FIRST PLY FAILURE ANALYSIS OF COMPOSITE PLATES

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Abstract: This paper is aimed to simulate the failure of selected fiber reinforced composite plates under transverse loading. A mathematical model and computational model are presented for the analysis. Higher Order Shear Deformation plate theory is utilized to predict the deformation of the plates. A failure criterion with the existence of coupling terms to determine the mode of failure for composite plates is employed to predict the failure. The uniqueness of this criterion compared to all other existing criteria is that it includes the coupling terms, which relate the interaction between the longitudinal stress and the transverse stresses. As a consequence, it allows the interaction between the fiber properties and the matrix properties in terms of the strength of the material, which other failure criteria have neglected. Variation of material properties through thickness is used and accommodated by a discrete layer approach. A program based on a finite element method is developed using Fotran-90 to determine the lamina stresses. These stresses are then used in the present failure model to determine the First Ply Failure. Finally, the First Ply results for various composite plates are analysed. The results obtained with current failure criterion are also compared with the results obtained with existing failure criteria. The stresses distribution obtained have proved that the present finite-element program could determine lamina and inter-lamina stresses accurately when compared to the exact solutions. The results of the failure analysis have shown that the present failure models could offer a better prediction of failure for any composite laminate.

Keywords: Laminated plate, Composite, FEA, Failure theory, First Ply Failure.

INTRODUCTION

In composite materials, failure is distinguished by its mode of failure. In fiber reinforced composite plates, failure in one direction of any single layer implies neither total failure of that layer, nor the whole structure. Load carrying capacity still exists not only in the structure, but also in the layer itself [1]. Therefore, the most common way to deal with failure of a composite laminate is by using definitions of First Ply Failure (FPF). First Ply Failure occurs when initial failure of a single layer in a laminate fails in any mode of failure. Therefore, the main objective of this paper is to determine the curves bounding the actual load carrying capacity in terms of the FPF of composite materials.

The most common and oldest method, in terms of finite element analysis for a laminated composite plate, is the standard laminate strength analysis. In 1982, Lee has performed the finite element based failure analysis by using his own direct mode determining failure criterion [1]. The major drawback of a three-dimensional failure analysis is the tremendous amount of memory space and calculation time required. This phenomenon leads to the search for more efficient finite element analysis of composite plates. Reddy and Pandey have developed a first ply failure analysis of composite laminates based on first order shear deformation plate theory [2]. Engblom and Ochoa develop a two-dimensional plate analysis to the above, but with increased interpolation in the through thickness direction [3]. Tolson and Zabaras have also developed two-dimensional progressive failure analysis of laminated composite plates, but employing higher order shear deformation theory [4]. Lee's [1] and Hashin's [5] failure criteria are used to determine the mode of failure. However, both criteria neglect the interaction of the coupling effect between the longitudinal stress and the transverse stress. Therefore, the main objective of this research is overcome this deficiency by developing a two-dimensional finite element computational formulation, which could perform the progressive failure analysis of selected fiber reinforced laminated composite plates by employing a failure criterion with interaction terms.

High Order Shear Deformation

Higher order shear deformation theory is developed to improve both the classical lamination theory and the first order shear deformation theory. A higher order term is included in the assumed displacements to describe the warping effect. According to the High-Order Shear Deformation Lamination Theory [6], the assumed displacements are as follows:

$$u(x,y,z) = u_0(x,y) - z\theta_x(x,y) + z^3\xi_x(x,y) \quad (1)$$

$$v(x,y,z) = v_0(x,y) - z\theta_y(x,y) + z^3\xi_y(x,y) \quad (2)$$

$$w(x,y,z) = w_0(x,y) \quad (3)$$

These formulations are employed in the finite-element program to determine the strains and stresses for the laminate analysis. Though the employment of this theory has made the computational analysis to become more complicated, the development of this theory has improved the results, especially for thick plates.

Algorithm for Computation

To determine the strength of a laminated plate, an incremental load analysis procedure is employed [7]. For a given load, the stresses in the material coordinates system for each lamina are calculated. These stresses are then inserted into the failure model to determine if failure has occurred within a lamina of any element. If no failure occurs, the load would be increased to initiate the first failure. The plate is meshed and each element has four Gauss points. The failure is checked for one by one layer of a Gauss point in an element. The mode of failure is distinguished by the present failure criterion. The criterion could predict compressive fiber failure, compressive matrix failure, tensile fiber failure or tensile matrix failure. Delamination is the final mode of failure. It is characterised by the interlaminar stresses acting between adjacent layers. An interface of two adjacent layers is identified as delamination failure if either

$$\frac{\sigma_3}{Y} = 1 \quad \text{or} \quad \frac{\left(\sigma_5^2 + \sigma_4^2\right)^{1/2}}{S_z} = 1 \quad (4)$$

where S_z is the through-thickness shear strength [8]. To ensure the reliability of the results, the present results are validated with other computational results [9,10]. A flow chart of the algorithm described is shown in Figure 1.

