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A Review on Various Methods for Analyzing the Laminated Composite Plates (LCP)

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Abstract - *The LCP materials in present day, are being used in various sectors such as, marine, civil, aerospace etc. because of their high strength to stiffness ratios and improved fatigue properties. Also they can be modified by altering the orientation of fibers, changing the stacking arrangement. Because of the high demand in various sectors, a wide research is going on, in improving the LCP properties and to support this, new methods (numerical & Analytical) for analyzing them, are also being developed. This paper will provide an overall review in the methods for analyzing the LCP.*

Key Words: Composite plate theories, shear deformation; classical plate theory, FSDT, HSDT, Lamina, etc.

1.INTRODUCTION

A composite structure is any structure formed from two or more distinct constituent structures. Usually, the new composite structure formed has a distinct property that is different from the chemical characteristics or physical properties of the individual materials used .The completed or newly formed composite material has individual layers that are distinguishable from one another. Composite materials have many advantages when compared to conventional materials. They are lightweight, cheaper, stiffer, stronger and eco-resistant.

These LCPs are very strong, stiff & resistant to expansion, etc. hence preferred in various industries. These are formed from fibre matrix layers and by stacking different laminates. Stacking sequence is the arrangement of laminated layers at a specific directions and orientations. Stacking sequence optimization requires the least number of layers with maximum fibre quality of each laminated layer. Different stacking sequence imparts different properties to the structural components.

This objective of this paper is to provide an overall review in the methods for analyzing the LCP

The Methods for analyzing the LCP are classified as Analytical methods, such as CPT (classical plate theory), FSDT, HSDT etc. and Computational Techniques such as Analysis by using Different theories such as FEM, ANSYS, MATLAB etc.

Brief summary of Analytical methods is given below:

Classical Plate Theory: it is also known as Love Krichhoff plate Theory, in this assumption is that, lines which are normal to neutral surface before deformation remain straight and normal to neutral surface after deformation. CPT has been used for variety of problems. In this theory, effects of transverse stresses are not accounted for. Thick plate analysis, transverse stresses play an important role, Since CPT does not include transverse stresses effects, it fails to accurately analyze thick plates. This drawback is affecting more in plates which are low shear modulus. Despite of its limitation of shear deformations; CPT was extended for composite plate analysis because of its simplicity.

Some Assumptions used in CPT:

- Bonding is perfect in laminates and it is very thin.
- No shear deformation
- Plate is very thin and acts as one layer
- lines which are normal to neutral surface remain straight and normal to neutral surface before and after deformation
- Displacements are small

First Order Shear Deformation Theory (FSDT): A new theory was proposed known as Reissner-Mindlin plate theory and also known as FSDT In this theory the in-plane displacement very linearly through the cross section and the normal to the midplane before deformation need not b normal to midplane after deformation. It means that the normals are allowed to rotate. This theory uses a shear correction factor in the analysis. This theory uses five unknowns. And theory is applied in analyzing conditions of static, lesser velocity impact, free vibrations.

Finite element model have been developed and used to solve the plate problems with various boundary conditions. This theory is simple to use and predicts good global behavior. It predicts constant shear stress across the cross section. In this shear correction factor is depending upon the particular problem.

Higher Order Shear Deformation Theories (HSDT): Here, Displacements are expressed in polynomials. Because of low shear modulus, transverse shear role is critical in composite plates Hence, an accurate understanding of their structural behavior is required, such as deflections and stresses.

MATLAB and ANSYS seawares are also used in analyzing the LCPs[28].

Table 1. Comparison of various equivalent single layer (ESL) theories [29].

Theory	Basis	Details
CLPT	Kirchhoff's plate theory	stress free boundary conditions are not satisfied.
FSDT	Reissner, Mindlin plate theory	To satisfy BC, shear correction factor are used
HSDT1	polynomial shear strain function are used	stress free boundary condition are satisfied
HSDT2	Trigonometric shear strain function are used	stress free boundary condition are more accurately satisfied
HSDT3	Exponential shear strain function are used	stress close to exact solution and stress free boundary condition are Satisfied

Table 2. Transverse shear and normal deformation consideration and Applicability [29].

