PROGRESSIVE FAILURE ANALYSIS OF LAMINATED COMPOSITE PLATES WITH ELLIPTICAL OR CIRCULAR CUTOUT USING FINITE ELEMENT METHOD

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Abstract. The progressive failure analysis of symmetrically laminated composite plate \([0°/+45°/-45°/90°]_2s\) with circular or elliptical cutout under uniform uniaxial compression loading is carried out using finite element method. Hashin’s failure criterion is used to predict the lamina failure. A parametric study has been carried out to study the effect of elliptical / circular cutout orientation, cutout size and plate thickness on the ultimate failure load of laminated composite plate under uni-axial compression loading. It is noticed that elliptical cutout orientation has influence on the strength of the notched composite plates. It is observed that the laminate size of the elliptical/circular cutout and plate thickness has substantial influence on the ultimate failure load of notched composite plates.

1. Introduction

Among the other structural materials, composites have become popular because of their high strength and stiffness-to-weight ratio. As the enthusiasm for using composite materials in marine, aerospace and automobile structures is increasing, designers are trying to understand the damage mechanisms under compressive, tensile and combined loading conditions and damage propagation and modes. For predicting the failure modes, damage propagation and failure loads in fibre-reinforced composite structures, progressive failure analysis methodology has been implemented in finite element analysis codes. Numerous finite element programs such as ABAQUS, NASTRAN and ANSYS are currently available for carrying out progressive failure analysis.

Damage modes such as fiber breakage in tension and compression, matrix cracking and delamination are generally observed in composite structures. Fiber breakage and matrix cracking are called as intra-laminar damage and delamination damage mode is called as called inter-laminar damage. These intra-laminar and inter-laminar damages can lead to major strength reduction in the post-damage performance of the structure. In general, A laminate failure may not be catastrophic
under thermal, environmental and mechanical loads. The layer which fails first is called as the first ply failure (FPF) and that the composite continues to take more loads until all the plies fail, the layer which fails at last is called as the Last ply failure (LPF). Failed plies may still contribute to the stiffness and strength of the laminate. The degradation of the stiffness and strength properties of each failed lamina depends on failure criteria followed by the designer. To predict the failure of the laminated composites, there are two categories of failure criteria; (i) Failure criteria associated with failure modes such as Tsai-Wu, Tsai-Hill, Modified Tsai-Wu and Hoffman (ii) Failure criteria not associated with failure modes such as Maximum stress, Maximum strain, Hashin and Puck criteria.

After the stress distribution in the laminate has been determined, a failure criterion is used to determine if the laminate has failed at a certain point. To predict the failure load and failure propagation, failure criteria should be used in conjunction with progressive failure analysis. New strength properties will be assigned failed elements according to the degradation rule and the failure mode until the final failure.

In recent years extensive research work has been done on the progressive failure analysis of laminated composite structures. Most of the investigations concerned with progressive failure analysis of composite plates without cutout [1-11] and plates with circular cutout [12-18]. However, very little concern has been shown regarding the progressive failure analysis of composite plates with elliptical/circular cutouts under in-plane compressive load. Reddy and Pandey [1,3] have carried out finite element analysis for first-ply failure analysis of laminated composite plates subjected to in-plane and/or transverse loads and later they have extended their earlier work on first-ply failure of two-dimensional laminated composites to include a progressive failure analysis procedure. B.G.Prusty [2] carried out a progressive failure analysis of unstiffened and stiffened composite panels under transverse loading using the finite element method. Tsai–Wu failure criterion was used in the progressive failure analysis to predict the failure. P.Pal and C.Ray [4] presented the progressive failure analysis of laminated composite plates under transverse static loading and parametric study has been carried out. Singh S.B and Ashwin K presented [5,6] the post buckling behaviour and progressive failure response of symmetric laminates under uniaxial compression and uniaxial compression combined with in-plane positive and negative shear. In the progressive failure analysis to predict the failure of ply, 3-D Tsai-Hill criterion is used. They have studied the influence of in-plane boundary conditions, aspect ratio of plate, lay up sequence and fiber orientations on the first ply failure load and ultimate failure loads using progressive failure method. T.Y. Kam et.al [7] studied on the first-ply failure of thin laminated composite plates subjected to transverse loading using nonlinear finite element method and numerous failure criteria were used to predict first-ply failure loads of the laminated plates. S.Tolson and N.Zabaras [8] carried out progressive failure analysis to determine first and last ply failure loads of a laminated composite plate subjected to a sinusoidal distributed transverse pressure load. Numerous failure criteria from various categories were used in the analysis. Pal and Bhattacharyya S.K [9] performed the progressive failure analysis of laminated composite plates under transverse static loading. They have studied the effect of ply layup, fiber orientation and thickness of the layer on ultimate failure load using progressive failure method. S.M. Spottswood and A. N. Palazotto [10] studied on progressive failure analysis of composite shells subjected to transverse loading. Analytical and experimental results were compared. G.S.Padhi et.al.[11] studied on progressive failure analysis of laminated composite plates with clamped edges, subjected to transverse pressure using the general propose finite element program ABAQUS. Numerical and experimental results were compared.
Tsau et al. [12] studied on progressive failure analysis using Hashin’s failure criterion to predict the damage initiation and accumulation process in the static strength of composite laminates with a circular hole subjected to equal biaxial uniform tensile load. Parma Nand Jah and Ashwin Kumar [13] used non-linear finite element method to study the first ply failure load of thin laminated composite plates under combined effect of in-plane (shear and uniaxial compression) and transverse loads using Maximum stress, Maximum strain, Tsai-hill, Hoffman and Tsai-Wu criterions. Jain and Kumar [14] investigated the post buckling analysis of symmetric square laminates with a central cutout under uniaxial compression using finite element method and they studied the effect of circular cutouts and size of circular cutout on the first-ply failure loads and buckling loads of laminated composite plates. D. R. Ambur et.al [15] studied on progressive failure analysis of composite curved panels subjected to compression loading and without and with a circular cutout using finite element analysis software ABAQUS. Results from finite element analysis compared with test data. P. P. Camanho et.al [18] examines the use of a continuum damage model to predict strength and size effects in notched carbon–epoxy laminates. The studies are very few on Progressive failure analysis of composite plates with cutouts under uniform axial compressive loads. In the literature it is observed that the effect of orientation of cutout, cutout size and laminate thickness on the ultimate failure load of rectangular composite plates is needed to be investigated in more detail. The objective of present study using progressive failure analysis method is to predict the strength of composite plate with circular/elliptical cutout. The damage mode and damage path also obtained using finite element methods. Hashin’s failure criterion is used in the present progressive failure analysis.

