An Extended Kantorovich Method Used for Static Solution of an Arbitrarily Edge Supported Sandwich Cylindrical Shell Panel

Ramesh Chandra Mohapatra, Shranish Kar, Poonam Kumari

Abstract: Exact solution of complex problems like composite shells with arbitrarily supported boundary conditions through analytical three-dimensional (3-D) approach is mathematically challenging. In the present work an analytical 3-D elasticity solution for the static bending problem of a laminated composite cylindrical shell panel having any arbitrary boundary conditions is proposed. The governing Partial Differential Equations (PDE) problems are obtained by the application of the Ressiner-type mixed variational principle in cylindrical coordinate system. The extended Kantorovich method [10] is applied to solve these equations by reducing them to Ordinary Differential Equations (ODE). Further, the set of ODEs corresponding to the radial component & the circumferential components are solved utilizing modified power series method & Pagano’s approach respectively. Through numerical studies of sandwich shell panels it is shown that this method accurately predicts the deflections, stresses, boundary effects and interfacial disruptions being generated of laminate scheme, material property variations and configuration of the shell panel. Crucially, this is achieved with just two or three terms and few iterations, hence attributes faster computation as compared to other numerical techniques.

Keywords: Modified power series method, Pagano’s approach, Boundary effects, Extended Kantorovich method, Sandwich shells.

I. INTRODUCTION

Advent of composite structures in customizable shapes and configurations has widened its scope of application in every industry. Sandwich structure is a type of multi-layered composite which is made and applied to fulfil multiple functionalities. Functionality range from applications demanding high stress to weight ratio, impact, shock load bearing, energy absorption capacity and various other cryothermal and insulation usage. The structural integrity of the sandwich structures is maintained by the thin face sheet which is tensile or compressively loaded and is embedded with a thick low density core for bearing the compression and shear load. Face sheets are made of aluminum, steel or composites and core is made of honeycombs, fold cores, foam cores, and lattice cores, respectively [9]. However, the significant material property variation causes stress concentration and edge effects at the boundaries. Such boundary conditions can be arbitrarily of any possible combination of clamped, free or simply supported. Unlike for structures with symmetric simply supported boundary conditions, exact solutions for arbitrary boundary conditions are unavailable in the literature. Many two-dimensional (2D) theories have been developed to obtain the deflections and stresses for arbitrarily supported structures, but the prediction is of low accuracy. This can be realised from the reason that 2D theories are developed on the basis of initial assumptions whereas 3D theories are not [7]. Hence, 3D solutions can predict them with significant accuracy not only for thin structures but also for thick ones. Yet, development of 3D solutions are mathematically challenging and moreover, developing those for shell structures with arbitrary boundary conditions has intrigued researchers worldwide. The limitations of the conventional 3-D finite element method predicting near some edges were well known in the literature [1, 6]. Qing et al.[2] presented a 3-D semi-analytical finite element solution in in-plane coordinates for static & free vibration analysis of hybrid piezoelectric plates. Vel et al. [3,4] applied the Eshelby-Stroh formalism method to find out a series solution for the cylindrical bending & general bending of hybrid plates with arbitrary edge conditions. Tahani et al. [8] presented a 3-D elasticity solution for general bending of rectangular elastic laminated plates. Kim et al. [5] applied a 2-D analysis of free edge effects in a composite using Extended Kantorovich Method [EKM]. In this paper, a 3-D solution is developed by using a multi-extended Kantorovich method (MMEKM).

II. THEORETICAL FORMULATION

A. Sandwich shell panel configuration

A cylindrical shell panel with sandwich laminate scheme is considered for study in the frame of cylindrical coordinate system \((r, \theta, z)\) as shown in Fig.1. The shell panel is supported arbitrarily on its opposite edges (i.e., \(\Theta=0, \psi\), where \(\psi\) is the circumferential span of the shell panel) which can be a combination of either of the clamped (C), free (F) or simply-supported (S). The shell panel is loaded uniformly (UDL) which can be distributed over either or both of its outer surface at \(R_0 = R + h/2\) and inner surface at \(R = R – h/2\). Here, \(R\) & \(h\) are the mean radius and total thickness of the shell panel, respectively. There are \(L\) perfectly bonded layers which are indexed as \(k\) and their corresponding thicknesses are denoted as \(t^k\). The \(k^{th}\) layer is bonded with \((k+1)^{th}\) layer at the interface which is \(R_k^{(k+1)}\) far from the origin.
Fig 1: Geometry of a laminated cylindrical shell panel

