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Mathematical Formulation of Laminated Composite Thick Conical Shells

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Abstract

The mathematical formulation of thick conical shells using third order shear deformation of thick shell theory are presented. The equations of motion are obtained using Hamilton's principle. For present analysis, we consider shell's system transverse normal stress, rotary inertia and shear deformation.

Keywords: Conical Shell, free vibrations, third order shear deformation thick shell theory, Equations of Motion, Lame' parameters.

1. Introduction

Many research articles investigated the theory of thick conical shells including (Qatu *et al*., 2013; Qatu et *al*., 2010). The vibration behavior of cantilevered laminated composite shallow conical shells were also explored recently (Korjakin et *al*.; Qatu et *al*., 2010; Mukhopadhyay et *al*., 2016). (Further, Reddy, 1984) explored vibrations of joined conical shells. Qatu (1994) carried out research about the steady-state torsional oscillations of multilayer truncated cones. The damping of the free vibrations of laminated composite conical shells was investigated by Qatu (1994) and while stiffened conical shells were studies by Reddy, (1984). A variable thickness of composite conical shells was discussed (Asadi & Qatu, 2012; Leissa & Qatu, 2011). Damping in multilayered conical shells was investigated by many researchers (Zannon and Qatu, 2014b). Pre-stressed conical shells were explored thoroughly by Qatu et *al.* (2014, 2015).

Towards this end, in this paper, we propose our contribution towards the mathematical theory of third order shear deformation thick conical shell theory (see Zannon et *al.* (TSDTZ); Qatu *et al*., 2013) and its stress-strain deformation at the mid thick conical shell surface (Duc & Cong, 2015; Akbari et *al*., 2015; Jam & Kiani, 2015, Viola et *al*., 2016).

2. Mathematical Formulation of Conical Shell

The displacement components using the third-order shear deformation shell theory are given in (Asadi & Qatu, 2012; Leissa & Qatu, 2011). Conical shells are one form of engineering solids that are formed by revolving two non-paralleled lines, mostly a line and axis of revolution. We are interested mainly in a particular type of shells which have a circular cross-section (Qatu, 1994).

A closed conical shell with circular sides (Figure 2.1) has a closed shape and the open conical shell can be obtained by cutting the sides of the solid between θ_1 *and* θ_2 (Roh et *al*, 2008). An open conical shell with sides less than the half of the radius of the curvature then the solid is shallow (Qatu et *al.*, 2010; Dung et *al.*, 2014).

A typical fundamental equation of such solid can be written as (with the help of Lame parameters) (Qatu et *al.*, 2010; Dung et *al*., 2014; Jam & Kiani, 2015; Akbari et *al*., 2015)

$$(ds)^2 = (d\alpha)^2 + \alpha^2 \sin^2(\varphi)\, \mathrm{d}\theta,$$
$$A = 1;\ B = \alpha \sin(\varphi),$$
$$R_\alpha = \infty;\ R_\beta = \alpha \tan(\varphi).$$

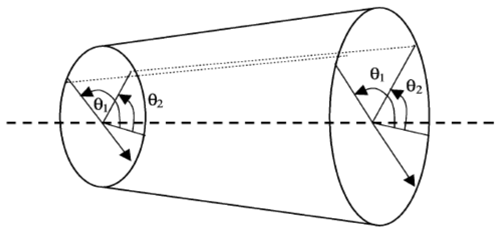

Figure 2.1 A closed coincal shell (Qatu, 1994)

Consider Figure 2.2, which is a side view of the closed conical shell described in Figure 2.1.

