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Stress Analysis and Ultimate Strength Prediction of Laminated Composite Panels With Cutouts

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***Abstract*—Composite materials consisting of stiff and strong fibers reinforcing compatible matrices in laminate configurations are engineered materials widely used in aerospace, automobile and other engineering applications. Stress analysis and strength prediction of laminated composite structures is complex due to highly nonlinear behavior resulting from progressive ply failure. The present study focus is on, how nonlinear progressive ply failure analysis can go beyound first ply failure and perform further damage propagation. This enable to make a fine estimation of conditions for ultimate failure so it optimize designs. The FEM in general and a commercial FEA software MSC NASTRAN in particular is demonstrated in this study for accurate stress analysis and ultimate strength prediction of laminated composite panels with circular and elliptical cutouts.**

Keywords—composite; progressive failure; ultimate strength.

I. INTRODUCTION

In current engineering technology, use of composite materials increased specially in aerospace and automotive applications over the last few decades and also in non-aerospace products. Composites offer a superior performance over the traditional materials in high strength, stiffness, cost effectiveness , durability, dimensional stability etc.The failure of a lamina in a laminate does not mean failure, as the failure of the laminate is progressive. The analysis of failure of a laminate is therefore more complicated than a single lamina. Various parameters such as stacking sequence, orientation of fibres and others prescribe the strength of the laminate.

The design of reinforced cutouts in laminated composite Structures is of great importance in aerospace, automobile, and mechanical engineering. Accurate stress analysis to predict layer wise stresses in the material coordinates and progressive failure analysis to predict the ultimate strength deserve in a depth study. In structural members circular openings are preferred generally but, there are other configurations which give certain distinct advantage over circular shape like elliptical etc. Progressive failure is an analysis technique that uses a stress based failure criteria to predict when material failure will initiate and then will reduce the siffness of failed material to simulate how failure progressive.

II. LITERATURE REVIEW

Many research studies have been carried out to analyse the performance of composite structures. This section sum up the few research done in progressive failure analyses over the past years.

David W. Sleight, Compose a progressive failure analysis method based upon classical theory of plate and shell elements. A Newton-Raphson solution technique was employed to solve the nonlinear Eqns. for either an applied load or displacement situation. Hashin, Christensen and maximum strain failure criteria were compared with the converged stresses. Results indicate good comparison with experimental data and the overprediction of the final failure load for all criterion considered.

Navin Jaunky, Damodar R. Ambur, Carlos G. Dávila, and Mark Hilburger, They carried out an analytical and experimental study to evaluate the initiation and progression of damage in nonlinearly deformed curved panels with and without cutout subjected to axial compression. Here the effect of initial geometric imperfections and cutout size is also investigated.

Th. Kermanidis, G. Labeas, K.I. Tserpes and Sp. Pantelakis, Auther developed 3D progressive damage model of bolted single lap composite joints under in-plane tensile Stresses analysis and ultimate strength prediction of laminated composite panels with cutout loading in order to predict the ultimate strength. Stress analysis of model is performed using FE code ANSYS and for progressive damage analysis a macro-routine is incorporated in ANSYS. Hashin's failure criteria is used for the progressive damage analysis. They concluded that the geometry of bolted of bolted hole configuration can dramatically influence both the initiation of damage and the residual strength.

Larry Pearce, demonstrated progressive ply failure analysis on open hole tension specimen using MSC NASTRAN finite element package. He used Puck failue criterion for progressive failure analysis and shows different progressive damages also make known the force v/s displacement graph to get ultimate failure load.

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III. PROBLEM STATEMENT

A 15-ply tensile specimen containing a centrally located circular hole is considered as shown in Fig 1. The composite laminate is 5.85 inches (148.59 mm) long and 1.5 inches (38.1 mm) wide with a hole diameter of 0.25 inches (6.35 mm). The thickness of each ply is 0.01inches (0.254 mm) and the laminate stacking sequence is $[(\pm45)_2/90/(\pm45)/\bar{0}]_s$. The material of model is T300/5208 Graphite/epoxy.