B. Governing equation

Upon loading, the developed stresses \( \{\sigma\} \) are related though linear constitutive relations to the strain \( \{\varepsilon\} \) components as given in Eq. (1)

\[
\{\varepsilon\} = [S] \{\sigma\},
\]

\[
[S] = S_{11} \sigma_{r} + S_{12} \sigma_{r} + S_{13} \sigma_{r},
\]

\[
[S] = \begin{bmatrix}
S_{11} & S_{12} & S_{13} \\
S_{21} & S_{22} & S_{23} \\
S_{31} & S_{32} & S_{33}
\end{bmatrix}
\]

(1)

Corresponding displacements along \((r, \theta, z)\) are \((u, v & w)\), respectively. As the panel is infinitely long and loading is invariant along \(z\), so a plane strain problem is derived where the field entities are independent of \(z\). Further \(w=0\) and the strains are related to radial \(u\) and circumferential \(v\) displacements by following relations

\[
\varepsilon_r = u_r, \quad \varepsilon_\theta = \frac{u + v}{r}, \quad \gamma_{rr} = \frac{u + v}{r}, \quad \gamma_{\theta\theta} = 0, \quad \gamma_{r\theta} = 0.
\]

(2)

where differentiations are denoted by comma. By imposing \(\varepsilon_z = 0\), from the 3D linear elastic constitutive relations,

\[
\sigma_z = -\frac{S_{21}}{S_{22}} \sigma_\theta - \frac{S_{23}}{S_{22}} \sigma_r, \quad \varepsilon_\theta = \frac{l_3}{l_1} \sigma_\theta + \frac{l_3}{l_1} \sigma_r, \quad \varepsilon_r = \frac{1}{S_{22}} \sigma_r + \frac{l_3}{S_{22}} \sigma_r.
\]

(3)

are the components of the compliance matrix. The Reissner-type mixed variational principle without body force for cylindrical bending case is given in Eq. (4)

\[
\int_0^V \{\delta u(r, \theta) \sqrt{r} + \frac{\sigma_r - \sigma_\theta}{r} + \delta v(r, \theta) + \frac{\sigma_\theta}{r} + \delta \sigma_\theta r (\varepsilon_\theta - \frac{u + v}{r}) + \delta \sigma_r (\varepsilon_r - u) + \delta \tau_{r\theta} (\gamma_{r\theta} - b)
\]

(4a)

where \(V\) is volume of the cylindrical shell panel. Considering unit length along \(z\) direction and as the variables are independent of \(z\) coordinate, thus Eq. (4a) reduces to Eq. (4b) as

\[
\int_0^V \{\delta u(r, \theta) \sqrt{r} + \frac{\sigma_r - \sigma_\theta}{r} + \delta v(r, \theta) + \frac{\sigma_\theta}{r} + \delta \sigma_\theta r (\varepsilon_\theta - \frac{u + v}{r}) + \delta \sigma_r (\varepsilon_r - u) + \delta \tau_{r\theta} (\gamma_{r\theta} - b)
\]

(4b)

The boundary conditions are given by:

At the span edges, \(\theta = 0, \psi\) the arbitrary boundary conditions can be:

\[
S : u = 0, \quad \sigma_\theta = 0, \quad \tau_{r\theta} = 0; \quad C : u = 0, \quad v = 0, \quad w = 0; \quad F : \sigma_\theta = 0, \quad \tau_{r\theta} = 0, \quad \tau_{rr} = 0 \quad \text{and} \quad \tau_{r\theta} = 0 \quad \text{and} \quad \tau_{rr} = 0.
\]

(5a)

Due to loading on the inner and outer surface transverse stresses are obtained as:

At \(r = -h/2\): \(\sigma_r = -p_1, \quad \tau_{rr} = \tau_{r\theta} = 0\) & At \(r = h/2\): \(\sigma_r = -p_2, \quad \tau_{rr} = \tau_{r\theta} = 0\) and interface continuity equation is given at the \(k\)th interface as:

\[
(\sigma_{r}, v, \sigma_{\theta}, \tau_{r\theta}, \tau_{rr}) = (\sigma_{r}, v, \sigma_{\theta}, \tau_{r\theta}, \tau_{rr})^{k+1}.
\]

