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Thermomechanical deflection and stress responses of delaminated shallow shell structure using higher-order theories

Chetan Kumar Hirwani[a], Subrata Kumar Panda[a,*], Trupti Ranjan Mahapatra[b]

[a] Department of Mechanical Engineering, National Institute of Technology Rourkela, Odisha 769008, India
[b] Production Engineering Department, Veer Surendra Sai University of Technology, Burla, Sambalpur, Odisha 768018, India

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ABSTRACT

The deflection responses of the damaged doubly curved shallow shell panels under the combined thermo-mechanical loading are investigated numerically in this article. The debonded layered structures are modeled mathematically using two higher-order displacement kinematic theories and solved via finite element method. The separation between the consecutive layers is included using two sub-laminate approaches in the current model including the intermittent displacement continuity conditions. Further, the weak form of the equilibrium equation for the deflected shell panel structure under the combined action of loading is achieved via two-dimensional nine noded isoparametric Lagrangian elements. The responses are obtained by minimising the total potential energy expression with the help of an original computer code (MATLAB) in association with the currently developed mathematical models. The consistency of the present numerical solutions is demonstrated by conducting the convergence test and the validity of the models checked through the proper comparison test. Lastly, some new examples are solved using the current models to show the consequence of the delamination (size and position) including the other structural parameters (the side to thickness ratio, the length to width ratio, the curvature ratio and the boundary condition) on the deflection responses under the influence of thermomechanical loading.

1. Introduction

Laminated composite is employed as the load-bearing parts in the major modern engineering structures of the weight sensitive industries (aircraft, aerospace, marine, automobile and civil structure) due to the unmatched properties (mechanical, chemical and thermal) in comparison to their metallic counterpart. The advance engineering structural components are generally exposed to the combined action of loading (thermal, mechanical and thermomechanical) during their service period. Further, the final strength and stiffness of the composite component may alter largely due to the reduction in structural strength and the distortion of geometries under the applied excess thermal loading. Additionally, the layered structure/structural components are prone to delamination (separation of two consecutive layers of the laminate) kind of defect during their service life and/or manufacturing processes. This, in turn, causes the reduction of overall structural stiffness and the final performance affected subsequently. Hence, the influence of the internal debonding on the final structural responses (deflection, frequency and buckling strength) of the layered composite structure is not only an important parameter to investigate but also essential to develop the clear understanding. In view of the above many numerical, analytical and exact solution techniques are employed in the past for the analysis of layered composite structure using the different kinematic theories. Now, the necessity of the current investigation is discussed in the following paragraphs. In order to highlight the knowledge gap in the current field of research, the comprehensive review of the available important articles (recent and recent past) related to the intact and debonded structures are presented in the following line.

The deflection and stress responses of the laminated composite and graded structures are computed either numerical [1,2] or the analytical techniques [3–5] using different types of mid-plane kinematic theories (higher-order and first-order plate theories) under the influence of the combined action of loading (thermal, mechanical and electrical). Further, the static and dynamic deflection responses of the functionally graded (FG) and laminated composite curved (single and doubly) panel structures under the influence of the thermomechanical loading are investigated numerically [6–14] via different kinematic models (higher-order and first-order) and implemented different solution techniques (penalty approach and differential quadrature method, DQM). The research related to the kinematic theories indicate that the higher-order

* Corresponding author.
E-mail addresses: chetanhirwani111@gmail.com (C.K. Hirwani), call2subrat@gmail.com, pandask@nitrkl.ac.in (S.K. Panda), truptiranjan01@gmail.com (T.R. Mahapatra).

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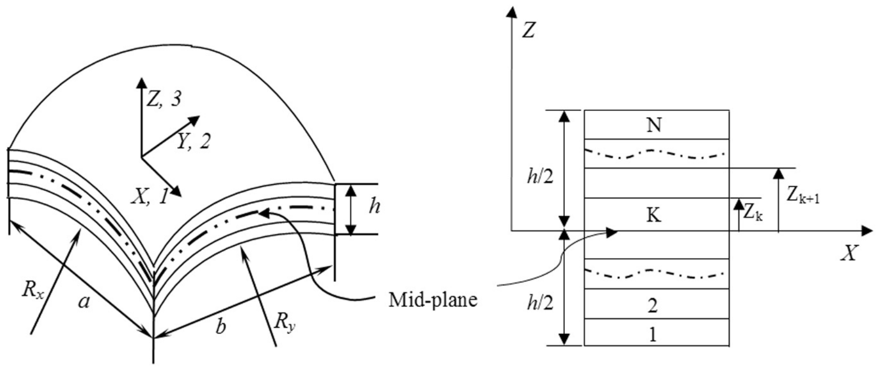

Fig. 1. Geometry and layer sequence of laminated doubly curved shallow shell panel.

kinematics are inevitable for the layered structure but accompanying with the mathematical complexities. Hence, to overcome such situation and maintain the necessary balance (between the mathematical complexities and adequate accuracy), numerous research articles are reported using new plate kinematic models [15–27] for the analysis purpose under the combined loading. Subsequently, few articles discussed on the thermomechanical stress behavior of the layered composite shell structure using the commercial tool [28] via the 3D elements (ANSYS) under the thermal environment. Han et al. [29] employed the efficient high-order zigzag theory to examined the thermo-mechanical behaviour of the layered composite plate structure.

