STRENGTH PREDICTION AND DAMAGE ASSESSMENT OF LAMINATED COMPOSITE PLATES WITH RECTANGULAR/SQUARE CUTOUT USING FINITE ELEMENT METHOD

A. Lakshminarayana, R. Vijayakumar  
Manager (Design), Senior Manager (Design)  
Rotary Wing R & D Centre (RWRDC)  
Hindustan Aeronautics Limited (HAL)  
Vimanapura Post  
Bangalore-560 017, India  
Email : alnarayana2005@gmail.com  
rayavarapu.rvk@gmail.com  

G. Krishnamohana Rao  
Professor  
Department of Mechanical Engineering  
Jawaharlal Nehru Technological University  
Hyderabad-500 085, India

Abstract

The progressive failure analysis of symmetrically laminated rectangular composite plate \([0^\circ +45^\circ /-45^\circ /90^\circ ]_2s\) with square/rectangular cutout under uniform uniaxial compression loading is carried out using finite element method. Hashin's failure criterion is used to predict the failure of lamina. A parametric study has been carried out to study the influence of square/rectangular cutout size, cutout orientation and plate thickness on the ultimate failure load of laminated composite plate under uniaxial compression loading. Ultimate failure loads were computed for six different laminate configurations \([0^\circ +45^\circ /-45^\circ /90^\circ ]_2s\), \([75^\circ /60^\circ /30^\circ /-15^\circ ]_2s\), \([0^\circ /90^\circ ]_4s\), \([-45^\circ /45^\circ ]_4s\), \([15^\circ /-75^\circ ]_4s\), \([30^\circ /-60^\circ ]_4s\). It is observed that the laminate stacking sequence, plate thickness, cutout size and cutout orientation has substantial influence on the ultimate failure load of notched composite plates.

Keywords: Cutout Size, Cutout Orientation, Material Property Degradation Method, Stacking Sequence, Plate Thickness, Progressive Failure Analysis, FEM

Introduction

In aeronautical, automobile and marine industries the use of composite laminates has increased due to their high stiffness and strength-to-weight ratios, long fatigue life, resistance to electrochemical corrosion and other superior material properties of composites. A true understanding of structural behaviour is essential. The buckling loads, ultimate loads and modal characteristics, deflections as well as through-thickness distributions of stresses and strains are important for obtaining strong, reliable multi-layered structures and to examine the failure characteristics.

The load carrying ability of the material after it undergoes the first ply failure and before last ply failure is of great importance in the study of composites. Since composite laminates can often withstand a much higher load after the first occurrence of localized damage such as matrix cracking, fiber breakage or delaminations. Knowledge of the failure characteristics related to the first ply failure, delaminations and the ultimate load of such structures is essential for designers to design efficient and reliable structure. In recent years extensive research work has been done on the progressive failure analysis of laminated composite structures. Cutouts are used in aircraft industry for inspection of hydraulic, electrical and fuel lines and some times to reduce the weight, as shown in Fig.1. 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 square/rectangular cutouts under in-plane compressive load. Reddy and Pandey [1] have presented a finite element procedure based on the first order shear deformation theory for
first-ply failure analysis of laminated composite plates subjected to in-plane and/or transverse loads. Prusty [2] presented a progressive failure analysis methodology using the finite element method for laminated unstiffened and stiffened composite panels under transverse loading cases. The progressive failure analysis using the Tsai-Wu failure criterion has been implemented into a general-purpose finite element code to predict the failure loading from the initial to the final stage. Pandey and Reddy [3] have extended their earlier work on first-ply failure of two-dimensional laminated composites to include a progressive failure analysis procedure. They have used a linear element. Pal and Ray [4] presented the progressive failure analysis of laminated composite plates under transverse static loading in linear and elastic range. The first-order shear deformation theory has been applied and a shear correction factor is used. A parametric study has been done on the progressive failure analysis.