(5b)

Further, dimensionless coordinates of range \([0, 1]\) are defined as:

\[
\zeta = (r - R_1^k) / l^k \quad \text{where} \quad R_1^k = R - h/2 + \sum_{i=1}^{k-1} l^i, \quad \forall k \quad \text{layer} & \zeta = \theta / \psi, \quad \forall V.
\]

III. GENERALIZED MMEKM SOLUTION

X is considered as a set of field variables where the \(l\)th component is given in a set of:

\[
X_l = [v \, w \, u \, \sigma_\theta \, \sigma_r \, \tau_{r\theta} \, \tau_{rr}]
\]

According to MMEKM, solution of the field variables \(X_l\) are assumed in terms of the \(n\) term series of the product of separable functions in the two independent variables \(\zeta\) & \(\phi\) as:

\[
X_l(\zeta, \phi) = \sum_{i=1}^{n} f_i(\zeta) g_i(\phi) + \delta_{l5} [p_a + r_d p_d] \quad \text{for} \quad l = 1, 2, ..., 8
\]

where \(f_i(\zeta)\) and \(g_i(\phi)\) are the univariate functions of \(\zeta\) and \(\phi\) respectively. There is no sum over \(l\) and \(\delta_{l5}\) is Kronecker’s delta. \(X_l\)s are to be determined iteratively such that they satisfy homogeneous boundary condition except for \(X_5, \forall \delta_{l5} = 1\) which requires to satisfy the non-homogeneous boundary condition due to loading as expressed in Eq. (5b).

\[
p_a = p_1 - \left(\frac{R - \frac{h}{2}}{2}\right) \text{ UDL}
\]

are \(p_d = \left(\frac{p_2 - p_1}{h}\right) \text{ UDL} \) on outer and
Constitutive equations from Eq. (1), strain-displacement relation from Eq. (2) and assumed relation in Eq. (6) for field variables are inserted into Eq. (4b) iteratively to obtain system of ODEs in each iteration step which are discussed in consequent sections.

**A. First iteration step:**

In this step, functions \( f_1^i(\xi) \) are assumed, for the variation \( \delta X_l \)

\[
\delta X_l = \sum_{i=1}^{n} f_1^i(\xi) \delta g_l^i(\xi) \quad l = 1,2,\ldots,8 \tag{8}
\]

Functions \( g_l^i(\xi) \) are partitioned into a column vector \( \vec{G} \) which contains 6 variables & a column vector \( \vec{\xi} \) consisting of remaining 2 variables. Thus after all substitutions including Eq. (6) in Eq. (4b), integrating over \( \xi \) direction and considering the variations \( \delta g_l^i \) are arbitrary, the coefficients of \( \delta g_l^i \) as equated to zero individually. This results in the following set of 8 differential-algebraic equation for the lamina

\[
M\vec{\xi} = \vec{A}_0 \vec{G} + \vec{A}_1 \frac{\partial \vec{G}}{\partial k} + \vec{A}_2 \frac{\partial^2 \vec{G}}{\partial k^2} \tag{9} \]

\[
K\vec{G} = \vec{A}_0 \hat{\vec{G}} + \vec{A}_1 \frac{\partial \hat{\vec{G}}}{\partial k} + \vec{A}_2 \frac{\partial^2 \hat{\vec{G}}}{\partial k^2} \tag{10}
\]

where \( M, \vec{A}_0, \vec{A}_1 \) are \( 6 \times 6 \), \( \hat{\vec{A}}_0, \hat{\vec{A}}_1 \) are \( 2 \times 6 \), \( \vec{A}_0, \vec{A}_1 \) are partitioned into vector \( \vec{F}_{01} \) & \( \vec{F}_{20} \). The algebraic equations in (7b) can be solved to obtain \( \vec{G} \) and put into (7a) which yields a system of 6 first-order non-homogeneous ODEs with variable coefficients of the form in Eq. (8) as follows:

\[
\vec{G} = k^i \left[ \vec{A}_0 + \frac{\vec{A}_1}{(\xi^k + R_k)} + \frac{\vec{A}_2}{(\xi^k + R_k)^2} \right] \vec{G} \tag{11}
\]

This system of ODEs is solved by assuming a solution of the form

\[
\vec{G}_n = \sum_{i=0}^{\infty} \frac{Y_i^{ij}}{i!} \quad \text{where} \quad Y_i = \hat{Z}_i + \hat{H}_i C_0 \tag{11}
\]

where \( \hat{Z}_i \) are known vector of dimension \( 6 \times 1 \) column vectors and \( \hat{H}_i \) is \( 6 \times 6 \) constant matrix. This completes the 1st iteration step.