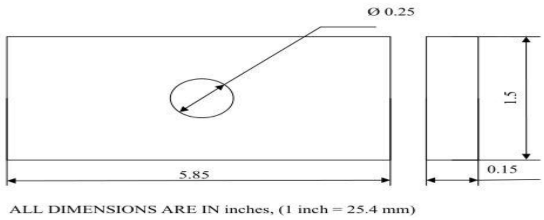

Fig.1. Geometric details of panel with circular cutout

Table 1. Material properties of T300/5208 Graphite/epoxy

Elastic constsnt's		
E 1 , young"s modulus in longitudinal direction	17e6 psi	117.212 Gpa
E 2 , young"s modulus in transverse direction	1.4e6 psi	9.653 Gpa
υ, Poissons ratio	0.34	0.34
G, Shear modulus	4.5e5 psi	3.103 Gpa
Failure data for Puck failure criteria		
Maximum fiber tension , X_t	200 ksi	1378.96 Mpa
Maximum fiber compression , X_c	100 ksi	689.48 Mpa
Maximum matrix tension, Y_t	15 ksi	103.422 Mpa
Maximum matrix compression, Y_c	30 ksi	206.844 Mpa
Layer shear strength, S_{12}	15 ksi	103.422 Mpa
Slope of failure envelope, P12C	0.35	0.35
Slope of failure envelope, P12T	0.35	0.35
Slope of failure envelope, P23C	0.27	0.35
Slope of failure envelope, P23T	0.27	0.35

IV. OBJECTIVE

The overall aim is to develop and validate the finite element model of composite panels with circular and elliptical cutouts, to perform the stress analysis and to predict the ultimate strength by progressive failure analysis.

Specific objectives of the project are:

- Development of finite element model for progressive failure analysis.
- Validation of finite element model using benchmark.
- Determination of failure locations and failure modes.
- Plot the graph of force v/s displacement.
- Predict the ultimate strength of composite laminate.

V. METHOD AND METHODOLOGY

A general purpose program based on Finite Element Method (FEM) executed on a computer provides a universal tool for engineering analysis, design optimisation, and simulation. Purpose of analysis is to justify a design prior to manfacture. There are several methods of engineering analysis, the most extensive is the Finite Element Analysis (FEA). The Finite Element Method is fundamentaly influenced for its capable performance use of the digital computers and its ability to deal with complex geometries, support conditions, applied loads, and material properties enter into this condition. A basic requirement to perform engineering analysis by FEM is a controlled mathematical model i.e the collection of all equations and data that can be used to foretell the performence. FEM provides numerical solutions to the selected mathematical model, which possibly different depending on the objectives of the analysis. In the following sections nonlinear finite elements for composite structures specifically formulated for progressive failure analysis, an overview of nonlinear finite element analysis software and the specific capability of MSC NASTRAN/ PATRAN used in the present study are presented.

VI. PROGRESSIVE PLY FAILURE ANALYSIS

A model has been put into MSC.Nastran Implicit Nonlinear to allow the progressive failure of certain types of composite materials. Progressive failure behavior for various materials can be simulated using the MATF Bulk Data entry. Failure occurs when any one of the specified failure criterion is satisfied. When failure index is larger than one, degrade material moduli. Upon failure, the elastic modulus reduces to 10% of the original, at the integration point are reduced to the lowest modulus specified. The behavior up to the failure point is linear elastic even if an elasto-plastic material is specified, which is followed by a nonlinear behavior for the post-failure analysis.

MSC/NASTRAN offers different methods to simulate the material degradation such as gradual degradation, immediate degradation etc. In the present study, gradual degradation option is used to simulate the PPF analysis.

Various software establish composites design analysis with more sophisticated predictions of stresses, strengths and failure modes. The Puck Criterion analytical model is the first that can analyze the strength of fibers separately from the matrix.The Puck criteria can separate fiber failure from matrix failure when analyzing composite strength. Before now, the Tsai/Wu Criterion has been the traditional analytical model, but it doesn't distinguish between fiber and matrix failure.

Performing step-by-step analysis by MSC NASTRAN/ PATRAN

a. Development of Finite Element Model with B.C

The geometric modeling of the panel with hole and base mesh for the model is generated in MSC PATRAN using CQUAD4 (Plane strain quadrilateral plate) element. Panel was discretized by 1200 number of elements and 1305 number of nodes. The left side edge of panel is fixed for rotation and traslation. The right side edge is subjected to displacement controlled tensile loading by using RBE2 (Rigid Bar Element). The RBE2 element is actually a constraint element that prescribes the displacement relationship between two or more grid points. An initial displacement of 0.2 inches (5.08 mm) is applied to the laminate. The finite element model with B.C for the problem is shown in Fig 2.

