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Behavior of composite laminates with embedded delaminations

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ABSTRACT

A Layerwise Higher Order Shear Deformation Theory is developed for plates containing rectangular embedded delaminations undergoing non negligible lateral deflections. The effects of different parameters of the composite laminate and delaminated area are investigated analytically under buckling load and the results are compared with the three dimensional finite element analysis. The results demonstrate the effects of different geometrical parameters of the delaminated area and thickness on the deflection of a composite laminate. Also the initiation of debonding in opening and sliding fracture modes is predicted using the developed formulation.

1. Introduction

Fiber-reinforced composite materials have been increasingly used over the past few decades in a variety of applications in which a fairly high ratio of stiffness and strength to weight is required, such as in marine structures. However, these materials are prone to wide range of defects and damages that can cause significant reductions in stiffness and strength. In particular, when the laminated composites are subjected to compressive loads, delamination becomes a constraint in the design process [1]. Delamination is one of the most serious failure modes and can be often pre-existing or generated during service life. It often occurs at stress free edges due to the mismatch of properties at ply interfaces. It can also be generated by external forces such as out of plane loading or low intensity impact during the service life [2–4]. It is therefore of great importance to understand the effect of delamination on the behavior of the composites.

One of the approaches to solve the delamination problems in plates is to use analytical theories. Ovesy and Kharazi [1] investigated the compressive buckling and post-buckling behavior of composite laminates with through-the-width and embedded delaminations analytically, based on the first order shear deformation theory (FSDT). Kharazi et al. [2] developed a novel layerwise theory based on FSDT to evaluate the buckling load of delaminated composite plates with through-the-width and rectangular embedded delaminations. They also continued their study using the above-mentioned theory to evaluate the buckling and post-buckling behavior of delaminated composite plates with multiple through-the-width delaminations [5]. Kharghani and Guedes Soares [6] investigated the effects of different parameters of the composite laminate and delaminated area analytically under buckling load based on a developed Layerwise Higher Order Shear Deformation Theory (LHSDT) and compared the results with the three dimensional Finite Element Analysis (FEM). Marjanović and Vuksanović [7] extended the layerwise plate theory of Reddy for the analysis of delaminations which was served as a basis for development of enriched finite elements. The proposed model assumes layerwise linear variation of in-plane displacements and constant transverse displacement through the plate thickness. The influence of this assumption as compared with other layerwise distributions is discussed in Mantari and Guedes Soares [8] who presented also a finite element formulation for the bending analysis of symmetric laminated and sandwich composite plates.

The ultimate strength of plates are important for marine structures, among others and Chen and Guedes Soares [9] presented a method for studying progressive collapse and the post-buckling compressive strength of laminated composite plates and stiffened panels under axial compression. The finite element technique has also played a significant role in the study of delamination under compressive loads. Hu et al. [10] conducted a buckling analysis of laminates with an embedded delamination by employing a finite-element method based on the Mindlin plate theory. An effective solution method was put forward to deal with the contact problem in the buckling mode. Riccio et al. [11] performed a crack growth analyses on composite panels containing embedded

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delaminations using a geometrically non-linear FEM code, based on the total Lagrangian formulation. Tafreshi and Oswald [12] developed finite element models to study global, local and mixed mode buckling behavior of composite plates with embedded delaminations under compression. The global modeling results were compared with corresponding experimental results. Wang et al. [13] applied the finite element method (FEM) using cohesive element to predict the delamination buckling and growth in slender laminated composite with embedded delamination under compressive load. In particular, the study is focused on the significant effects of delamination buckling for various parameters in slender composite laminate, such as model length–width ratio, delamination shape, delamination size, and delamination depth position. Carrera [14] developed a unified description of several models based on displacements and transverse stress assumptions. The order of the expansion in the thickness directions was taken as a free parameter. 2D modellings which include Zig–Zag effects, interlaminar continuity as well as Layer-Wise (LW), and Equivalent Single Layer (ESL) description were addressed. He also applied the unified formulation to assess theories of multilayered plates for various bending problems [15].

Han et al. [16] presented the analytical solution for composite plates with arbitrary embedded delaminations based on beam-shaped-function. The deflection function of the delaminated plate was composed by those of beams with the corresponding loading and support conditions, which can be easily and accurately derived from the beam analysis and the deflection amplitude was derived by the minimum potential energy principle.

The researchers who applied other methods in this area include Wang and Lu [17], who carried out an investigation to understand the buckling behavior of local delamination near the surface of fiber reinforced laminated plates under mechanical and thermal loads. The shape of the delaminated region considered is rectangular and triangular. Pradhan and Panda [18] investigated the influence of ply lay-up and the interaction of residual thermal stresses and mechanical loading on the inter-laminar asymmetric embedded delamination crack growth behavior. Park and Lee [19] dealt with parametric effects on bucking behaviors of laminated composite structures containing an embedded rectangular delamination using the enhanced assumed strain (EAS) three-dimensional element.