Theory	Transverse shear and normal deformation consideration	Applicability
CLPT	Not considered. Violates stress free boundary conditions (BC) at top, bottom surfaces	Thin plates
FSDT	Constant variation of transverse shear. Neglects cross sectional warping and no stress free BC	Moderately thick plates
HSDT1	Realistic variation of transverse shear, includes cross-section warping. Stress free BC considered	Thin and Thick plates, shells, beams
HSDT2	Provides stress free BC at top, bottom surfaces	
HSDT3	parabolic distribution of the transverse shear strains. meets stress free BC at top, bottom surfaces	

2. REVIEW OF LITERATURE

A detailed study of the available literature was conducted to know the present state of knowledge available in the open literature, which help in understanding the various methodology adopted in the analysis of laminated composite plates.

V M Sreehari [1] has calculated and compare the response of laminated composite plate using first order and higher order shear deformation theories. For this analysis, he developed a finite element formulation. He has developed mathematical formulation andMatlab coding using First Order Shear Deformation Theory (FSDT) and Higher Order Shear Deformation Theory (HSDT).

Ghazi Abu-Farsakh, Yasser Hunaiti and Asaad Al Bustami [2] have investigated the effect of nonlinear material behavior on four layered, symmetric; angle-ply laminated composite plate with various fiber-orientation angles;(30,45and 60 degree) having central square hole and subjected to out-of-plane uniformly distributed load by using utilizing the ANSYS-computer program. The effect of Stress Concentration Factor (SCF) resulting from redistribution of in-plane stresses around the hole was taken into consideration.

Patryk Rozylol and Daniel Lukasik [3] have studied the critical load at which buckling occurs, the form of buckling and operating characteristics in critical condition for a thin-walled profile with Z-shaped cross section made of the carbon-epoxy composite. They utilized ABAQUS software to prepare model and for analysis.

C K Hirwani, H Mittal, S K Panda, S S Mahapatra and S K Mandal [4] have studied, Under UDL conditions, the bending strength and deformation parameters of the de-bonded . ANSYS based model is used based on FSDT and APDL code for simulation.

Rehs T. Gerrit, Shun Kokubo, Tomohiro Yokozeki [5] have developed an appropriate modeling methodology forthe simulation of intra-laminar damage in laminated composites under complexloadings. The intra-laminar damages are modeled by stiffness reductioncontrolled by thermodynamic forces as defined in continuum damage mechanicsmodel proposed by Ladeveze and discussed the effect oftransverse stress in the identification process on the damage modeling.

Yu Wang, Guangyu Shi, and Xiaodan Wang [6] have done modeling and analysis of laminated composite plates using an eight nodequasi-conforming solid-shell element, named asQCSS8. It possesses the explicit element stiffness matrix. All the six components of stresses can be evaluated directly by QCSS8 interms of the 3-D constitutive equations and the appropriately assumed element strain field. The numerical results show that QCSS8 can give accurate displacements and stresses of laminated composite plates even with coarse meshes.

Mahmoud Yassin Osman and Osama Mohammed Elmardi Suleiman [7] have used Finite element method (FEM) to obtain numerical solution of the governing differential equations in the Buckling analysis of rectangular laminated

plates with rectangular cross-section for various combinations of boundary conditions and aspect ratios. New numerical results are generated for uniaxial and biaxial compression loading of symmetrically laminated composite plates.

A. Maji1, P.K. Mahato [8] have studied free vibration analysis of orthotropic laminated composite plates using first orders hear deformation theory. And this FSDT contains only four unknowns and has much similarity with the classical plate theory such as equation of motion, boundary condition and stress resultant expressions. Analytical closed form solution of simply supported anti-symmetric cross-ply and angle-ply laminated composite are obtained and results are verified with the exact 3D solutions.

A.R.Vosoughia, A.Darabia, N.Anjabinb, and U.Topalc [9] have used genetic algorithm and FE method. HSDT equations are solved by FE method. Particle swarm optimization technique is used in genetic algorithm to solve the problem.

Chien H.Thaia, Magdabdel Wahab, HungNguyen-Xuane [10] have proposed a novel layer wise C0-type higher order shear deformation theory (layer wise C0-type HSDT) for the analysis of laminated composite and sandwich plates which is orthotropic in nature and having cross ply fiber orientation. A C0-type HSDT is used in each lamina layer and the continuity of in-plane displacements and transverse shear stresses at inner-laminar layer is consolidated.

