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Diagnosis of the Subsequent Failure Mechanisms of Composite Laminates

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ABSTRACT

The post-failure analysis of symmetric E-glass/Epoxy and Graphite/Epoxy (T300/934) laminates is presented in this paper. The main thrust of this research was to predict the progressive fracture mechanisms of composite laminates under load. Several composite laminates were tested under the three-point-bending configuration to observe and record the subsequent failure events. On the other hand, an analytical computational procedure based on lamination theory, Tsai-Hill failure theory, and an assumed stiffness reduction scheme was developed in an attempt to predict the failure mechanisms.

INTRODUCTION

In general, a composite laminate does not fail catastrophically but rather in a progressive manner. In other words, the final fracture of composite laminates always occurs after a sequence of ply failures. It is believed that a clear understanding of the potential failure mechanisms of composite laminates under designed loading will allow an in-depth risk assessment. To accomplish this, an analytical scheme for analyzing subsequent ply failure of composite laminates must be established. In addition, the subsequent failure analysis can even provide a database a field inspection engineer can use to evaluate the state of integrity of a composite structure when failure events are sited.

At present the subsequent failure analysis procedures that involve characterizing the failure mechanisms of actual structural components are still lacking. Petit and Waddoups (1969), introduced a negative tangent method to characterize the nonlinear stress-strain behavior (produced by the ply failure process) of composite laminates. Chiu (1969) introduced a stepwise stiffness reduction scheme to determine the post-failure strength of composite laminates. Craddock (1985) made a comparison among three stiffness reduction schemes, stepwise stiffness reduction, total stiffness reduction, and negative tangent method on their predictive capability on the stress-strain behavior of composite laminates. For all the cases, the Tsai-Hill (1950) failure criterion was used to assess the ply failure. It should be pointed out that these efforts have been concentrated on the axial stress-strain behavior of composite laminates. The effects of a biaxial or 3-dimensional state of stress were not taken into consideration. Furthermore, the effect of delamination during the failure process under 2-D and 3-D state of stress was not discussed.

In this paper, a subsequent failure analysis scheme that predicts the subsequent ply failure mechanisms of composite laminates under beam bending conditions is presented. Experimental data corresponding to two composite laminates under three-point-bending condition were obtained to evaluate the proposed procedures. Basically, the subsequent failure analysis presented here contains subroutines that perform the stress analysis of laminates, the failure analysis of each individual ply, the estimation of applied load, the stiffness reduction, and the geometrical restructuring. The delamination fracture was introduced based on the fact that it always developed in between an abrupt change in two subsequent failure mechanism. Also, the overall effect of delamination on the bending stiffness of damaged laminate was not accounted for. However, it is believed that the failure analysis scheme presented here represents a step closer to predicting the failure mechanisms of composite laminates than the methodologies presented in the literature.

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THEORETICAL BACKGROUND

The subsequent failure analysis procedure presented in this paper consists of three parts: (a) laminate analysis based on lamination theory, (b) assessment of ply failure load using the Tsai-Hill theory, (c) reconstruction of the laminate geometry and stiffness. To carry the analysis of a composite laminate from the first ply failure to the final rupture, steps (a) to (c) are repeated (Fig. 1). Some details about the theoretical background are given below.

Lamination Theory

The lamination theory is the most fundamental approach to analyze the mechanical response of a composite laminate under loading. The loading (Fig. 2) may include the bending moments $\{M_x, M_y, M_{xy}\}$, and/or in-plane forces $\{N_x, N_y, N_{xy}\}$ induced by temperature change, external mechanical loads, etc. The typical load deformation relation of a composite laminate is given as follows:

$$\{N\}=[A]\{\varepsilon_o\}+[B]\{\kappa\}$$
$$\{M\}=[B]\{\varepsilon_o\}+[D]\{\kappa\} \qquad (1)$$

where

$\{\varepsilon_o\}$ = the midplane strains of a laminate
$\{\kappa\}$ = the out-of-plane curvatures of a laminate

and $[A]$, $[B]$ and $[D]$ are the stretching, coupling and bending stiffness matrix, respectively. The stiffness matrices are related to the