Singh and Ashwin studied [5] the post-buckling behaviour and progressive failure response of thin, symmetric laminates under uniaxial compression load. First-order shear deformation theory has been applied and geometric non-linearity in the von Karman sense were used with a finite-element procedure. The 3-D Tsai-Hill criterion was used to predict failure of a lamina and the maximum stress criterion is used to predict onset of delamination at the interface of two adjacent layers. The effect of plate aspect ratio and ply lay-ups on the buckling load, first-ply failure load and ultimate failure load were studied. Singh and Ashwin [6] investigated the post-buckling behaviour and progressive failure response of thin, symmetric laminates under in-plane positive and negative shear load. First-order shear deformation theory has been applied and geometric non-linearity in the von Karman sense are used with a finite-element procedure. The 3-D Tsai-Hill criterion was used to predict failure of a lamina and the maximum stress criterion is used to predict onset of delamination at the interface of two adjacent layers. The effect of in-plane boundary conditions, lamina material properties, plate lay-ups, plate aspect ratio, and fiber orientations on the buckling load, first-ply failure load, ultimate load and the maximum transverse were studied. Kam et al. [7] investigated on the deformation and first-ply failure of thin laminated composite plates subjected to transverse loading using nonlinear finite element method. Using several phenomenological failure criteria first-ply failure loads of the laminated plates were determined. Tolson and Zabaras [8] used the composite failure analysis computer program to determine first and last ply failure of a laminated composite plate subjected to a sinusoidal distributed transverse pressure load. They have used seven degree of freedom higher order shear deformation plate theory. Five failure criteria from various categories were used in the analysis. Pal and Bhattacharyya [9] studied the progressive failure analysis of laminated composite plates under transverse static loading. They have investigated the influence of stacking sequence, fiber orientation and layer thickness on ultimate failure load using progressive failure method. Spottswood and Palazotto [10] studied on progressive failure analysis of composite shells subjected to transverse loading. Analytical and experimental results were compared. Padhi et al. [11] studied on progressive failure analysis of laminated composite plates with clamped edges, subjected to transverse pressure. The general propose finite element program ABAQUS was used for the analysis. Numerical and experimental results were compared.

Tsau et al. [12] studied on progressive failure analysis 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. Hashin’s failure criterion [17] is used to predict the failure of lamina. Parmanand 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. The finite element formulation was based on first-order shear deformation theory. They have used Maximum stress, Maximum strain, Tsai-hill, Hoffman and Tsai-Wu criterions to predict the first ply failure loads. Jain and Kumar criteria [14] performed the post-buckling analysis of symmetric square laminates with a central cutout under uniaxial compression by finite element method. Jain and Kumar investigated the effect of circular cutouts and size of the on the first-ply failure and buckling loads of laminates. Ambur et al. [15] studied on progressive failure analysis of composite curved panels with and without a circular cutout and subjected to axial compression loading using finite element analysis. ABAQUS software was used for the analysis. Results from finite element analysis compared with test data. Some investigators [19-21] examines the use of a Continuum Damage Model (CDM) to predict strength of laminated plates. Lakshmi Narayana et al. studied effect of circular/elliptical/rectangular/square cutouts on the ultimate strength of composite plate using progressive failure analysis in ANSYS [22-23].

A very few Studies have been carried out on Progressive failure analysis of composite plates with cutouts
under compressive loads. The results presented in the literature indicate that the effect of cutout shape, size and laminate stacking sequence on the ultimate failure load of rectangular composite plates is needed to investigate in more detail.

In this paper the effect of square and rectangular cutouts on the ultimate failure load of graphite/epoxy symmetrically laminated rectangular composite plates subjected to uniform uniaxial compressive loading is examined using FEM. Hashin’s failure criterion is used in the present progressive failure analysis.