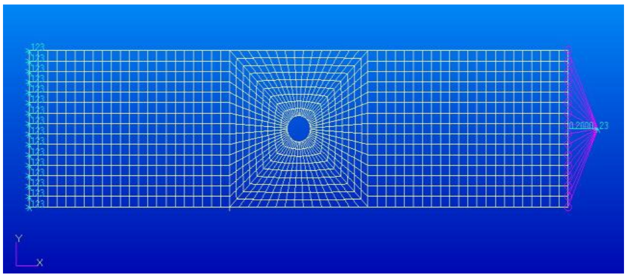

Fig 2. The FE model with B.C for panel with cutout

b. Defining failure criteria and Laminated Composite panel

The composite laminate is a rectangular panel with thickness 0.15 inches (3.81mm) consisting of 15 layers stacked in the sequence $[(\pm45)_2/90/(\pm45)/\overline{0}]_s$. A progressive failure analysis is performed using Puck criterion

c. Analysis procedure and results

The progressive failure analysis of the tensile specimen is analyzed using implicit nonlinear application module. Progressive failure behavior for various materials can be simulated using the MATF (Material failure model) Bulk Data entry. Fist analyze entire model by analysis deck method, then Open the newly created input file .bdf wih world editor, search for MATF and change third field to 2 (for gradual progressive failure analysis) and save modified file. And run the modifed file into MD NASTRAN.

Results of progressive ply failure analysis to get ultimate load on T300/5208 Graphite/epoxy panel is presented here. Fig 3(a to d) to Fig 5(a to d) shows plots for fiber, matrix and total damage progressive failure for different ply angles.