2. Present study

In this study, progressive failure analysis of symmetrically laminated composite plate \([0^\circ/+45^\circ/-45^\circ/90^\circ]\) with circular or elliptical cutout under uniform uniaxial compression loading is carried out using finite element method. Furthermore, orientation of elliptical cutout, size of elliptical/circular cutout, thickness of plate on ultimate failure load are investigated.

Figure 1 shows loading and geometry of the composite model. The width \((b)\) and length \((a)\) of the composite plate are 100mm and 200mm, respectively. Each layer thickness of this composite plate is 0.125mm and the thickness of the composite plate is “t”. In the present work the elliptical cutout was placed in the center of the rectangular composite plate. The major and minor axis dimension are \(c\) and \(d\) and major and minor axis diameters are changed to selected ratios i.e \(c/b\) and \(d/b\) ratios, so that the elliptical hole will become as circular hole when \(c/b\) and \(d/b\) ratios are equal. Briefly, progressive failure analysis is performed for both different sized circular and elliptical holes. The plate is modeled using ANSYS software using [16] eight-node shell elements (Shell 281). Finite element mesh for laminated composite plate with elliptical cutout is shown in figure-2. The two edges \((y = 0\) and \(y = b))\) are free, whereas the other two edges are fixed \((x = 0\) and \(x = a))\). The applied compression loading is considered displacement.
controlled. Thermal residual stresses due to composite processing temperature ($T_{ref} = 180^\circ C$) are considered. In the analysis, the loading is applied over three load steps. During the first load step thermal loading is applied, as a result of the temperature difference between the processing and operating temperature; thermal residual stresses are calculated. During the second load step displacements are assigned resulting from free thermal expansion. During the third load step mechanical loading is applied. The progressive damage of the composite plate is simulated using the MPDG method. The damage evolution method used in the present analysis using ANSYS is material property degradation method (MPDG). Any physical failure criteria (for example Hashin criteria) can be used to detect the onset of the damage. The material stiffness is instantly reduced based on the damage variables. In the present analysis hashin failure criteria is used.

**Table 1.** Material properties of the Graphite/Epoxy composite material.

| $E_{11}$ (GPa) | $E_{22}$ (GPa) | $G_{12}$ (GPa) | $G_{13}$ (GPa) | $G_{23}$ (GPa) | $\alpha_{11}$ (µm/m/°C) | $\alpha_{22}$ (µm/m/°C) | XT (MPa) | XC (MPa) | YT (MPa) | YC (MPa) | S (MPa) |
|---------------|---------------|----------------|----------------|----------------|-------------------------|-------------------------|----------|----------|----------|----------|--------|
| 181           | 10.3          | 0.28           | 7.17           | 1.53           | 0.02                    | 22.5                    | 1500     | 1500     | 40       | 246      | 68     |

4. **Verification of the results**

The validity of the present method is checked by comparing the ultimate failure strength with the available literature results. Table 2 shows the comparison of the ultimate failure strength in the present study and literature study. Laminate dimensions, circular cutout size, boundary conditions and material properties were taken as given in Ref. [19]. Literature results [19] and present methodology results are in agreement.