Present Study

In this study, a numerical study using finite element method has been carried out to investigate the effect of square and rectangular cutouts on the ultimate failure load of quasi-isotropic \([0^\circ/+45^\circ/-45^\circ/90^\circ]_2s\) graphite/epoxy symmetrically laminated rectangular composite plates subjected to uniform uniaxial compressive loading. Furthermore, the effects of size of cutout, orientation of cutout, laminate layup and plate length/thickness ratio on ultimate failure load is investigated.

Figure 2 shows the geometry and loading of the model. The width ‘b’ and length ‘a’ of the plate are 100mm and 200mm, respectively. The thickness of each layer of this sixteen layer laminated composite plate is 0.125mm and ‘t’ is the thickness of the composite plate. In this study the cutout shape was assumed rectangular hole and placed in the center of the rectangular plate and \(\beta\) is taken as 0° and 90°. The length of the cutout denoted by ‘c’ and width of the cutout denoted by ‘d’. In Table-1, the material properties of graphite/epoxy are listed.

Finite Element Modelling

In this study, progressive failure analysis in ANSYS (non linear analysis) is used for predicting the ultimate failure load of a rectangular composite plate with a rectangular/square cutout. Using Hashin failure criterion ultimate failure loads are predicted. The plates are modeled using [16] eight-node shell elements (Shell 281) and each node have six degrees of freedom. Finite element mesh for laminated composite plate with square cutout is shown in Fig.3.Two edges of the plate are fixed, whereas the other two edges are free. The two longitudinal edges (\(x = 0\) and \(x = a\)) are clamped, whereas the other two edges are free (\(y = 0\) and \(y = b\)). The applied compression loading is considered displacement controlled. Thermal residual stresses due to composite processing temperature (\(T_{\text{ref}} = 180^\circ\text{C}\)) 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.

Progressive failure/damage analysis for the composite plate with cutout (square/rectangular/elliptical/circular) was conducted in ANSYS using the Material property degradation model implemented in ANSYS [16] to represent the intralaminar damage modes such as matrix failure and fiber failure. The intralaminar damage models such as matrix failure and fiber failure, implemented in ANSYS are briefly explained below.

The Material property degradation model implemented in ANSYS to simulate intralaminar damage such as matrix failure and fiber failure. Four failure modes including fiber tension [rupture] and fiber compression [kinking], matrix tension [cracking] and matrix compression [crushing] are considered and are separately represented. Onset of damage at a material point which refers to the Initiation of damage is based on Hashin’s failure theory [17]. The Hashin’s failure criteria for the four
different failure modes are explained in equations 1 to 4 as follows:

Fiber tension \((\sigma_{11} \geq 0)\)

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

(1)

Fiber compression \((\sigma_{11} \leq 0)\)

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

(2)

Matrix tension \((\sigma_{22} \geq 0)\)

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

(3)

Matrix compression \((\sigma_{22} \leq 0)\)

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

(4)

In the above equations, \(\sigma_{ij}\) are the components of the effective stress tensor, and \(X^T\) and \(X^C\) are the longitudinal tensile and compressive strengths, \(Y^T\) and \(Y^C\) are the tensile and compressive strengths in the matrix direction, and \(S_L\) and \(S_T\) denote the longitudinal and transverse shear strengths.

Damage initiation refers to the onset of damage at a material point. In the present analysis using ANSYS, the damage initiation criteria used is Hashin’s criteria. For every step and substep of nonlinear FE solution, the components \(\sigma_{11}, \sigma_{22}, \tau_{12}\), of the effective stress tensor \(\sigma\) at every material point are calculated and used to reevaluate the initiation criteria. The effective stress tensor is assumed to be the stress acting over the area of section that still remains undamaged. \(\sigma\) is the nominal stress over the entire section area, including the damaged and undamaged portions. Prior to the damage initiation the material is linearly elastic with the stiffness matrix of a plane stress orthotropic material. There after the response of the material is computed from the constitutive equations.

\[\sigma = D_d \varepsilon\]