**B. Second iteration step:**

In this step, the solution of the previous step is taken as the known solution for \( g_l^i(\xi) \) while functions \( f_1^i \) are considered as unknown. The variation \( \delta X_l \) for this case is

\[
\delta X_l = \sum_{i=1}^{n} g_l^i(\xi) \delta f_1^i(\xi) \quad l = 1,2,\ldots,8 \tag{12}
\]

The functions \( f_1^i(\xi) \) are partitioned into vector \( \vec{F} \) & a vector \( \vec{L}. \) Applying integration by parts where-ever necessary & equating the coefficients of \( \delta f_1^i \) to zero individually yields the following system of differential-algebraic equations for \( f_1^i \):

\[
N\vec{F}_i + \vec{B} = \vec{F} + \vec{p}_m \tag{13}
\]

\[
L\vec{F} = \vec{B} + \vec{p}_m \tag{14}
\]

This system of ODEs is solved by assuming \( \vec{F} \) in the form used by Kapuria et al. [2]. This completes the 2nd iteration step.

**IV. RESULTS & DISCUSSION**

In this section, the numerical results are presented with a view to assess accuracy of the EKM for 3D elasticity problem. The results are produced after non-dimensionalization (ref. Table 1) for a sandwich cylindrical composite shell panel of following material properties listed in Table 1. The face sheets are of 0.05h on the outer and inner part of the shell panel and the core made of Klegecell foam [4] makes up 0.9h.

**Table 1: Material Constants and non-dimensionalization of field variables**

| Material       | \( Y_1 \) | \( Y_2 \) | \( Y_3 \) | \( G_{12} \) | \( G_{13} \) | \( G_{23} \) | \( v_{12} \) | \( v_{13} \) | \( v \) |
|----------------|----------|----------|----------|-------------|-------------|-------------|-------------|-------------|-------|
| Face (Al)      | 70       | 70       | 70       | 26.3        | 26.3        | 26.3        | 0.33        | 0.33        | 0     |
| Core [4]       | 0.1457   | 0.1457   | 0.186    | 0.056       | 0.056       | 0.056       | 0.3         | 0.3         | 0     |

Units: Young’s moduli \( Y \), shear moduli \( G_{ij} \) in GPa; poission’s ratio \( \nu = 0.1457 \) GPa, \( P_z = 1 = P_0 \), \( P_z = 0 \).

| Variables | \( \bar{\sigma}_{11} \), \( \bar{\sigma}_{22} \), \( \bar{\sigma}_{12} \) | \( \bar{\tau}_{12} \) |
|-----------|---------------------------------------------------------------|-------------------|
| Non-dim.  | \( (\bar{\sigma}_{11}, \bar{\sigma}_{22}) \)                  | \( \bar{\tau}_{12} \) |

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The boundary condition can be arbitrarily of any combination among simply supported (S), Clamped (C) and free (F) for the panel at edges $\xi = 0,1$ and UDL is applied as $P_2 \& P_1$ of magnitude given in Table 1. The results obtained through EKM are shown for a thick and a moderately thick shell panel with mid-surface radius (R) to total thickness (h) ratios S=5, and 10 respectively. In fig.2, the circumferential variations of deflections $\bar{U}$ and stresses $\sigma_\theta, \sigma_r$ and $\tau_{\theta r}$ at $\xi$ -locations where they are large are plotted for a SS boundary condition. Distribution of field variables can be observed as symmetric about the mid plane ($\xi = 0.5$) of the shell panel. Validity of the obtained results are assessed with those obtained from 3D finite element (FE) from ABAQUS (3D element C3D20R). It can be seen that the results converged in a single iteration and single term (Iter. 1, 2 in the figure) in the multi-term function of Eq.6. This ensured EKM to be computationally efficient. It had been shown by Kumari and Kar [1] that the 3D exact solution is valid for only simply-supported boundary conditions, whereas the present EKM has been proved to be applicable for arbitrary boundary conditions.