Amirhadi Alesadi, Marzieh Galehdari, Saeed Shojaee [11] have studied free vibration and linearized buckling analysis of laminated composite plates by employing Isogeometric approach (IGA) and Carrera's Unified Formulation (CUF).

J.A. Artero-Guerrero, J. Pernas, J. Martín, D. Varas, Lopez-Puente [12] have studied the influence of laminate stacking sequence on ballistic limit using a combined Experimental, FEM, Artificial Neural Networks (ANN)methodology. The ANN allows studying very efficiently the whole possibilities of laminate stacking sequence using the common orientations, in symmetric 12 plies laminates (4096 cases).

Durgesh Bahadur Singh, B.N. Singh [13] have developed two new shear deformation theories namely Trigonometric Deformation Theory (TDT) and Trigonometric-Hyperbolic Deformation Theory (THDT) and implemented for the analysis of laminated and three dimensional braided composite plate. Both models are based upon shear strain shape function which yields non-linear distribution of transverse shear stresses and these models also satisfy the traction free boundary conditions on top and bottom surfaces of the plate. Analysis was done on symmetric plate with cross ply fiber orientation.

Y.S.Joshana, NeerajGrovera, B.N.Singhb [14] has investigated the thermo-mechanical response characteristics of cross-ply as well as angle-ply laminated composite plates in closed form. Model is done in an axiomatic framework based on an inverse hyperbolic shear deformation theory (IHSDT).The sinusoidal and uniform transverse mechanical loading is considered.

Xinwei Wang [15] has studied free vibration analysis of three-layer angle-ply symmetric laminated plates with free boundaries, including laminated plates with two adjacent free edges using by the discrete singular convolution discrete singular convolution (DSC) method. During formulating the weighting coefficients of derivatives having different orders, two Taylor series expansions with different orders are used to eliminate the degrees of freedom at fictitious points outside the physical domain. Thus, the difficulty in handling free boundary conditions by using the DSC is overcome.

Yanan Yuan, Xuefeng Yao, Bin Liu, Heng Yang, Haroon Imtiaz [16] have investigated the tensile strength and failure modes of thin ply carbon fiber-reinforced polymer (CFRP)angle-ply laminates by experiments and predicted by Finite element method (FEM)and theoretical model. Experimental results show that thin ply angle-ply laminates present different failure modes, and also the tensile strengths do not increase monotonically with the decrease in fiber areal weight. Second, both theoretical and FEM models are established to predict the strength and failure modes of thin ply CFRP angle-ply laminates with different ply thickness and fiber volume fraction.

Y.S. Joshan, Neeraj Grover, B.N. Singh [17] have developed a new non-polynomial shear deformation theory having four variables and assessed for hygro-thermo-mechanical response of laminated composite plates. An inverse hyperbolic function of thickness coordinate is used in the displacement field in order to consider the shear deformation effects. The analysis is on a laminated composite plate having cross ply fiber orientation.

Mokhtar Bouazza, Yamina Kenouza, Noureddine Benseddiq, Ashraf M.Zenkour [18] has investigated vibration behavior of orthotropic composite rectangular plate's withbyusing a refined simple nth-higher-order shear deformation theory. The transverse displacement is dividing into two bending and shear components and so the unknown involved functions is reduced to four, as against five or more in other plate theories. There is no need for any shear correction factors to the present theory.

Balakrishna Adhikari, B.N Singh [19] have developed a new simple Quasi 3-D theory based on linear variation of transverse displacement along the thickness of plate for free and forced vibration of laminated composite plates which are symmetric-cross ply and of square geometry. The theory satisfies both zero transverse shear stress conditions at top and bottom surfaces of the plate and non-linear distribution of transverse shear stresses across the thickness of plate.

Gao Lin, Pengchong Zhang, Jun Liu, Jianbo Li [20] have proposed A novel approach using scaled boundary finite element method (SBFEM)associated with the precise integration technique (PIT)for the analysis of laminated composite and sandwich plates. The approach is a layer-wise one. The governing equation is derived strictly based on the three-dimensional theory of elasticity, however, the formulation uses two-dimensional modeling in terms of translational displacements uz, ux and uy at the nodes. High-order spectral elements enable desired smoothness of the continuity to be achieved.