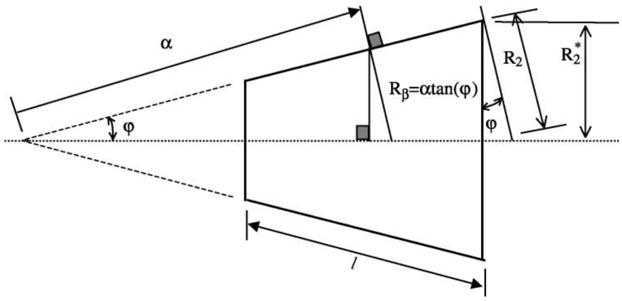

Figure 2.2 A a side view of the closed coincal shell (Qatu, 1994)

3. Equilibrium Equations of Motion

A conical laminated shell with Lame parameters is considered above. The Lame' parameters of middle surface are substituted in moment and force resultants (see Zannon et al, 2015) to formulate the conical shell equations for TSDTZ. Therefore, the strain-displacement equations and middle surface strains are obtained (Qatu et *al.*, 2010; Dung et *al.*, 2014; Jam & Kiani, 2015; Akbari et *al.*, 2015)

$$\varepsilon_{\alpha}=\varepsilon_{0\alpha}+z\kappa_{\alpha}^{(1)}+z^{2}\kappa_{\alpha}^{(2)},$$

$$\varepsilon_{\theta}=\frac{1}{(1+z/\alpha\tan(\varphi))}(\varepsilon_{0\theta}+z\kappa_{\theta}^{(1)}+z^{2}\kappa_{\theta}^{(2)}),$$

$$\varepsilon_{z}=\psi_{z}(\alpha,\beta)\neq 0,$$

$$\varepsilon_{\alpha\theta}=\varepsilon_{0\alpha\theta}+z\kappa_{\alpha\theta}^{(1)}+z^{2}\kappa_{\alpha\theta}^{(2)},$$

$$\varepsilon_{\theta\alpha}=\frac{1}{(1+z/\alpha\tan(\varphi))}(\varepsilon_{0\theta\alpha}+z\kappa_{\theta\alpha}^{(1)}+z^{2}\kappa_{\theta\alpha}^{(2)}),$$

$$\gamma_{\alpha z}=\gamma_{0\alpha z}+zG^{(1)}+z^{2}G^{(2)},$$

$$\gamma_{\theta z}=\frac{1}{(1+z/\alpha\tan(\varphi))}(\gamma_{0\theta z}+zE^{(1)}+z^{2}E^{(2)}),$$

$$\varepsilon_{0\alpha}=\frac{\partial u_{0}}{\partial\alpha}$$

$$\varepsilon_{0\theta}=\frac{1}{\alpha\sin(\varphi)}\frac{\partial v_{0}}{\partial\theta}+\frac{u_{0}}{\alpha}+\frac{w_{0}}{\alpha\tan(\varphi)},$$

$$\varepsilon_{0\alpha\theta}=\frac{\partial v_{0}}{\partial\alpha},$$

$$\varepsilon_{0\theta\alpha}=\frac{1}{\alpha\sin(\varphi)}\frac{\partial u_{0}}{\partial\theta}-\frac{v_{0}}{\alpha},$$

$$\gamma_{0\alpha z}=\frac{\partial w_{0}}{\partial\alpha}+\psi_{\alpha},$$

$$\gamma_{0\theta z}=\frac{1}{\alpha\sin(\varphi)}\frac{\partial w_{0}}{\partial\theta}-\frac{v_{0}}{\alpha\tan(\varphi)}+\psi_{\beta}.$$

The curvature and twist of the conical thick shells are considered

$$\kappa_{\alpha}^{(1)} = \frac{\partial \psi_{\alpha}}{\partial \alpha},$$
$$\kappa_{\theta}^{(1)} = \frac{\partial \psi_{\beta}}{\partial \theta} + \frac{\psi_{\alpha}}{\alpha} + \frac{\psi_{z}}{\alpha \tan(\varphi)},$$
$$\kappa_{\alpha\theta}^{(1)} = \frac{\partial \psi_{\beta}}{\partial \alpha},$$
$$\kappa_{\theta\alpha}^{(1)} = \frac{1}{\alpha \sin(\varphi)} \frac{\partial \psi_{\alpha}}{\partial \theta} - \frac{\psi_{\beta}}{\alpha}.$$