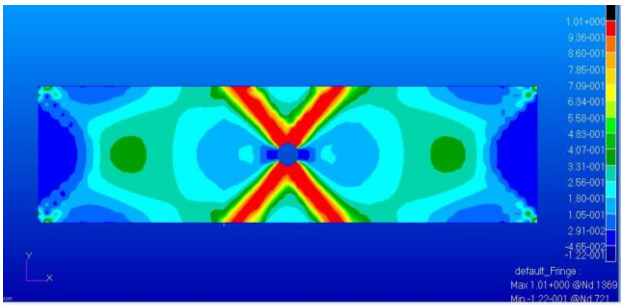

Fig 3a, Fiber damage for progressive failure, ϴ = 0˚

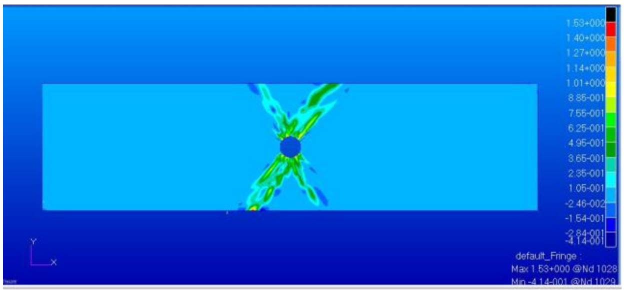

Fig 3b, Fiber damage for progressive failure, ϴ = 45˚

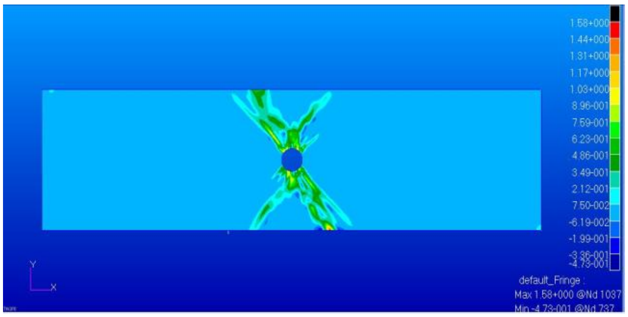

Fig 3c, Fiber damage for progressive failure, ϴ = -45˚

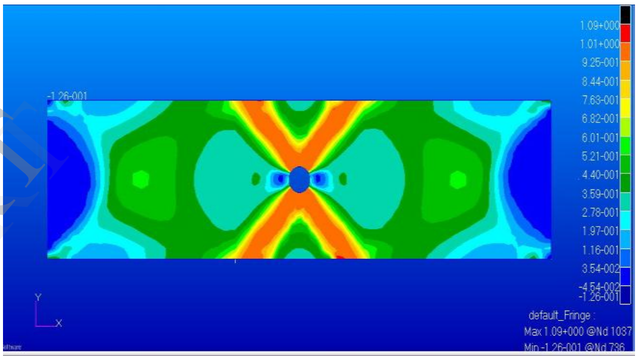

Fig 3d, Fiber damage for progressive failure, ϴ = 90˚

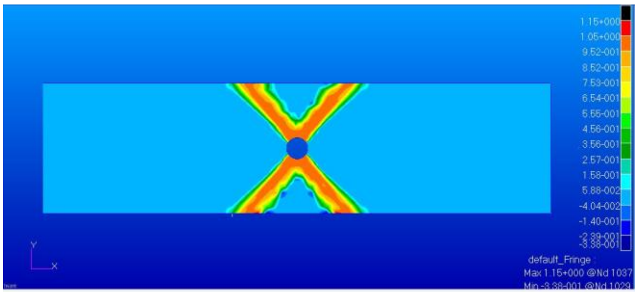

Fig 4a, Matrix damage for progressive failure, ϴ = 0˚

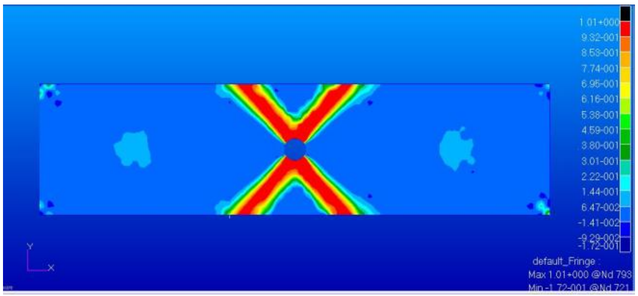

Fig 4b, Matrix damage for progressive failure, ϴ = 45˚

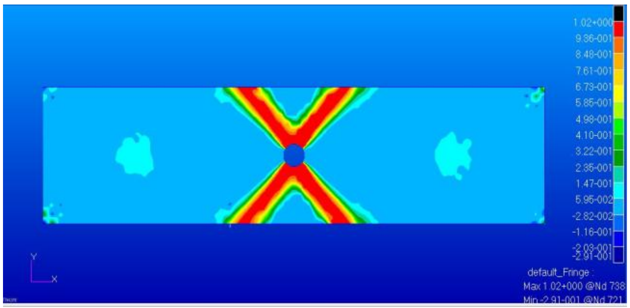

Fig 4c, Matrix damage for progressive failure, ϴ = -45˚

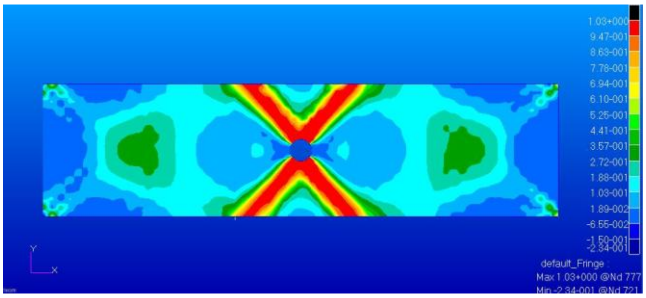

Fig 4d, Matrix damage for progressive failure, ϴ = 90˚

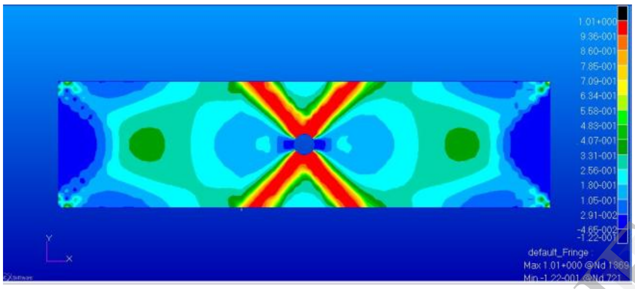

Fig 5a, Total damage for progressive failure, ϴ = 0˚

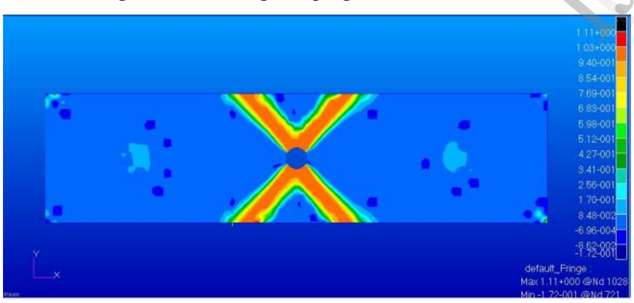

Fig 5b, Total damage for progressive failure, ϴ = 45˚

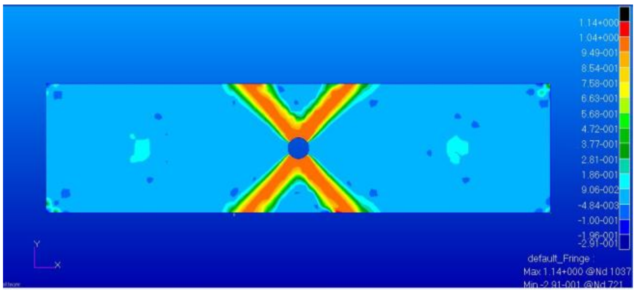

Fig 5c, Total damage for progressive failure, ϴ = -45˚

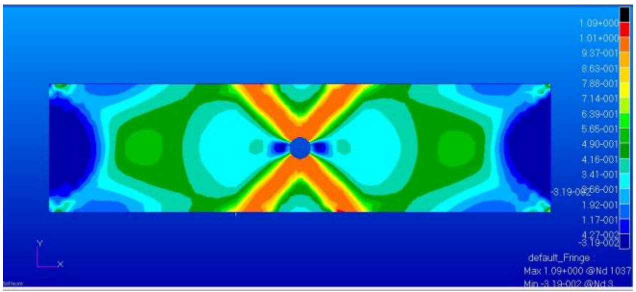

Fig 5d, Total damage for progressive failure, ϴ = 90˚

Fig 6. shows the force v/s displacement graph from that we get the first ply failure load and ultimate ply failure load, which is written in table 2.

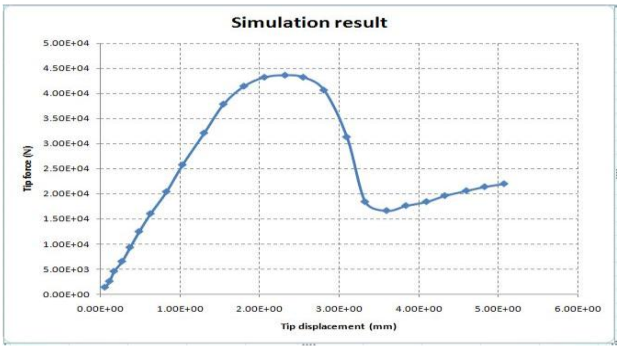

Fig 6, Force v/s displacement plot

Table 2, Simulated failure load result

First ply failure load	25800 N
Ultimate ply failure load	43700 N