Jun Zhu, Jihui Wang, Aiqing Ni, Wantao Guo [21] have developed an analytical multi-parameter model based on the

classical lamination theory (CLT) and the study of the stiffness response for unidirectional composite laminates with out-of-plane ply waviness is followed. A range of parameters associated with the waviness defect, including the waviness geometry, the fiber off-axis angle, the extent of wavy region and the waviness pattern, are incorporated into the analytical model. The fiber volume fraction and the type of reinforcement are also taken into account in the parametric analysis.

Metin Aydogdu, Tolga Aksencer [22] have studied the Buckling of composite plates with linearly varying in-plane loads. First order and third order shear deformation plate theories are used in the formulation of the problem. Ritzmethod has been utilized with simple polynomials in displacement field. By modifying displacement field components, the continuity of transverse stresses is satisfied among the layers of cross-ply symmetric lay-up composite plates.

E. Carrera, M. Cinefra, G. Li [23] have presented some solutions for mechanical responses of angle-ply laminated plates under transverse distributed loads, which are obtained by using refined finite element models adopting variable kinematics based on Carrera's Unified Formulation (CUF).

G.S. Pavan, K.S. Nanjunda Rao [24] proposed the Isogeometric collocation for the linear static bending analysis of laminated composite plates governed by Reissner-Mindlin theory. The plates are having cross ply fiber orientation with square geometry. Three formulations are presented in this paper namely, standard primal formulation, mixed formulation and a locking-free primal formulation.

Detao Wan, Dean Hu, Sundararajan Natarajan [25] have developed a linear smoothed eight-nodeReissner-Mindlin plate element (Q8 plate element) based on the first order shear deformation theory for the static and free vibration analysis of laminated composite plates, the computation of the interior derivatives of shape function and isoperimetric mapping can be removed.

Marina Rakočević, Svetislav Popović, Nenad Ivanišević [26] have presented a new computational method for stress-strain analysis of simply supported rectangular cross-ply laminated composite plates subjected to transverse loads which was applied in the authors FORTRAN program code. The algorithm of the program is based on the layer wise theory of Reddy.Equations obtained by applying the principle of virtual displacements were solved in a closed form using double trigonometric series. For the adopted simply supported rectangular four-layer plate with anti-symmetric layer an analysis of dimensionless deflection change in the middle of the plate and displacement on the edge of the plate was performed, as well as the analysis of the ratio between the maximum values σxy/σyy and σyz/σyydue to the change of the aspect ratio a/b, the side-to-thickness ratio b/h and elastic modulus ratio E1/E2.

Tan-Van Vua, Ngoc-Hung Nguyenb, Amir Khosravifardc, and M.R. Hematiyanc [27] have presented an efficient numerical meshfreeapproach to analyze static bending and free vibration of functionally graded (FG) plates. The kinematics of plates is based on a novel simple FSDT, termed as S-FSDT, which is an effective four-variable refined plate theory. The S-FSDT requires C1-continuity that is satisfied with the basis functions based on moving Kriging interpolation. Some major features of the approach can be summarized: (a) it is less computationally expensive due to having fewer unknowns; (b) it is naturally free from shear-locking; (c) it captures the physics of shear deformation effect present in the conventional FSDT; (d) the essential boundary conditions can straight for wardlybe treated, the same as the FEM; and (e) it can deal with both thin and thick plates.

3. CONCLUSIONS

A review of the evolution of plate theories for composites along with the details of recent research work in the structural analysis based on available literature is presented in the present article. An effort has been made to include the important contribution in a range of composite plate problems with focus on recent work and emerging trends. The general remarks from the research survey are as follows:

(1) Usage of the composite material is increasing in the critical applications and research is based on criteria such as accuracy with 3D elastic solution (b) consideration of realistic boundary conditions, and material property discontinuity at the layer interfaces [29].

(2) The research evolved from classical, first order and other approximation of equivalent single layer theories to higher order theories which contains polynomial, exponential, trigonometric, hyperbolic shape functions so to calculate transverse shear strain effects and fulfills stress-free surface conditions and shear correction factors are avoided. The HSDT will give accurate plate models compared others [29].

(3) For bending, buckling analysis and effect of thermal analysis higher order shear deformation theory is more effective as compared to other methods of analysis of composite plates. By using finite element model of the plate for the various sides to thickness ratio, aspect ratio and modular ratio can give more accurate results [28].

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