$$\kappa_{\alpha}^{(2)} = \frac{\partial \phi_{\alpha}}{\partial \alpha},$$
$$\kappa_{\theta}^{(2)} = \frac{\partial \phi_{\beta}}{\partial \theta} + \frac{\phi_{\alpha}}{\alpha},$$
$$\kappa_{\alpha\theta}^{(2)} = \frac{\partial \phi_{\beta}}{\partial \alpha},$$
$$\kappa_{\theta\alpha}^{(2)} = \frac{1}{\alpha \sin(\varphi)} \frac{\partial \phi_{\alpha}}{\partial \theta} - \frac{\phi_{\beta}}{\alpha}.$$

Therefore, the equations of motion are (Qatu et *al.*, 2013; Zannon & Qatu, 2014b; Qatu et *al.*, 2010; Asadi & Qatu, 2012; Jam & Kiani, 2015; Duc & Cong, 2015; Akbari et *al.*, 2015)

$$\frac{\partial}{\partial \alpha}(\alpha \sin(\varphi) N_{\alpha}) - \sin(\varphi) N_{\theta} + \frac{\partial}{\partial \theta}(N_{\theta\alpha}) + \alpha \sin(\varphi) q_{\alpha} = \alpha \sin(\varphi)(\bar{I}_1 \ddot{u}_0 + \bar{I}_2 \ddot{\psi}_{\alpha}),$$
$$\frac{\partial}{\partial \alpha}(\alpha \sin(\varphi) N_{\alpha\theta}) + \sin(\varphi) N_{\theta\alpha} + \frac{\partial}{\partial \theta}(N_{\theta}) + \frac{\sin(\varphi)}{\tan(\varphi)} Q_{\theta} + \alpha \sin(\varphi) q_{\theta} = \alpha \sin(\varphi)(\bar{I}_1 \ddot{v}_0 + \bar{I}_2 \ddot{\psi}_{\theta}),$$
$$\frac{\partial}{\partial \alpha}(\alpha \sin(\varphi) Q_{\alpha}) + \frac{\partial}{\partial \theta} Q_{\theta} - \alpha \sin(\varphi)\left(\frac{N_{\theta}}{\alpha \tan(\varphi)}\right) + \alpha \sin(\varphi) q_{n} = \alpha \sin(\varphi)(\bar{I}_1 \ddot{w}_0),$$
$$\frac{\partial}{\partial \alpha}(\alpha \sin(\varphi) M_{\alpha}^{(1)}) - \sin(\varphi) M_{\theta}^{(1)} + \frac{\partial}{\partial \theta}(M_{\theta\alpha}^{(1)}) - \alpha \sin(\varphi) Q_{\alpha} + \alpha \sin(\varphi) m_{\alpha}^{(1)} = \alpha \sin(\varphi)(\bar{I}_2 \ddot{u}_0 + \bar{I}_3 \ddot{\psi}_{\alpha}),$$