Where

\(D_d = \) Damaged elasticity matrix
\(\varepsilon = \) Total elastic strain

The damaged elastic matrix \(D_d\) can be expressed as

\[
D_d = \frac{1}{A}\begin{bmatrix}
(1-d)E_f & (1-d) (1-d_m) \nu_{12} E_f & 0 \\
(1-d) (1-d_m) \nu_{21} E_m & (1-d) E_m & 0 \\
0 & 0 & A (1-d) G_{jm}
\end{bmatrix}
\]

(5)

Where

\[A = -\nu_{12} \nu_{21} (1-d_f) (1-d_m)\]

\(E_f, E_m\) and \(G_{jm}\) = Undamaged elastic and shear moduli

\(\nu_{12}, \nu_{21}\) = Poisson’s ratios for the undamaged material

\(d_f, d_m, d_s\) = Fiber, matrix and shear damage variables. Valid values are between 0 and 1 where 0 = no damage and 1 = complete loss of stiffness in the affected mode. The damage variables \((d_f, d_m, d_s)\) for calculating the damaged elasticity matrix are determined as follows:

\[D_f = \begin{cases}
\tilde{\sigma}_{11} \geq 0 \\
\tilde{\sigma}_{11} < 0
\end{cases}
\]

\[D_m = \begin{cases}
\tilde{\sigma}_{22} \geq 0 \\
\tilde{\sigma}_{22} < 0
\end{cases}
\]

\[d_s = (1-d_f) (1-d_f) (1-d_m) (1-d_m)
\]

The damage variables \((d_f, d_m, d_s)\) are calculated for all plies of each laminated element and are derived from the damage variables \(d_f, d_f, d_m, d_m\) corresponding to four failure modes as discussed above. In the present analysis damage variables are taken as 0.9 when the corresponding damage mode is initiated.

**Verification of Results**

The accuracy of the method is reviewed by comparing the ultimate failure strength with the results available in the literature. Table-2 presents the comparison of the
ultimately failure strength in the literature and those in this study. For comparison, laminate dimensions, material properties, and boundary conditions were similar to those given in Ref.[18]. The results available in literature are in agreement with those in this study. In Liu’s et al. work the experimental failure strength was 397.1Mpa, while the failure strength obtained from the progressive failure analysis using ABAQUS was 360.6 Mpa which give 9.2% variation from the experimental strength). In the present method, failure strength obtained from the progressive failure analysis using ANSYS is 386.47Mpa which give 2.67% variation from the experimental strength from the Liu et al. model.

**Discussion of Results**

**Effects of Cutout Size (d/b ratio) as well as Laminate Stacking Sequence on the Ultimate Failure Load of a Composite Plate with a Rectangular/Square Cutout**

This section deals with the effects of cutout size (d/b ratio) as well as composite ply layup sequence on the ultimate failure load of a rectangular composite plate with a square/rectangular cutout. In this section c/b ratio is taken as 0.4, d/b ratio varied from 0.1 to 0.4. The effects of cutout size (d/b ratio) as well as composite ply layup sequence on the ultimate failure load of a rectangular composite plate with a square/rectangular cutout is shown in Fig.4. Hashin failure criterion is used to predict the ultimate failure load in this analysis. Fig.5 indicates that the ultimate load decreases when the cutout size increases i.e., d/b ratio increases. For the composite plate [0°/+45°/-45°/90°]_{2s}, 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 12%, 39% and 52%, respectively. From the Fig.4, it is also observed that, as the cutout size increases from d/b=0.1 to 0.2, 0.3 and 0.4, the reduction in ultimate load is different for different stacking sequences.