![Graphs showing deflections and stresses](image_url)

**Fig.2.** Variation of deflections & stresses in sandwich cylindrical shell panel of S=5,10 for SS boundary condition along the circumferential span.
In fig.3, through-the-thickness variations of deflections $\bar{U}$ and stresses $\sigma_\theta, \sigma_r$ and $r_{r\theta}$ at $\zeta$-locations where they are large are plotted for a SS boundary condition. Again the present results match accurately with those obtained from 3D FE.

Fig. 3. Through the thickness variation of deflections & stresses in a sandwich cylindrical shell panel of $S = 5, 10$ for SS boundary condition.

It can be observed for $r_{r\theta}$ in fig.3, that at the extreme ends of the circumferential span of the shell panel, 3D FE is unable to satisfy the essential boundary condition of $r_{r\theta} = 0$ at the outer and inner surfaces.

In fig.4, the circumferential variations of deflections $\bar{U}$ and stresses $\sigma_\theta, \sigma_r$ and $r_{r\theta}$ at $\zeta$-locations where they are large are plotted for a CF boundary condition. Obtained results are assessed with those obtained from 3D finite element (FE) from ABAQUS.
Although, results for SS boundary condition are available in the literature, but for arbitrary boundary conditions those are in paucity. Hence, numerical results obtained from 3D FE are used for assessment. For CF boundary condition, the EKM results agree exactly with those of the 3D FE and even the boundary edge effects at the clamped edge. Computational efficiency can be confirmed from the fact that EKM results are obtained in just a single iteration, although higher number of terms are required which increases the size of the matrices involved. Similar case is also found for the CS boundary condition, where boundary edge conditions are also calculated accurately by the EKM as shown in the circumferential plot in fig.5.

Fig. 4. Variation of deflections & stresses in sandwich cylindrical shell panel of S = 5,10 for CF (at $\xi = 0$) boundary condition along the circumferential span.
Fig. 5. Variation of deflections & stresses in sandwich cylindrical shell panel of S = 5,10 for CS (C at $\xi = 0$) boundary condition along the circumferential span.
Fig. 6. Through the thickness variation of deflections & stresses in sandwich cylindrical shell panel of $S = 5$ for CS & CF (C at $\zeta = 0$ ) boundary condition.

In fig.6, through-the-thickness variations of deflections $\bar{\bar{u}}$ and stresses $\bar{\bar{\sigma}}_r, \bar{\bar{\sigma}}_{\theta}$, and $\bar{\bar{\tau}}_{r\theta}$ at $\zeta$-locations where they are large are plotted for the arbitrary CF and CS boundary conditions. Again the present results match accurately with those obtained from 3D FE. It is observed that, single term solution cannot predict the results with substantial accuracy. It is noteworthy, that 3D FE deviates completely at the very clamped edge of the shell panel. It can be seen in fig.7, that EKM satisfies the
essential boundary condition of $\tau_{r\theta} = 0$ at the outer and inner surfaces which the 3D FE doesn’t satisfy and consequently the results at other points of the clamped edge are affected. This is because, in the present EKM solution a mixed variational principle is used which includes variation of all the field variables including stresses and displacements. Hence, the variables are predicted accurately at each and every point in the domain of the shell panel.

![Graph](Image 47x557 to 510x741)

**Fig.7.** Through-the-thickness variation of deflections and stresses in sandwich cylindrical shell panel of S=5 for CS and CF (C at $\xi = 0$ ) boundary condition showing deviation of 3D FE results.

V. CONCLUSIONS

A 3D solution approach has been developed to obtain stresses and displacements for a sandwich cylindrical composite shell panel with arbitrary boundary conditions. 3D closed form solution for elasticity problem with nonhomogeneous boundary condition has been obtained. The results have been obtained for thick shell panels which is otherwise impossible to obtain through other 2D theories. Faster converging results have been observed due to lesser terms and lesser number of iteration steps involved in EKM. The results are obtained both along the circumferential and thickness span. Present single term EKM results are in good agreement with 3D FE results for SS boundary condition. Although higher number of terms are required for arbitrary boundary conditions of CS and CF shell panels, but this is computationally efficient as accurate results were obtained in the 1st or 2nd iteration step itself. Crucially, the boundary edge effects are accurately obtained which are the stress concentration zones in case of clamped shell panels. As compared to 3D FE, the EKM predicts accurate results at each and every point in the domain of the shell panel including the extreme clamped edge.

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