$$\frac{\partial}{\partial \theta}(M_{\theta}^{(1)}) + \frac{\partial}{\partial \alpha}(\alpha \sin(\varphi) M_{\alpha\theta}^{(1)}) + \sin(\varphi) M_{\theta\alpha}^{(1)} - \alpha \sin(\varphi) Q_{\theta} + \alpha \sin(\varphi) m_{\theta}^{(1)} = \alpha \sin(\varphi)(\bar{I}_2 \ddot{v}_0 + \bar{I}_3 \ddot{\psi}_{\theta}),$$
$$\frac{\partial}{\partial \alpha}(\alpha \sin(\varphi) P_{\alpha}^{(1)}) + \frac{\partial}{\partial \theta}(P_{\theta}^{(1)}) - \alpha \sin(\varphi)\left(N_{z} + \frac{M_{\theta}^{(1)}}{\alpha \tan(\varphi)}\right) + \alpha \sin(\varphi) m_{z} = \alpha \sin(\varphi)(\bar{I}_3 \ddot{\psi}_{z}),$$
$$\frac{\partial}{\partial \alpha}(\alpha \sin(\varphi) M_{\alpha}^{(2)}) - \sin(\varphi) M_{\theta}^{(2)} + \frac{\partial}{\partial \theta}(M_{\theta\alpha}^{(2)}) - 2\alpha \sin(\varphi) P_{\alpha}^{(1)} + \alpha \sin(\varphi) m_{\alpha}^{(2)} = \alpha \sin(\varphi)(\bar{I}_3 \ddot{u}_0 + \bar{I}_4 \ddot{\varphi}_{\alpha}),$$
$$\frac{\partial}{\partial \theta}(M_{\theta}^{(2)}) + \frac{\partial}{\partial \alpha}(\alpha \sin(\varphi) M_{\alpha\theta}^{(2)}) - \left(\frac{\sin(\varphi)}{\tan(\varphi)} P_{\theta}^{(2)} + 2\alpha \sin(\varphi) P_{\theta}^{(1)}\right) + \alpha \sin(\varphi) m_{\theta}^{(2)} = \alpha \sin(\varphi)(\bar{I}_3 \ddot{v}_0 + \bar{I}_4 \ddot{\varphi}_{\theta}).$$

The boundary conditions are given (see Zannon et *al.*, 2015; Qatu et *al.*, 2013)

4. Mathematical Analysis

One cannot find an exact solution for a general lamination structure shell with general boundary conditions and/or lamination having series of sequence and layers (Qatu et *al.*, 2013; Zannon et *al.*, 2015; Qatu, 1994). Many researchers talked about the vibration of shells as in Leissa & Qatu, (2011), she considered a thin plate in her paper "vibration of shells". One can be permitted to obtain a fundamental frequency with good accuracy as in Qatu et *al.*, (2013) by using the classical thin plate (CPT), now using the shear deformation plate theories (SDPTs) can largely eliminate the inaccuracies. Later Qatu et *al.*, (2010) and Reddy (1994) developed this subject, Leissa & Qatu (2011) studied the exact solutions "solutions which satisfy both the equations of motion, and boundary conditions'' for simply supported cross-ply thick shell.

The partial differential equations of motions can be found from Qatu et *al.* (2013) and their solution forms can be found in many sources (Qatu et *al.*, 2013; Zannon & Qatu, 2014b; Duc & Cong, 2015; Akbari et *al.*, 2015). Substituting the solution forms in (Zannon & Qatu, 2014a; Qatu et *al.*, 2010) we give a system of equations, rewrite the coefficient as an eigenvalue problem (Qatu et *al.*, 2013; Qatu et *al.*, 2010; Reddy, 1994), hence we get the form $([Z]-\lambda\,[N])\{\Delta\}=\{F(t)\}$ where $\lambda=\omega^2$, ω is the natural frequency and $\{\Delta\}$ is the displacement vector (Qatu et *al.*, 2013).The structural stiffness parameters $\{Z_{ij}\}$ of the thick conical shell are following:

$$Z_{11}=-\bar{A}_{11}\cdot A^{*2}-\hat{A}_{66}\cdot B^{*2},\ Z_{12}=-A_{12}\cdot A^{*}\cdot B^{*}-A_{66}\cdot A^{*}\cdot B^{*},$$

$$Z_{13}=\frac{A_{12}\cdot A^{*}}{\alpha\tan(\varphi)},\quad Z_{14}=-\bar{B}_{11}\cdot A^{*2}-\hat{B}_{66}\cdot B^{*2},$$