It can be seen that, [0°/+45°/-45°/90°]_{2s} composite plate is stronger than [0°/+45°/-45°/90°]_{2s}, [75°/60°/30°/15°]_{2s}, [15°/-75°]_{4s}, [30°/-60°]_{4s}, composite plates. [0°]_{4s}, composite plate is strongest and [30°/-60°]_{4s} composite plate is weakest than other analyzed laminated composite plates. Strength of [0°]_{4s} composite plate is 12.6 times of the strength of [30°/-60°]_{4s}, [0°/+45°/-45°/90°]_{2s} and [75°/60°/30°/15°]_{2s} respectively.

**Effect of Cutout Orientation β and Cutout Size on the Ultimate Failure Load of a Rectangular Composite Plate with a Square/Rectangular Cutout**

In this section, the effects of orientation of cutout β and cutout size (d/b ratio) on the ultimate failure load of a laminated composite plate with a square/rectangular cutout has been studied. 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 β and cutout size (d/b ratio) on the ultimate failure load of a lamianted composite plate with a square/rectangular cutout is shown in Fig.5. Hashin failure criterion is used to predict the ultimate failure load in this analysis. Fig.5 indicates that the ultimate load decreases when the cutout size increases i.e., d/b ratio increases. For the composite plate [0°/+45°/-45°/90°]_{2s}, 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 18%, 31% and 42%, respectively. For the composite plate [0°/+45°/-45°/90°]_{2s}, as the cutout size increases from d/b=0.1 to 0.2, 0.3 and 0.4, the increase in ultimate failure load is marginal. From the Fig.5, it is also observed that, reduction rate in ultimate failure load decreases, as the cutout size increases.

From Fig.5, it is understood that the ultimate load decreases as the orientation of cutout β increases from 0° to 90°. For the laminated composite plate [0°/+45°/-45°/90°]_{2s}, 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 12%, 39% and 52%, respectively. From the Fig.4, it is also observed that, as the cutout size increases from d/b=0.1 to 0.2, 0.3 and 0.4, the reduction in ultimate load is different for different stacking sequences.
Effect of the Plate Aspect Ratio on the Ultimate Failure Load of a Rectangular Composite Plate with a Square/Rectangular Cutout

This section deals with the effect of plate aspect ratio on the ultimate failure load of a rectangular composite plate with a square/rectangular 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 rectangular composite plate with a square/rectangular cutout is shown in Fig.6. As the thickness of the plate increases ultimate failure load also increases. \([0/45/-45/90]_{1s}\) (32 layers) composite plate is 1.3, 2 and 4 times stronger of the composite plates \([0/45/-45/90]_{2s}\) (24 layers), \([0/45/-45/90]_{2s}\) (16 layers), \([0/45/-45/90]_{1s}\) (8 layers), respectively.

First Ply Failure Location for Composite Plate \([0/45/-45/90]_{2s}\) with Rectangular or Square Cutouts

This section deals with the location of first ply failure of composite plate with rectangular/square cutout. Damaged elements are represented in red color and undamaged elements are represented in blue color. It is seen from the detailed investigation that the Location of the first ply failure of composite plate with rectangular/square cutout is at two edges of the cutout as shown in Fig.7. Location of the first ply failure of composite plate without cutout is at outer edge corner of the laminate as shown in Fig.7. The mode of first ply failure is matrix tension for all cutout sizes. For composite plate with rectangular/square cutout, first ply failure layer is 0 degree layer. For composite plate without cutout, first ply failure layers are 45 degrees and -45 degrees.

Damage Evolution Pattern for Composite Plate \([0/45/-45/90]_{2s}\) with Rectangular Cutout (c/b=0.4 and d/b=0.1)

Progressive damage pattern is shown in Fig.8. Damaged elements are represented by red color and undamaged elements are represented by blue color. Fig.8(a) represents fiber tensile failure pattern, Fig.8(b) represents fiber compressive failure pattern, Fig.8(c) represents matrix tensile failure pattern and Fig.8(d) represents matrix compressive failure pattern. It is seen from the detailed investigation that the location of damage of composite plate with square/rectangular cutout is at cutout edge. Figs.9 and 10 represents damage evolution pattern for composite plate \([0/45/-45/90]_{2s}\) with rectangular cutout (c/b=0.4 and d/b=0.1) and cutout orientation \(\beta=0\) and \(\beta=90\) degrees.

