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Post-buckling analysis of delaminated composite laminates with multiple through-the-width delaminations using a novel layerwise theory

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ABSTRACT

A novel layerwise theory based on the first order shear deformation theory (FSDT) has been proposed to evaluate the buckling and post-buckling behavior of delaminated composite plates with multiple through-the-width delaminations. The Rayleigh–Ritz Method has been adopted and displacement fields are obtained by incorporating simple and complete polynomial series which result in much less computational cost. The proposed layerwise theory provides a more realistic description of the kinematics of composite laminates when compared to Equivalent Single Layer theories. Both local buckling of the delaminated sublaminates and global buckling of the whole plate can be handled. The method is capable of predicting response of thick delaminated composite plates. Presence of multiple delaminations can also be handled. In order to prevent unacceptable penetration, contact constraints are imposed on the delaminated area. The three dimensional finite element analysis is performed using ANSYS5.4 commercial software. The results show a very good agreement with those obtained by the analytical Model.

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1. Introduction

Fiber-reinforced composite laminates are gaining importance in advanced lightweight applications such as aerospace and automotive structures due to their high stiffness and strength to-weight ratios as compared to metallic structures.

Beside their advantages, composite materials are prone to different types of damage. Delamination is one of the primary failure types in composite laminates and can arise from various causes such as technological imperfections, stress concentration near geometrical/material discontinuity and local or global buckling of plies. Once delamination has occurred, stresses within the composites redistribute themselves lowering the load carrying capacity of structure particularly in case of compressively loaded structures as the loss of stiffness may lead to buckling, the consequences of which can be catastrophic. Delaminations tend to grow rapidly under post-buckling loads, causing further reduction in structural strength which ultimately leads to structural failure. It is therefore of great importance to study the effect of delamination on the load-carrying capacity of the composites.

Generally, the laminated plate theories can be classified as either equivalent single-layer theories (ESL) or layerwise theories. In both cases, the 3D elasticity problem is reduced to a two dimensional (2D) problem. The classical laminate plate theories (CLPT) based on Kirchhoff's hypothesis ignores the effect of transverse shear deformation. The first-order shear deformation theory (FSDT) based on Raissner and Mindlin, assumes constant transverse shear stresses in the thickness direction, resulting in a need for shear correction factor to adjust for unrealistic variation of the shear strain/stress. In order to overcome the limitations of CLPT and FSDT, higher order shear deformation theories (HSDT) which involve higher-order terms in Taylor's expansion of the displacements in the thickness direction were developed [1]. The hypothesis commonly used in the ESL theories leads to a poor representation of strains in thick composite laminates or in case of having dissimilar material layers. Also, these methods cannot give accurate results of interlaminar stresses. In order to improve the quality of the analysis beyond what provided by conventional ESL theories without resorting to a full 3D analysis, layerwise theories have been developed in which displacement fields are defined for each layer, thus including discrete material and shear effects into the assumed displacement field. This leads to a greater degree of accuracy at the expense of more computational cost in comparison to ESL theories. These theories can present the zigzag behavior of the inplane displacements through the thickness which is more

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pronounced for thick laminates [1]. For a comprehensive review on laminated composite plate theories, the reader is referred to the work by Chen and Jia [2].

Experimental, analytical and numerical methods have been carried out by many researchers to analyze the buckling and post-buckling behavior of delaminated composite structures. Chai et al. [3] may have been the first who investigated this problem. They established a one dimensional analytical model to assess the compressive strength of a delaminated composites beam-plate. Kardomateas and Schmueser [4] investigated the effect of transverse shear on buckling and post-buckling of delaminated composites using a one-dimensional beam-plate model. They found that the transverse shear effects caused a reduction in the critical buckling load and an increase in the energy release rate. Kharazi and Ovesy [5] investigated the compressive stability behavior of composite laminates with through-the-width delaminations by developing an analytical method based on Rayleigh–Ritz approximation technique employing CLPT requirements. Kharazi et al. [6] further extended the method proposed in [5] to investigate the buckling load of composite plates with through-the-width delaminations using CLPT, FSDT, and HSDT. The early works in the field of layerwise modeling of structures date from the mid-30s and have been extensively reviewed by Carrera [7]. The early layerwise theory was proposed by Reddy [8]. On the basis of layerwise theory of Reddy, various exact solutions and finite element methodologies have been published and have been thoroughly reviewed by Reddy and Robbins [9] and Noor et al. [10]. Na and Reddy [11] developed a finite element model based on layerwise theory of Reddy for the analysis of delamination in cross-ply laminated beams which was able to capture accurate local stress fields and the strain energy release rates. The influence of boundary conditions and number of layers on the strain energy release rates and growth of delamination were studied. Hosseini-Toudeshky et al. [12], developed a finite element method (FEM) based on full layerwise theory of Reddy to study the post buckling behavior of delaminated composite laminates. Kharazi et al. [13] proposed a novel layerwise theory based on FSDT to predict the buckling load of delaminated composite plates. The theory was capable of predicting buckling response of relatively thick delaminated composite plates with a good degree of accuracy and much less computational cost as compared with common layerwise theories in the literature. Barbero and Reddy [14] extended the layerwise laminate theory of Reddy to study multiple delamination between the layers of a composite laminate and included geometric non-linearities. Lee et al. [15,16] discussed the buckling and post-buckling of axially loaded composite beam plates with multiple through the width delaminations using FEM based on a layerwise plate theory. Ovesy and Kharazi [17] proposed an analytical method based on FSDT to investigate the buckling and post buckling behavior of composite plates with multiple through-the-width delaminations.