$$Z_{15}=-B_{12}\cdot A^{*}\cdot B^{*}-B_{66}\cdot A^{*}\cdot B^{*},\ Z_{16}=A_{13}\cdot A^{*}+\frac{B_{12}\cdot A^{*}}{\alpha\tan(\varphi)},$$

$$Z_{17}=-\bar{D}_{11}\cdot A^{*2}-\hat{D}_{66}\cdot B^{*2},Z_{18}=-D_{12}\cdot A^{*}\cdot B^{*}-D_{66}\cdot A^{*}\cdot B^{*},$$

$$Z_{21}=-A_{12}\cdot A^{*}\cdot B^{*}-A_{66}\cdot A^{*}\cdot B^{*},$$

$$Z_{22}=-\frac{\hat{A}_{22}\cdot B^{*2}}{\alpha\tan(\varphi)}-\bar{A}_{66}\cdot A^{*2}+\frac{\hat{A}_{44}}{(\alpha\tan(\varphi))^{2}},\ Z_{23}=\hat{A}_{22}\cdot B^{*},$$

$$Z_{24}=-B_{12}\cdot A^{*}\cdot B^{*}-B_{66}\cdot A^{*}\cdot B^{*},$$

$$Z_{25}=-\hat{B}_{22}\cdot B^{*2}-\bar{B}_{66}\cdot A^{*2}+\frac{\hat{A}_{44}}{\alpha\tan(\varphi)},$$

$$Z_{26}=A_{23}\cdot B^{*}+\frac{\hat{B}_{22}\cdot B^{*}}{\alpha\tan(\varphi)}+\frac{\hat{B}_{44}\cdot B^{*}}{\alpha\tan(\varphi)},Z_{27}=-D_{12}\cdot A^{*}\cdot B^{*}-D_{66}\cdot A^{*}\cdot B^{*},$$

$$Z_{28}=-\hat{D}_{22}\cdot B^{*2}-\bar{D}_{66}\cdot A^{*2}+\frac{2\cdot\hat{B}_{44}}{\alpha\tan(\varphi)}+\frac{\hat{D}_{44}}{(\alpha\tan(\varphi))^{2}},$$

$$Z_{31}=\frac{A_{12}\cdot A^{*}}{\alpha\tan(\varphi)},\ Z_{32}=\frac{\hat{A}_{44}\cdot B^{*}}{\alpha\tan(\varphi)},Z_{33}=-\bar{A}_{55}\cdot A^{*2}-\hat{A}_{44}\cdot B^{*2},$$

$$Z_{34}=-\bar{A}_{55}\cdot A^{*}+\frac{B_{12}\cdot A^{*}}{\alpha\tan(\varphi)},\ Z_{35}=-\hat{A}_{44}\cdot B^{*}+\frac{\hat{B}_{22}\cdot B^{*}}{\alpha\tan(\varphi)},$$

$$Z_{36}=-A^{*2}\cdot\bar{B}_{55}-B^{*2}\hat{B}_{44}-\frac{\hat{A}_{22}}{\alpha\tan(\varphi)}+\frac{\hat{B}_{22}}{(\alpha\tan(\varphi))^{2}}$$

$$Z_{37} = 2 \cdot A^* \cdot \overline{B}_{55} + \frac{D_{12} \cdot A^*}{\alpha \tan(\varphi)},\ Z_{38} = -2 \cdot B^* \cdot \hat{B}_{44} + \frac{\hat{D}_{22} \cdot B^*}{\alpha \tan(\varphi)},$$

$$Z_{41} = Z_{14},\ Z_{42} = Z_{24},\ Z_{43} = Z_{34}$$

$$Z_{44} = -\overline{D}_{11} \cdot A^{*2} - \hat{D}_{66} \cdot B^{*2} - \overline{A}_{55},$$