**Table 2.** Comparison of ultimate failure strengths of composite plate with circular cutout.

| Reference         | Experimental result in reference [19] | In reference (ABAQUS) | In present study (ANSYS) |
|-------------------|----------------------------------------|-----------------------|--------------------------|
| Liu et.al. 2010 [19] | 397.1                                  | 360.6                 | 386.47                   |
As investigated by Liu’s et al.[19], the Experimental ultimate failure strength and ultimate failure strength obtained by using ABAQUS software were 397.1Mpa and 360.6 Mpa, respectively and which gives 9.2% variation from the experimental ultimate failure strength. In the present method, failure strength obtained from the progressive failure analysis using ANSYS software is 386.47Mpa which give 2.67% variation from the experimental strength from the Liu et al. model.

5. Hashin failure criterion
In the present analysis Hashin failure criterion is used in which four failure modes are used to estimate the failure of the laminates [17]. These failure modes are as follows: (i) Matrix tensile failure (ii) Matrix compression failure (iii) Fibre tensile failure (iv) Fibre compression failure. In the present analysis Hashin failure criterion [17] is used to predict the damage initiation or the onset of damage in the laminate. The Hashin Criteria for the four different failure modes are described in Equations (1) – (4) as follows. In the below equations, σ_{ij} are the components of the effective stress tensor, and X^T and X^C are the tensile and compressive strengths in the longitudinal direction, Y^T and Y^C are the tensile and compressive strengths in the transverse direction, and S^L and S^T are the shear strengths in longitudinal and transverse directions.

Fiber tension (σ_{11} ≥ 0)

\[ 1 = \left( \frac{\sigma_{11}}{X^T} \right)^2 + \left( \frac{\tau_{12}}{S^L} \right)^2 \]  

(1)

Fiber Compression (σ_{11} ≤ 0)

\[ 1 = \left( \frac{\sigma_{11}}{X^C} \right)^2 \]  

(2)

Matrix tension (σ_{22} ≥ 0)

\[ 1 = \left( \frac{\sigma_{22}}{Y^T} \right)^2 + \left( \frac{\tau_{12}}{S^L} \right)^2 \]  

(3)

Matrix compression (σ_{22} ≤ 0)

\[ 1 = \left( \frac{\sigma_{22}}{2S^T} \right)^2 + \left( \frac{\tau_{12}}{2S^L} \right)^2 - 1 \]  

(4)

Figure 1. Loading and geometry of the Model.
6. Results and discussion

6.1 Effects of cutout orientation and cutout size (d/b ratio) on the ultimate failure load of a composite plate with a elliptical/circular cutout

In this section the effects of orientation of cutout $\beta$ and cutout size (d/b ratio) on the ultimate failure load of a laminated composite plate with a elliptical/circular cutout. In this section c/b ratio is taken as 0.4 and d/b ratio varied from 0.1 to 0.4. The effects of cutout orientation $\beta$ and cutout size (d/b ratio) on the ultimate failure load of a laminated composite plate with a elliptical/circular cutout is shown in Fig. 3. Hashin failure criterion is used to predict the ultimate failure load in this analysis. Figure 3 indicates that the ultimate load decreases when the cutout size increases i.e., d/b ratio increases. For the composite plate $\{0^\circ/\pm45^\circ/\pm45^\circ/90^\circ\}_{2s}$ with c/b=0.4 & a/b=2, as the cutout size increases from d/b=0.1 to 0.2, 0.3 and 0.4, the reduction in ultimate failure load is 26%, 42% and 54%, respectively. From the Fig. 3, it is also observed that, reduction rate in ultimate failure load decreases, as the cutout size increases.

