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Variational analysis of free-edge stress and displacement fields in general un-symmetric and thin-ply laminates under in-plane, bending and thermal loading

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Abstract

A variational approach based on the minimization of complementary energy is developed to determine accurately a complete solution for both free-edge stress and displacement distributions of a laminate with arbitrary lay-ups (possibly un-symmetric and made of thin plies) under combined in-plane, bending and thermal loading. The key idea is partitioning the total stresses/displacements in a laminate with free edges into unperturbed (without free edges) and unknown perturbation stresses/displacements caused by the presence of free edges. It enables the theory of variational stress-transfer to deal easily with both applied traction and displacement boundary conditions. A methodology is introduced to obtain displacement fields for a stress-based variational approach. The resulting stress and displacement fields exactly satisfy local equilibrium equations, strain-displacement relations together with all traction/displacement boundary and continuity conditions. By comparing the results with those obtained from the finite element method, the accuracy and computational efficiency of the developed model, is confirmed.

Keywords: A. Laminates; B. Stress concentrations; B. stress transfer; C. Analytical modelling.

1. Introduction

It is well known that edge effects in laminated composites may lead to unstable growth of ply cracks and delaminations [1-5]. In order to prevent/predict such damage mechanisms, it is essential that a reliable methodology is developed to determine accurately the three-dimensional (3D) stress/displacement states near free edges caused by the mismatch of elastic properties between layers. Therefore, the capability of interlaminar stress analysis in laminates with straight free edges has been a major concern and its understanding has evolved over decades, from very first approximate shear-lag analysis of Puppo and Evensen [6] in 1970s, to equivalent single-layer (ESL) models [7] and more accurate layer-wise (LW) approaches [8, 9]. It is very difficult to find a closed form solution for the 3D differential equations of elasticity describing the free-edge effect and satisfying the required traction free

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