d. Validation

The present problem is validated by a benchmark and is standard test problem with known target solutions in the form of ply contours and graphs obtained using analytical method. Analytical procedures used to validate Finite Element Models developed using MSC NASTRAN/ PATRAN software for the progressive ply failure analysis of composite panel.The test problem used in this study is the work of Larry Pearce, Sr.Lead application engineer, MSC Software reported in reference.

VII. CASE STUDY

The focus of this work is to examine the progressive failure analysis of laminated composite panels with different cutout shape. In case study a simple panel with elliptical hole subjected to displacement controlled tensile loading have been studied using MSC NASTRAN/ PATRAN. This model demonstrates a several different failure mechanisms and show how load is redistributed. Also the above same study is carried out by replacing some fiber orientations, to inspect the changes by ploting combined graph.

a. Problem statement

A 15-ply tensile specimen containing a centrally located elliptical hole is considered and is shown in Fig 6. The composite laminate is 148.59 mm long and 38.1 mm wide with a hole major axis radius of 6.35 mm and minor axis radius of 3.175 mm. The thickness of each ply is 0.254 mm and the laminate stacking sequence is $[(\pm45)_2/90/(\pm45)/\bar{0}]_S$. The material of model is T300/5208 Graphite/epoxy and material properties are in table 1.