From figure 3 it is understood that the ultimate load decreases as the orientation of cutout $\beta$ increases from $0^\circ$ to $90^\circ$. For the laminated composite plate $\{0^\circ/\pm45^\circ/\pm45^\circ/90^\circ\}_{2s}$ with a/b=2 & c/b=0.4 & d/b=0.1, as the cutout orientation $\beta$ increases from $0^\circ$ to $90^\circ$, the reduction in ultimate failure load is 60%. For the composite plate $\{0^\circ/\pm45^\circ/\pm45^\circ/90^\circ\}_{2s}$ with c/b=0.4, d/b=0.2 & a/b=2, as the orientation of cutout $\beta$ increases from $0^\circ$ to $90^\circ$, the reduction in ultimate failure load is 45%. For the composite plate $\{0^\circ/\pm45^\circ/\pm45^\circ/90^\circ\}_{2s}$ with d/b=0.3 & c/b=0.4 & a/b=2, as the orientation of cutout $\beta$ increases from $0^\circ$ to $90^\circ$, the reduction in ultimate failure load is 24%. Hence as the cutout size increases, the influence of orientation of cutout decreases on the ultimate failure load. As seen from figure 3e and 3f, when the orientation of cutout is $\beta = 90^\circ$, the effect of cutout size on ultimate failure load is not significant. When the orientation of cutout is $\beta = 0^\circ$, the effect of cutout size on ultimate failure load is significant.
Figure 3. Effect of the cutout orientation and cutout size (d/b ratio) on the ultimate failure load.
6.2 Effect of the plate thickness on the ultimate failure load of a laminated composite plate with a elliptical/circular cutout

In this section, the effect of thickness of plate on the ultimate failure load of a laminated composite plate with an elliptical/circular cutout cutout. In this section c/b ratio is taken as 0.4 and d/b ratio varied from 0.1 to 0.4. The effect of the plate thickness on the ultimate load of a laminated composite plate with a elliptical/circular cutout cutout is shown in Figure 4. As the thickness of the plate increases ultimate failure load also increases. [0°/+45°/-45°/90°]4s (32 layers) composite plate is 1.3, 2 and 4 times stronger of the composite plates [0°/+45°/-45°/90°]3s (24 layers), [0°/+45°/-45°/90°]2s (16 layers), [0°/+45°/-45°/90°]1s (8 layers), respectively. It is seen from the detailed investigation that the Location of the first ply failure of composite plate with elliptical/circular cutout is at two sharp corners of the cutout. Location of the first ply failure of composite plate without cutout is at outer edge of the laminate. The mode of first ply failure is matrix tension. For composite plate with elliptical cutout, first ply failure layer is 0° layer. For composite plate without cutout, first ply failure layers are 45° and -45°.
6.3 Damage evolution pattern for [0°/+45°/-45°/90°]2s laminated composite plate with elliptical cutout (c/b=0.4 & d/b=0.1)

Progressive damage pattern is shown in Figure 5. Figure 5(a) represents fiber tensile failure pattern, Figure 5(b) represents fiber compressive failure pattern, Figure 5(c) represents matrix tensile failure pattern and Figure 5(d) represents matrix compressive failure pattern. It is seen from the detailed investigation that the location of damage of laminated composite plate with elliptical cutout is at cutout edge.

**Figure 4.** Effect of the plate thickness on the ultimate failure Load.
Figure 5. Damage evolution pattern for composite plate $[0^\circ/+45^\circ/-45^\circ/90^\circ]_{2s}$ with elliptical cutout ($c/b=0.4$ & $d/b=0.1$) (a) Fiber tensile failure (b) Fiber compressive failure (c) Matrix tensile failure (d) Matrix compressive failure.
7. Conclusions
Based on the progressive failure analysis of a symmetrically laminated $[0^\circ/+45^\circ/-45^\circ/90^\circ]_2s$ graphite/epoxy rectangular composite plate with a central elliptical/circular cutout under uniform uniaxial compression loading, the following conclusions are drawn:

i) For a rectangular composite plate with a central elliptical/circular cutout, ultimate failure loads magnitudes are decreased by increasing the d/b ratio. i.e., as the cutout size increases ultimate failure load decreases.

ii) Ultimate failure loads magnitudes are decreased by increasing the orientation of cutout $\beta$ ie. 0° to 90°.

iii) As thickness of the plate increases ultimate failure load increases. $[0^\circ/+45^\circ/-45^\circ/90^\circ]_4s$ composite plate is 1.3, 2 and 4 times stronger of the composite plates $[0^\circ/+45^\circ/-45^\circ/90^\circ]_3s$, $[0^\circ/+45^\circ/-45^\circ/90^\circ]_2s$, $[0^\circ/+45^\circ/-45^\circ/90^\circ]_1s$, respectively.

iv) It is seen from the detailed investigation that the Location of damage of composite plate with elliptical/circular cutout is at cutout edges. It is seen from the detailed investigation that the Location of the first ply failure of composite plate with elliptical/circular cutout is at two sharp corners of the cutout. Location of the first ply failure of composite plate without cutout is at outer edge of the laminate.

v) For composite plate $[0^\circ/+45^\circ/-45^\circ/90^\circ]_2s$ , the mode of first ply failure is matrix tension. For composite plate $[0^\circ/+45^\circ/-45^\circ/90^\circ]_2s$ with elliptical cutout, first ply failure layer is 0° layer. For composite plate without cutout, first ply failure layers are 45° and -45°.

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