncated conical

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shells are modeled by eight-node isoparametric shell elements. For each node, there are three degrees of freedom for displacements and three for rotations. The reduced integration rule together with hourglass stiffness control is employed to formulate the element stiffness matrix [53].

The stress-strain relations for a lamina in the material coordinate (1,2,3) (Fig. 1) can be written as

$$\{\sigma'\} = [Q_1']\{\varepsilon'\}, \quad [Q_1'] = \begin{bmatrix} \dfrac{E_{11}}{1-\nu_{12}\nu_{21}} & \dfrac{\nu_{12}E_{22}}{1-\nu_{12}\nu_{21}} & 0 \\ \dfrac{\nu_{21}E_{11}}{1-\nu_{12}\nu_{21}} & \dfrac{E_{22}}{1-\nu_{12}\nu_{21}} & 0 \\ 0 & 0 & G_{12} \end{bmatrix} \tag{1}$$

$$\{\tau'\} = [Q_2']\{\gamma'\}, \quad [Q_2'] = \begin{bmatrix} \alpha_1 G_{13} & 0 \\ 0 & \alpha_2 G_{23} \end{bmatrix} \tag{2}$$

where $\{\sigma'\} = \{\sigma_1, \sigma_2, \tau_{12}\}^T$, $\{\tau'\} = \{\tau_{13}, \tau_{23}\}^T$, $\{\varepsilon'\} = \{\varepsilon_1, \varepsilon_2, \gamma_{12}\}^T$, $\{\gamma'\} = \{\gamma_{13}, \gamma_{23}\}^T$. The α_1 and α_2 in Eq. (2) are shear correction factors, which are calculated in Abaqus by assuming that the transverse shear energy through the thickness of laminate is equal to that in unidirectional bending [53,54].

The constitutive equations for the lamina in the element coordinate (x,y,z) (Fig. 1) then become

$$\{\sigma\} = [Q_1]\{\varepsilon\}, \quad [Q_1] = [T_1]^T [Q_1'][T_1] \tag{3}$$

$$\{\tau\} = [Q_2]\{\gamma\}, \quad [Q_2] = [T_2]^T [Q_2'][T_2] \tag{4}$$

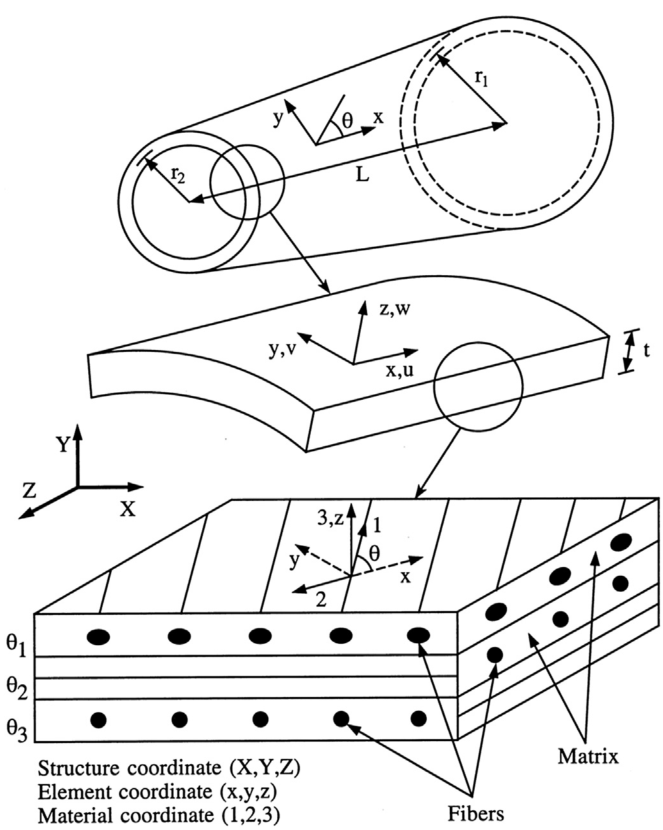

Fig. 1. Material, element and structure coordinates of laminated truncated conical shells.