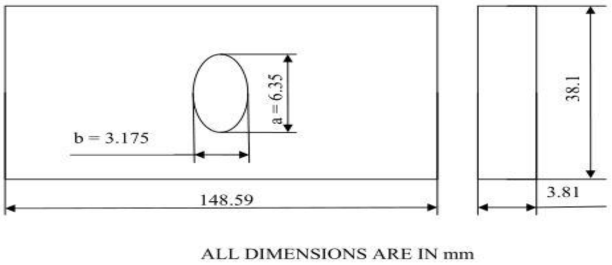

Fig 6. Geometric details of panel with elliptical cutout

b. Development of Finite Element Model with B.C

The geometric modeling of the panel with elliptical cutout and base mesh for the model is generated in MSC PATRAN using CQUAD4 (Plane strain quadrilateral plate) element. Panel was discretized by 1200 number of elements and 1305 number of nodes. The left side edge of panel is fixed for rotation and traslation. The right side edge is subjected to displacement controlled tensile loading by using RBE2 (Rigid Bar Element). An initial displacement of 5.08 mm (0.2 inches) is applied to the laminate. The finite element model with B.C for the problem is shown in Fig 7.

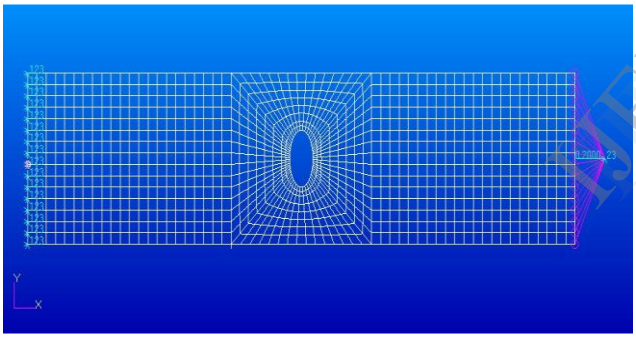

Fig 7. The FE model with B.C for panel with elliptical cutout

c. Analysis procedure and results

Progressive failure behavior for various materials can be simulated using the MATF (Material failure model) Bulk Data entry. Fist analyze entire model by analysis deck method, then Open the newly created input file .bdf wih world editor, search for MATF and change third field to 2 (for gradual progressive failure analysis) and save modified file. And run the modifed file into MD NASTRAN.

Results of progressive ply failure analysis to get ultimate load on T300/5208 Graphite/epoxy panel is presented here. Fig 8(a to d) to Fig 10(a to d) shows plots for fiber, matrix and total damage progressive failure for different ply angles.