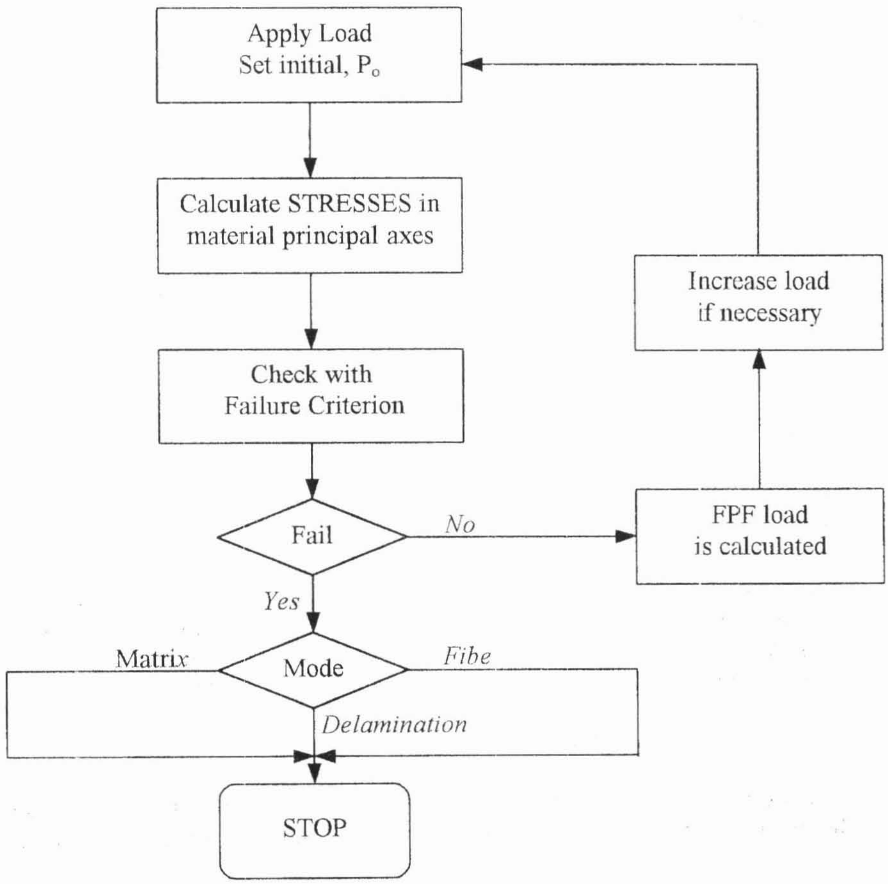

Figure 1: Flow chart diagram of the procedure for the first ply failure analysis

Failure Model

Considering transversely isotropic material [11], the equation used to determine the tensile failure in fiber mode is

$$(1+A)\frac{\sigma_1}{X_T}-\frac{\sqrt{AB}}{X_T Y_T}(\sigma_1\sigma_2+\sigma_1\sigma_3)-A\left(\frac{\sigma_1}{X_T}\right)^2+\frac{1}{S^2}\left(\tau_5^2+\tau_6^2\right)=1 \quad (5)$$

where $A=\frac{X_T}{X_C}$ and $B=\frac{Y_T}{Y_C}$.

The equation [11] used to determine the tensile failure in matrix mode is

$$(1+B)\frac{(\sigma_2+\sigma_3)}{Y_T}-\frac{\sqrt{AB}}{X_T Y_T}(\sigma_1\sigma_2+\sigma_1\sigma_3)-\frac{B}{Y_T^2}(\sigma_2+\sigma_3)^2+\frac{\tau_4^2}{R^2}+\frac{1}{S^2}\left(\tau_5^2+\tau_6^2\right)=1 \quad (6)$$

The equation [11] used to determine the compressive failure in fiber mode is

$$\sigma_1=X_C \quad (7)$$

The equation [11] used to determine the compressive failure in matrix mode is

$$\left(\frac{1+B}{B}\right)\left(\frac{\sigma_2+\sigma_3}{Y_C}\right)-\frac{1}{\sqrt{AB}}\left(\frac{\sigma_1\sigma_2+\sigma_1\sigma_3}{X_C Y_C}\right)-\frac{1}{BY_C^2}(\sigma_2+\sigma_3)^2+\frac{\tau_4^2}{R^2}+\frac{1}{S^2}\left(\tau_5^2+\tau_6^2\right)=1 \quad (8)$$

These failure criteria are employed in the analysis to check the failure of the fiber reinforced composite analysis. The advantage of this set of failure criterion is that it relates the strength of the fiber and the strength of the matrix, which ensures better predictions of failure.