The current paper contributes to the field of analyzing the post-buckling behavior of composite plates with multiple through-the-width delaminations using a novel layerwise theory proposed by authors (Kharazi et al. [13]). The analytical method is based on FSDT and the formulations are developed on the basis of the Rayleigh–Ritz approximation technique. The main difference between various layerwise theories proposed in the literature is in the different displacement fields considered e.g. polynomial or higher order functions. These theories require a finite element analysis with a large number of degrees of freedom for many layered composite structures. The proposed theory in this paper treats each numerical layer as a super element and does not require discretization of inplane displacements which reduces the number of degrees of freedom and hence results in much less computational cost. This method can handle both local buckling of the delaminated sublaminate and global buckling of the whole plate. It is also capable of predicting buckling response of relatively thick delaminated composite plates with a good degree of accuracy. The contact among sublaminates is also handled. The finite element analysis is carried out using ANSYS5.4 commercial software for verification. The agreement between the results is very good.

2. Modeling of delamination

The proposed layerwise theory can be successfully utilized for modeling single and/or multiple through-the-width delaminations. For the case of single delaminations, the reader is referred to the previous work by authors (Kharazi et al. [13]) for a detailed description of the theory and just the post-buckling results will be presented. In this part the analytical model and the applied theory in this study are briefly outlined for the case of modeling multiple through-the-width delaminations whether with equal or different lengths.

For layerwise modeling of displacement fields based on the theory proposed in this paper, the delaminated composite plate is divided into different plates in two general steps. First, the delaminated plateis divided into some regions. Fig. 1 shows typical discretization models for two different cases of multiple trough-the-width delaminations, one with two equal length delaminations and the other with two delaminations having different lengths. For the sake of brevity, just the latter case is described here. Second, for modeling the zigzag behavior of in-plane displacements through the thickness, each region is divided into a number of plates through the thickness. The number of plates in the thickness direction can be larger, smaller or equal to the number of layers in the composite plate based on the required amount of accuracy. However, the computational cost increases by increasing the number of plates in the thickness direction.

As shown in Fig. 1(b), the composite laminate is divided into seven regions. Each region is then divided into some plates through the thickness. Although the proposed theory can be applied for any number of layers in the laminate, for the sake of brevity, the displacement field are given for a case in which 13 different plates are considered (Fig. 2).

Different displacement fields should be considered for each separate plate. In this paper, FSDT is applied in the analytical formulation to account for the displacement fields in each plate. The FSDT assumptions are:

$u(x, y, z, t) = u_0(x, y, t) + z\varphi_x(x, y, t)$

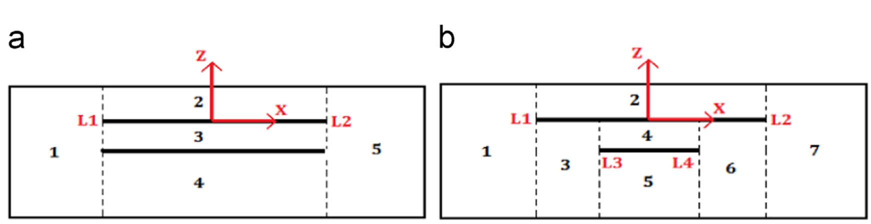

Fig. 1. Division of the laminate with multiple through-the-width delaminations into regions. (a) Equal length delaminations (b) Delaminations with different lengths.

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