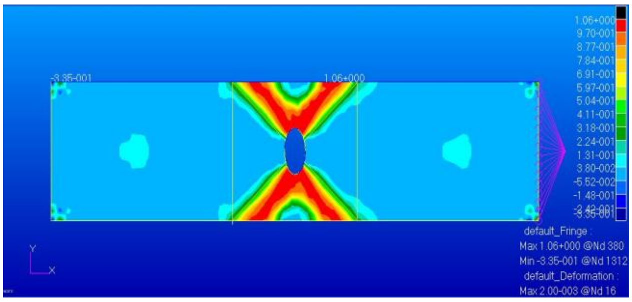

Fig 8a, Fiber damage for progressive failure, $\Theta = 0^\circ$

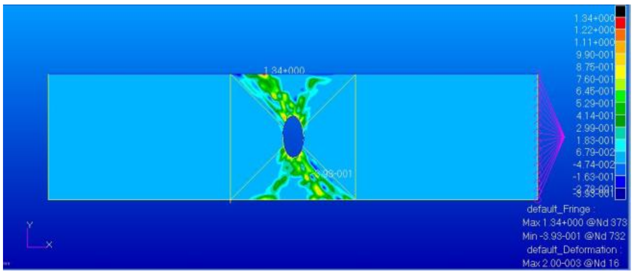

Fig 8b, Fiber damage for progressive failure, $\Theta = 45^\circ$

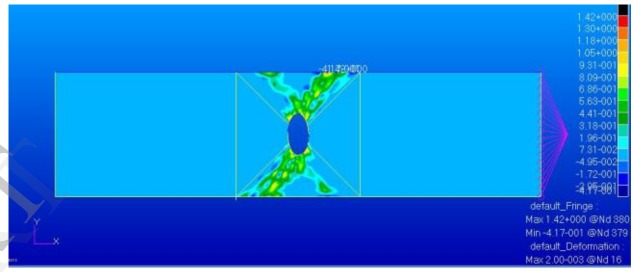

Fig 8c, Fiber damage for progressive failure, $\Theta = -45^\circ$

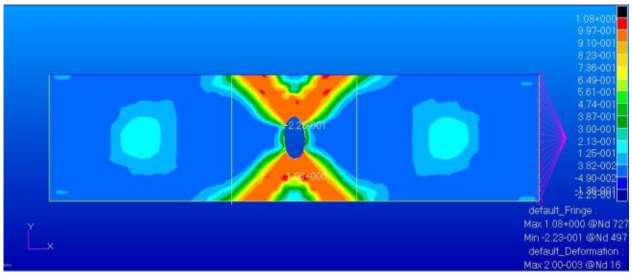

Fig 8d, Fiber damage for progressive failure, $\Theta = 90^\circ$

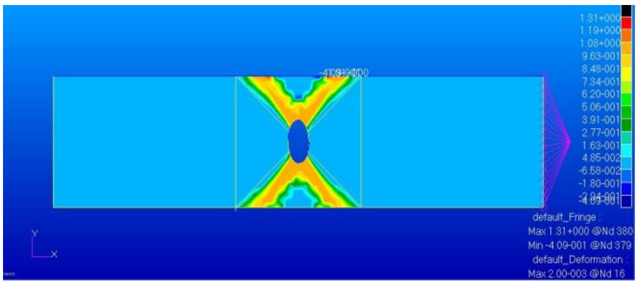

Fig 9a, Matrix damage for progressive failure, $\Theta = 0^\circ$

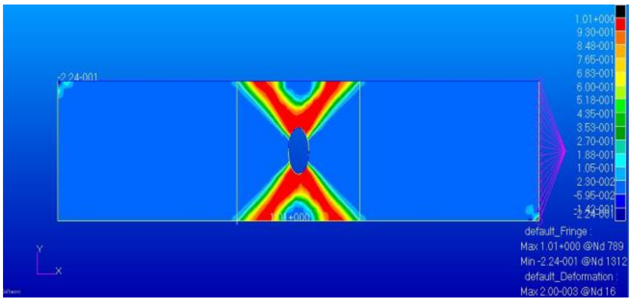

Fig 9b, Matrix damage for progressive failure, ϴ = 45˚

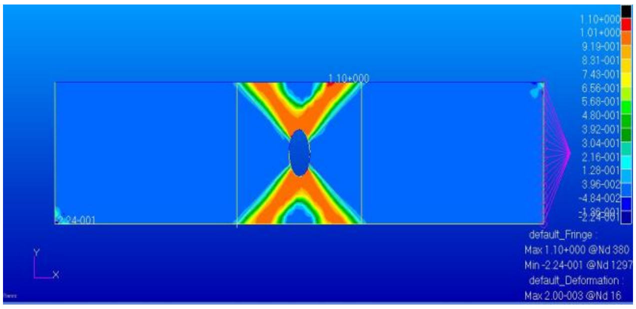

Fig 9c, Matrix damage for progressive failure, ϴ = -45˚

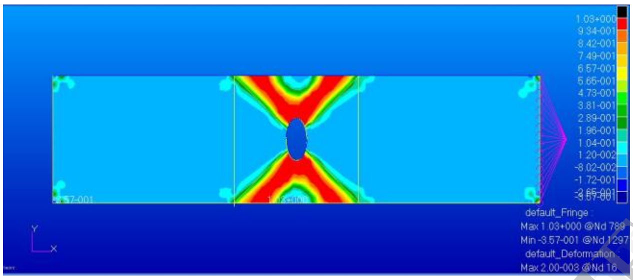

Fig 9d, Matrix damage for progressive failure, ϴ = 90˚

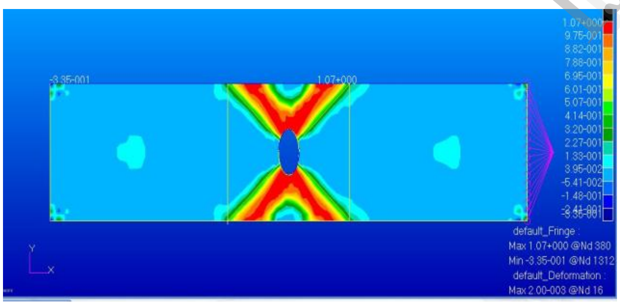