After reviewing the articles related to the intact layered composite structure, the current section focused on the research completed in the field of damaged structures. As discussed previously that the delaminated structure modeling is not easy as like as the laminated case. Hence, to build the confidence on the issue few research articles investigated the responses using the commercial FE (ABAQUS) tool [30,31] via shell/3D modeling and validated with experimental data. Later, with the development of the numerical tool (FEM) and computational facility, the responses (deflection and stress) of the delaminated composite flat/curved panel structures are reported using various kinematic theories (FSDT/layer wise), delamination growth, structural stability and types of loading [32–42].

The extensive review of the published articles on the laminated composite including the internal debonding for the analysis of deflection responses under the external mechanical and/or thermal load indicates that the adequate numbers of research articles are published in the open forum using different solution techniques (analytical, simulation and numerical model) via the well-developed shear deformation and classical kinematic theories. It is important to indicate that the reported research majorly based on the FSDT kinematics instead of the higher-order shear deformation theory (HSDT). However, the HSDT mid-plane kinematics are demonstrated the degree of accuracy at many instances in comparison to the FSDT for the layered structure or the structural components when investigated numerically. Hence, the present article aims to develop a general mathematical models for the analysis of stress and deflection responses of the internally debonded layered (flat/curved) structure using two higher-order kinematics under the transverse mechanical loading (uniformly distributed load) and the elevated thermal environment. Further, the responses are obtained computationally using MATLAB code in association with the current higher-order models and FEM. In this analysis, the composite properties are assumed to be independent of the temperature loading. The convergence behavior of the current model is carried out for the necessary check and again employed for the validation purpose. Lastly, the variety of numerical examples have been solved to show the influence of the delamination (size, position and location) including the geometrical parameters (aspect ratios, boundary conditions, curvature ratios, thickness ratios) on final flexural strength and discussed in details.

2. Panel geometry

In this analysis, a layered composite doubly curved shell panel structure consists of '*N*' number of orthotropic layers of equal thickness is considered. The geometrical parameters (length '*a*', breadth '*b*' and thickness '*h*') and the corresponding visual presentation of the current model can be seen in Fig. 1. The displacement field models of the layered composite are explained using two different HSDT types of mid-plane kinematics [43–44]. The displacement field functions along the in-plane direction are defined as the cubic functions of the thickness coordinate whereas the displacement functions along the thickness direction is either constant or linearly varying through the thickness.

3. Displacement field and strain-displacement relations

Now, the displacement field variable for the first kind of HSDT model (Model-1) is expressed in Eq. (1) [43]:

$$\begin{aligned} u(x,y,z) &= u_0(x,y) + z\theta_x(x,y) + z^2\phi_x(x,y) + z^3\lambda_x(x,y) \\ v(x,y,z) &= v_0(x,y) + z\theta_y(x,y) + z^2\phi_y(x,y) + z^3\lambda_y(x,y) \\ w(x,y,z) &= w_0(x,y) \end{aligned} \tag{1}$$

Similarly, the second HSDT kinematic model says, Model-2 is also employed for the current mathematical modeling of the layered composite shell panel, where the displacement functions through the thickness are assumed to varying linearly [44]:

$$\begin{aligned} u(x,y,z) &= u_0(x,y) + z\theta_x(x,y) + z^2\phi_x(x,y) + z^3\lambda_x(x,y) \\ v(x,y,z) &= v_0(x,y) + z\theta_y(x,y) + z^2\phi_y(x,y) + z^3\lambda_y(x,y) \\ w(x,y,z) &= w_0(x,y) + z\theta_z(x,y) \end{aligned} \tag{2}$$

where, u, v and w represents the global displacements of any point (within the laminate) along x, y and z-direction, respectively. Likewise, u_0, v_0 and w_0 are the mid-plane displacements, θ_x and θ_y denotes the rotations of the normal to the mid-plane about y and x-direction, respectively. The rest of the terms $\phi_x,\phi_y,\lambda_x,\lambda_y$ and θ_z (stretch along the thickness) are the higher-order terms of Taylor series expansion. The current higher-order terms are ensuring to maintain the actual profile of shear stress (parabolic variation) through the thickness of the laminated structure.

Further, the same kinematic models are extended to express the delaminated segment (having '*p*' number of delamination, Fig. 2) for the internally debonded structure. For this, a different axis system namely, $0'$, x', y' and z' similar to the laminate segment is considered