$$[T_1] = \begin{bmatrix} \cos^2\theta & \sin^2\theta & \sin\theta\cos\theta \\ \sin^2\theta & \cos^2\theta & -\sin\theta\cos\theta \\ -2\sin\theta\cos\theta & 2\sin\theta\cos\theta & \cos^2\theta - \sin^2\theta \end{bmatrix}, \quad [T_2] = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \tag{5}$$

where $\{\sigma\} = \{\sigma_x, \sigma_y, \tau_{xy}\}^T$, $\{\tau\} = \{\tau_{xz}, \tau_{yz}\}^T$, $\{\varepsilon\} = \{\varepsilon_x, \varepsilon_y, \gamma_{xy}\}^T$, $\{\gamma\} = \{\gamma_{xz}, \gamma_{yz}\}^T$ and θ is measured counterclockwise about the z axis from the element local x-axis to the material 1-axis. While the element x axis is in the longitudinal direction of the truncated conical shell, element y and z axes are in the circumferential and the radial directions of the truncated conical shell. Let $\{\varepsilon_o\} = \{\varepsilon_{xo}, \varepsilon_{yo}, \gamma_{xyo}\}^T$ be the in-plane strains at the mid-surface of the laminate section, $\{\kappa\} = \{\kappa_x, \kappa_y, \kappa_{xy}\}^T$ the curvatures, and h the total thickness of the section. If there are n layers in the layup, the stress resultants, $\{N\} = \{N_x, N_y, N_{xy}\}^T$, $\{M\} = \{M_x, M_y, M_{xy}\}^T$ and $\{V\} = \{V_x, V_y\}^T$, can be defined as

$$\begin{Bmatrix} \{N\} \\ \{M\} \\ \{V\} \end{Bmatrix} = \int_{-h/2}^{h/2} \begin{Bmatrix} \{\sigma\} \\ z\{\sigma\} \\ \{\tau\} \end{Bmatrix} dz = \int_{j=1}^{n} \begin{bmatrix} \left(z_{jt}-z_{jb}\right)[Q_1] & \frac{1}{2}\left(z_{jt}^2-z_{jb}^2\right)[Q_1] & [0] \\ \frac{1}{2}\left(z_{jt}^2-z_{jb}^2\right)[Q_1] & \frac{1}{3}\left(z_{jt}^3-z_{jb}^3\right)[Q_1] & [0] \\ [0]^T & [0]^T & \left(z_{jt}-z_{jb}\right)[Q_2] \end{bmatrix} \times \begin{Bmatrix} \{\varepsilon_o\} \\ \{\kappa\} \\ \{\gamma\} \end{Bmatrix} \tag{6}$$

where z_{jt} and z_{jb} are the distance from the mid-surface of the section to the top and the bottom of the j-th layer respectively. The [0] is a 3 by 2 matrix with all the coefficients equal to zero.

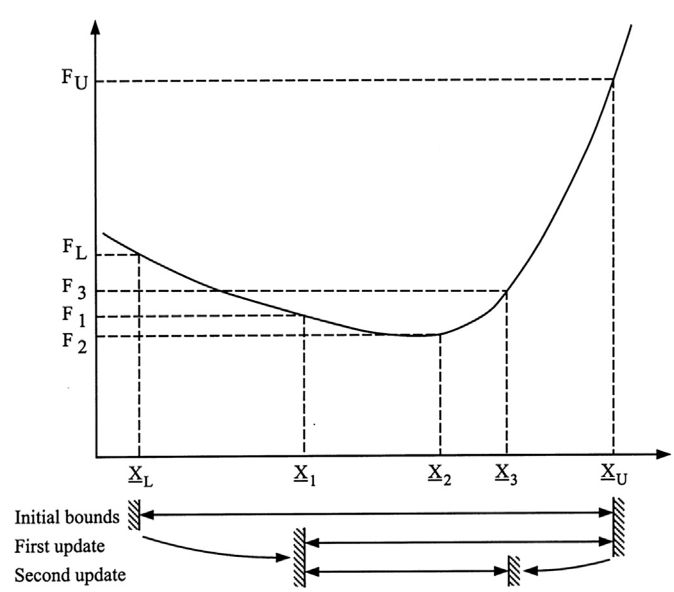

Fig. 2. The golden section method.