The current paper develops the formulation which had been presented based on Layerwise Higher Order Shear Deformation Theory (LHSDT) in [6] to be applied in conditions that the delaminated area and the laminate undergo non negligible lateral deflections and rotations. In this study, this formulation is used to investigate the consequences of different geometrical parameters of the delaminated area and thickness of the laminate on the deflection of a composite laminate containing rectangular embedded delamination under buckling condition. The formulation is obtained on the basis of Rayleigh–Ritz approximation technique and Pascal's triangle has been used to demonstrate the lateral direction effects in the modeling of the delaminated area. The number of degrees of freedom in LHSDT method is considerably less than Finite Element Analysis (FEA), therefore this method reduces the computational costs. ANSYS commercial software has been used for FEA.

2. Modeling of the rectangular embedded delamination

2.1. Layerwise HSDT (LHSDT)

When a thick composite laminate containing a small embedded delamination is subjected to uniaxial in-plane compression, only the global buckling mode can be observed (See Fig. 1). The in-plane compression can increase the possibility of the debonding propagation.

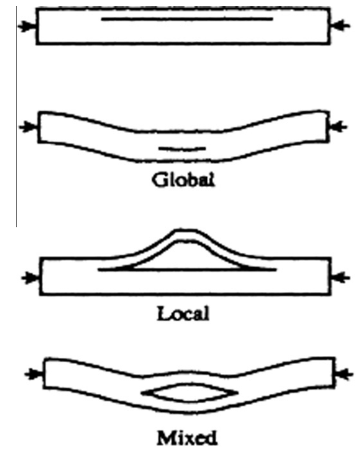

Fig. 1. Buckling modes for a delaminated composite plate.

In this section the rectangular embedded delamination has been modeled using Layerwise Higher Order Shear Deformation Theory (LHSDT) to predict the displacement fields. The HSDT assumptions according to the Reddy's third order shear deformation theory are:

$$\begin{Bmatrix}\bar{u}(x,y,z)\\ \bar{v}(x,y,z)\\ \bar{w}(x,y,z)\end{Bmatrix}=\begin{Bmatrix}u(x,y)\\ v(x,y)\\ w(x,y)\end{Bmatrix}+z\begin{Bmatrix}\varphi_x(x,y)\\ \varphi_y(x,y)\\ 0\end{Bmatrix}-z^3\alpha\begin{Bmatrix}\varphi_x+\frac{\partial w}{\partial x}\\ \varphi_y+\frac{\partial w}{\partial y}\\ 0\end{Bmatrix},\quad \alpha=4/(3t^2) \tag{1}$$

where $\bar{u}$, $\bar{v}$ and $\bar{w}$ are the components of displacements at a general point and u, v and w are similar components at the middle surface ($z=0$). In addition φ_x and φ_y are the rotations of the mid-plane normals about y and x axis respectively. "t" is the total thickness of the whole laminate (See Fig. 2). It should be mentioned that u, v and w are independent parameters from z direction. This implies neglecting the stretching effects ($\frac{\partial w}{\partial z}=0,$) and generating some discrepancies in the shear strain values γ_{xz} and γ_{yz} ($\frac{\partial u}{\partial z}=\frac{\partial v}{\partial z}=0$) along the thickness. This assumption simplifies the prediction of the shape functions and further calculations considerably. The advantage of this developed method is reducing the calculation cost despite of good agreement with the finite element results (see Section 3).

Some numerical methods such as Carrera Unified Formulation (CUF) have been mentioned in the literature, that present transvers-shear and thickness stretching in detail. (See [14,15,20,21]).

Using Eq. (1) in the Green's expression for nonlinear strains and neglecting lower order terms gives the following general expressions for strain at a general point:

$$\begin{Bmatrix}\bar{\varepsilon}_{xx}\\ \bar{\varepsilon}_{yy}\\ \bar{\varepsilon}_{xy}\\ \bar{\gamma}_{yz}\\ \bar{\gamma}_{xz}\end{Bmatrix}=\begin{Bmatrix}\frac{\partial u}{\partial x}+\frac{1}{2}\left(\frac{\partial w}{\partial x}\right)^2\\ \frac{\partial v}{\partial y}+\frac{1}{2}\left(\frac{\partial w}{\partial y}\right)^2\\ \frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}+\left(\frac{\partial w}{\partial x}\frac{\partial w}{\partial y}\right)\\ \varphi_y+\frac{\partial w}{\partial y}\\ \varphi_x+\frac{\partial w}{\partial x}\end{Bmatrix}+z\begin{Bmatrix}\frac{\partial \varphi_x}{\partial x}\\ \frac{\partial \varphi_y}{\partial y}\\ \frac{\partial \varphi_x}{\partial y}+\frac{\partial \varphi_y}{\partial x}\\ 0\\ 0\end{Bmatrix}\beta z^2\begin{Bmatrix}0\\ 0\\ 0\\ \varphi_y+\frac{\partial w}{\partial y}\\ \varphi_x+\frac{\partial w}{\partial x}\end{Bmatrix} \tag{2}$$

$$-\alpha z^3\begin{Bmatrix}\frac{\partial \varphi_x}{\partial x}+\frac{\partial^2 w}{\partial x^2}\\ \frac{\partial \varphi_x}{\partial y}+\frac{\partial \varphi_y}{\partial x}+2\frac{\partial^2 w}{\partial x\partial y}\\ \frac{\partial \varphi_y}{\partial y}+\frac{\partial^2 w}{\partial y^2}\\ 0\\ 0\end{Bmatrix},\quad \beta=3\alpha$$