Failure Analysis

The computer program is used to investigate the first ply failure loads of 0/45/45/0 laminated composite plates. The plate is subjected to a sinusoidally distributed transverse load where $P=P_0(\sin\pi x/a)(\sin\pi y/a)$. The plate is square with the dimensions of a x a. The thickness of the plate is h, with the aspect ratio, $S=a/h$. The analysis is performed on different aspect ratios. The aspect ratio is varied from 5 to 100. The length of the plate is 40 mm. Only a quarter of the plate needs to be modelled due to the geometric symmetry of the problem. The plate is simply supported and the boundary conditions are shown in Figure 2. In this analysis, sixteen eight-noded elements are used to insure reasonable accuracy in stress calculations. The material and strength properties used are glass/epoxy, E-glass/epoxy, and S-glass/epoxy composites. Further analysis is done on glass/epoxy composite plate. The lay-up studied is 0/θ/θ/0, where θ is varied from 0° to 90°.

RESULTS AND DISCUSSIONS

The normalised FPF loads, FPF* loads are calculated and plotted against the aspect ratio and the graphs are shown in Figure 3 and Figure 4. The graphs are plotted in such a way to compare the three selected plate. 'Unnormalised Load' refers to the actual FPF load, $\boldsymbol{P_0}$. The failure loads in the graph have been normalised as

$$FPF^* = (FPF)S^2/10^6 \quad (9)$$

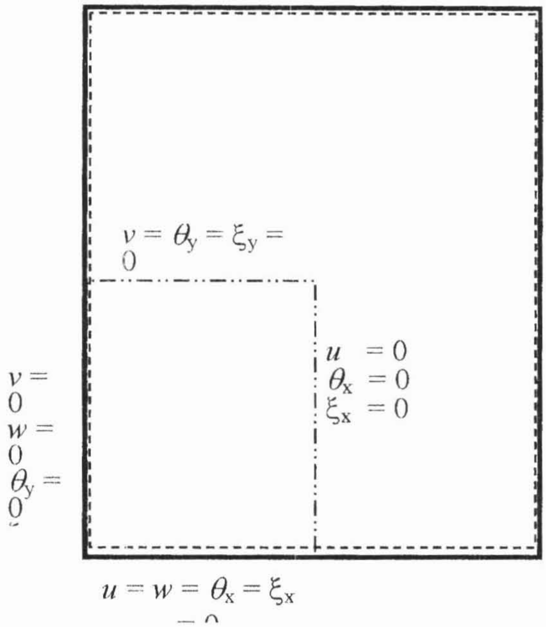

Figure 2: The boundary condition for quarter of a square plate.

Figure 3 shows the First Ply failure curves for the 0/45/45/0 composite plates as a function of aspect ratio. This graph exhibits significantly the true load carrying capacities for the analysed plate. The results show that FPF curve maintains an equal percent difference throughout. This is due to the coupling terms in the present criterion, where the interaction of the stresses in the longitudinal and transverse direction has improved the boundary of the FPF laminate. Figure 3 also shows the FPF of the three different types of composite plates, which are Glass/epoxy, E-glass/epoxy, and S-glass/epoxy. It is obvious that generally, the behaviour of the plates that constitute the failure is the same. However, the loads that fail the S-glass/epoxy plate are much higher than the E-glass-epoxy. Also, the loads that fail the E-glass-epoxy plate are much higher than the Glass/epoxy. This is true based on the material properties compared. The strengths of S-glass/epoxy are much higher than E-glass/epoxy. Similarly, the strengths of E-glass/epoxy are much higher than Glass/epoxy. However, the first ply failure that occurred on all plates is tensile matrix failure.