Conclusions

Based on the progressive failure analysis of a graphite/epoxy symmetrically laminated rectangular composite plate with a central rectangular/square cutout under uniform uni-axial compression loading, the following conclusions are drawn:

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

- Ultimate failure loads magnitudes are decreased by increasing the orientation of cutout \(\beta\) i.e. 0° to 90°. When the orientation of cutout is \(\beta=0\)°, the effect of cutout size on ultimate failure load is not significant.

- \([0/90\]_{1s}\) composite plate is stronger than other analysed \([0/45/-45/90]_{2s}\), \([15/-75/30/-15]_{2s}\), \([-45/45]_{1s}\), \([15/-75]_{1s}\), \([30/-60]_{1s}\) composite plates.

- \([0/90]_{1s}\) composite plate is strongest and \([30/-60]_{1s}\) composite plate is weakest than other analysed laminated composite plates. Ultimate failure strength of \([0/90]_{1s}\) composite plate is 12.6 times of the \([30/-60]_{1s}\) composite plate.

- As thickness of the plate increases ultimate failure load increases. \([0/45/-45/90]_{4s}\) composite plate is 1.3, 2 and 4 times stronger of the composite plates \([0/45/-45/90]_{1s}\), \([0/45/-45/90]_{2s}\), \([0/45/-45/90]_{3s}\), respectively.

- It is seen from the detailed investigation that the Location of the first ply failure of composite plate with rectangular/square cutout is at two edges the cutout. Location of the first ply failure of composite plate without cutout is at outer edge corner of the laminate.
• For composite plate $[0/+45/-45/90]_2s$, the mode of first ply failure is matrix tension for all cutout sizes. For composite plate $[0/+45/-45/90]_2s$ with rectangular/square cutout, first ply failure layer is $0^\circ$ layer. For composite plate without cutout, first ply failure layers are $45^\circ$ and $-45^\circ$.

References


Technical Memorandum 214282, National Aeronautics and Space Administration, 2006.


Fig. 4 Influence of the d/b Ratio on the Ultimate Failure Load
Fig. 5 Effect of the Cutout Orientation and Cutout Size (d/b Ratio) on the Ultimate Failure Load

Fig. 6 Effect of the Plate Thickness on the Ultimate Failure Load
Fig. 7 First Ply Failure Location for Composite Plate \([0/\pm 45/-45/90]_2\) with \(c/b=0.4\) and \(\beta=0\) degrees
(a) Without Cutout  (b) \(d/b=0.1\)  (c) \(d/b=0.2\)  (d) \(d/b=0.3\)  (e) \(d/b=0.4\)
Fig. 8 Damage Evolution Pattern for Composite Plate \([0/45/-45/90]_2\) with Rectangular Cutout \((c/b=0.4 \text{ and } d/b=0.1)\)

(a) Fiber Tensile Failure  (b) Fiber Compressive Failure
Fig. 8 Damage Evolution Pattern for Composite Plate \([0/\pm 45/90]_2\), with Rectangular Cutout \((c/b=0.4 \text{ and } d/b=0.1)\)

(c) Matrix Tensile Failure  
(b) Matrix Compressive Failure
Fig. 9 Damage Evolution Pattern for Composite Plate $[0^\circ/+45^\circ/-45^\circ/90^\circ]_2$ with Rectangular/Square Cutout
$(c/b=0.4, d/b=0.2$ and $\beta=0^\circ$)

Fig. 10 Damage Evolution Pattern for Composite Plate $[0^\circ/+45^\circ/-45^\circ/90^\circ]_2$ with Rectangular Cutout
$(c/b=0.4, d/b=0.2$ and $\beta=90$ degrees)