$$Z_{45} = -D_{12} \cdot A^* \cdot B^* - D_{66} \cdot A^* \cdot B^*$$

$$Z_{46} = B_{13} \cdot A^* + \frac{D_{12} \cdot A^*}{\alpha \tan(\varphi)} - \overline{B}_{55} \cdot A^*,$$

$$Z_{47} = -\overline{E}_{11} \cdot A^* - \hat{E}_{66} \cdot B^{*2} - 2 \cdot \overline{B}_{55},$$

$$Z_{48} = -E_{12} \cdot A^* \cdot B^* - E_{66} \cdot A^* \cdot B^*, Z_{51} = Z_{15},$$

$$Z_{52} = Z_{25},\ Z_{53} = Z_{35},\ Z_{54} = Z_{45},$$

$$Z_{55} = -\hat{D}_{22} \cdot B^* - D_{66} \cdot A^{*2} - \hat{A}_{44},$$

$$Z_{56} = -\hat{B}_{44} \cdot B^*, Z_{57} = -E_{12} \cdot A^* \cdot B^* - E_{66} \cdot A^* \cdot B^*,$$

$$Z_{58} = -\hat{E}_{22} \cdot B^{*2} - \overline{E}_{66} \cdot A^{*2} - 2 \cdot \hat{B}_{44} - \frac{\hat{D}_{44}}{\alpha \tan(\varphi)},$$

$$Z_{61} = Z_{16},\ Z_{62} = Z_{26},\ Z_{63} = Z_{36},\ Z_{64} = Z_{46},\ Z_{65} = Z_{56}$$

$$Z_{66} = -\overline{D}_{55} \cdot A^{*2} - \hat{D}_{44} \cdot B^{*2} - A_{33} - \frac{B_{23}}{\alpha \tan(\varphi)} - \frac{\hat{D}_{22}}{(\alpha \tan(\varphi))^2},$$

$$Z_{67} = -2 \cdot \overline{D}_{55} \cdot A^* + \frac{E_{12} \cdot A^*}{\alpha \tan(\varphi)},$$

$$Z_{68} = -2 \cdot \hat{D}_{55} \cdot B^* + \frac{\hat{E}_{44} \cdot B^*}{R_\beta} + \frac{E_{12} \cdot B^*}{R_\alpha} + \frac{\hat{E}_{22} \cdot B^*}{R_\beta},$$

$$Z_{71} = Z_{17},\ Z_{72} = Z_{27},\ Z_{73} = Z_{37},\ Z_{74} = Z_{47},\ Z_{75} = Z_{57},$$

$$Z_{76} = Z_{67},\ Z_{81} = Z_{18}, Z_{84} = Z_{48},\ Z_{85} = Z_{58},$$

$$Z_{77} = -\overline{F}_{11} \cdot A^{*2} - \hat{F}_{66} \cdot B^{*2} - 4 \cdot \overline{D}_{55},$$

$$Z_{78} = -F_{12} \cdot A^* \cdot B^* - F_{66} \cdot A^* \cdot B^*,$$

$$Z_{82} = Z_{28},\ Z_{83} = Z_{38}, Z_{86} = Z_{68}, Z_{87} = Z_{78},$$

$$Z_{88} = -\hat{F}_{22} \cdot B^{*2} - \overline{F}_{66} \cdot A^{*2} - \frac{\hat{E}_{44}}{\alpha \tan(\varphi)} - \frac{\hat{F}_{44}}{(\alpha \tan(\varphi))^2} - 4 \cdot \hat{D}_{44}.$$

The structural mass parameters $\{N_{ij}\}$ and the external applied load vector, as a function of time $\{F_{ij}\}$ are given (see Qatu et *al.*, 2013; Zannon et *al.*, 2015).

5. Conclusions

The mathematical analysis of the third order shear deformation theory (see Zannon et *al.*, 2015; Qatu et *al.*,2013) are presented for simply supported with circular cross section of a thick conical shell. This solution will be used in further investigations to assess the results for free vibration analysis of the circular cross section thick shells.

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