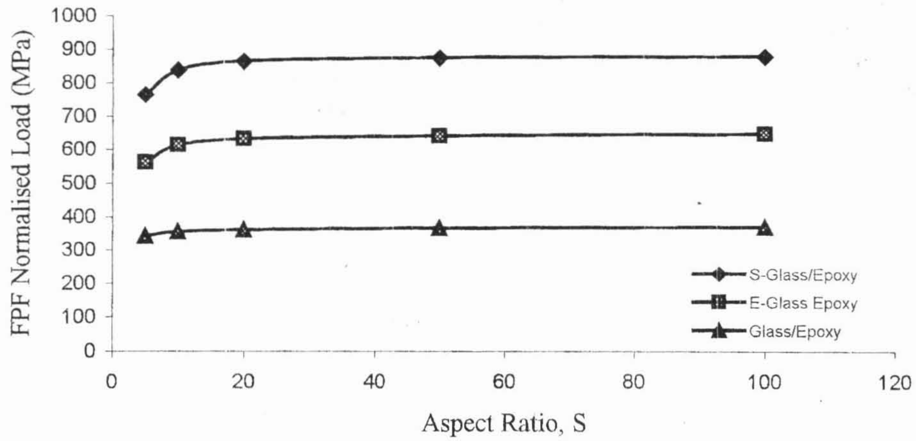

Figure 3: The normalized FPF loads of composite plates

Figure 4 shows the First Ply failure curves for Glass/epoxy composite plate with lay-up 0/θ/θ/0, where θ ranges from 0° to 90°. It is observed that the behaviour of the composite plates that constitute the failure is the same for all different lay-up. Nevertheless, the loads that fail the Glass/epoxy plate for 0/45/45/0 lay-up are the highest. It is also observed that the loads that fail the plates for 0/0/0/0 and 0/90/90/0 [7] are closer to each other as the aspect ratio is increased. Similarly, the curves are also same for the pair of 0/15/15/0 and 0/75/75/0 as well as for pair of 0/30/30/0 and 0/60/60/0 plates.

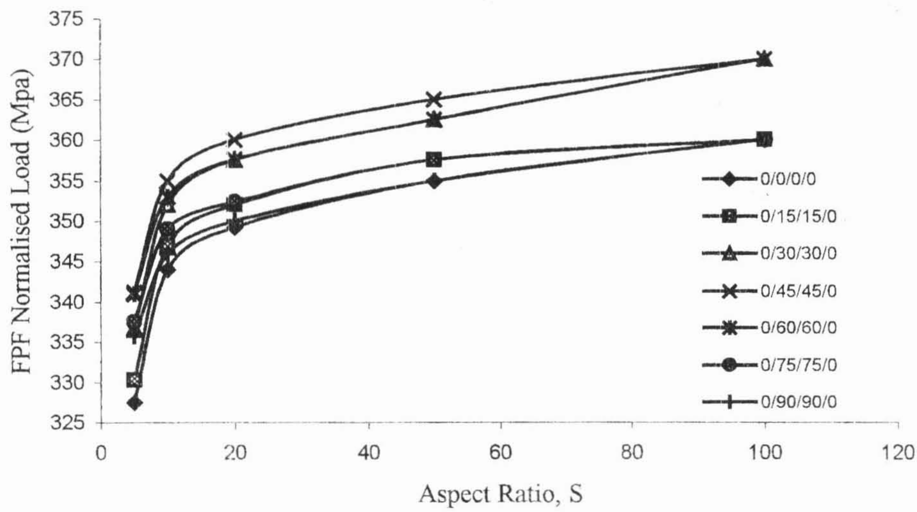

Figure 4: Normalised FPF load for different lay-up of Glass/Epoxy composite plate

As shown in Figure 4, the weakest plate is the plate with lay-up of 0/0/0/0 and 0/90/90/0. The lay-up of 0/45/45/0 is the best lay-up for glass/epoxy composite plates for designer or engineer to select, as it requires high load for first ply failure to occur. However the Glass/epoxy plate for the lay-up of 0/45/45/0 is much lower than the other composite plates present in Figure 3.

CONCLUSION

This paper presented the application of numerical analysis using Finite Element Method to predict the deformation of composite materials based on the Higher Order Shear Deformation Theory. The stresses are calculated and checked with present failure criteria, which include the coupling terms to predict failure. The First Ply Failure is analysed to determine the region of the true load carrying capacity. The results of the analysis shown in Figure 3 and 4 shows that the main objective of the research that to perform the first ply failure analysis of fiber reinforced composite materials has been achieved successfully. In ensuring the reliability of the results, before conducting the simulation, the finite-element based program has been validated with exact solutions gained from reliable referred sources, as well as other numerical solution. Finally, the results show that the present failure criterion with the existence of coupling terms, improve the prediction of the First Ply Failure.

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