Fig 10a, Total damage for progressive failure, ϴ = 0˚

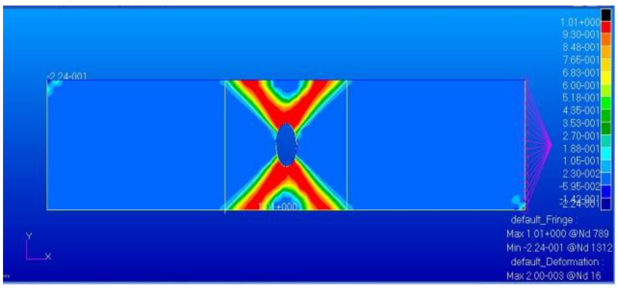

Fig 10b, Total damage for progressive failure, ϴ = 45˚

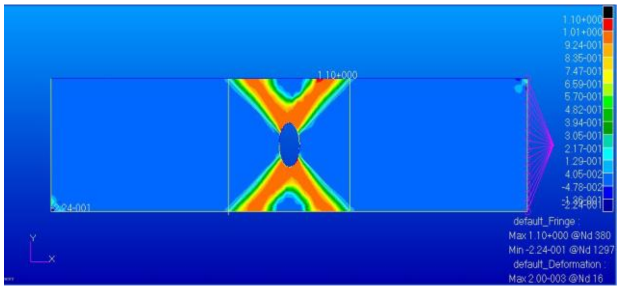

Fig 10c, Total damage for progressive failure, ϴ = -45˚

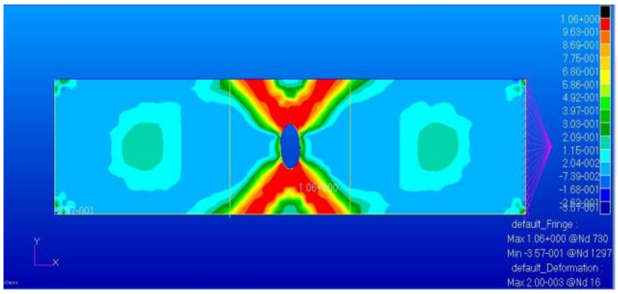

Fig 10d, Total damage for progressive failure, ϴ = 90˚

Fig 11. shows the force v/s displacement graph from that we get the first ply failure load and ultimate ply failure load, which is written in table 3.

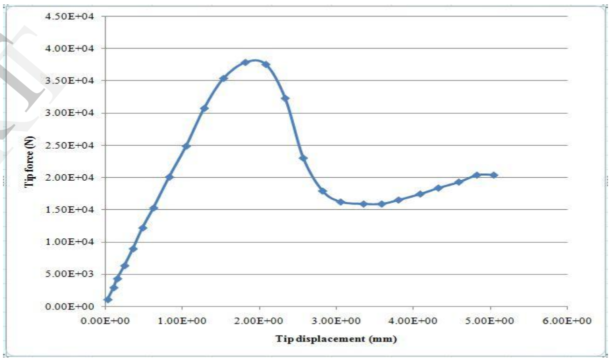

Fig 11, Force v/s displacement plot

Table 3 Failure load result

First ply failure load	20100 N
Ultimate ply failure load	37900 N

d. Comparison

Significant results are presented in the Fig 12. to show the effect of hole shape and ply orentations on the behavior of panels up to final failure.

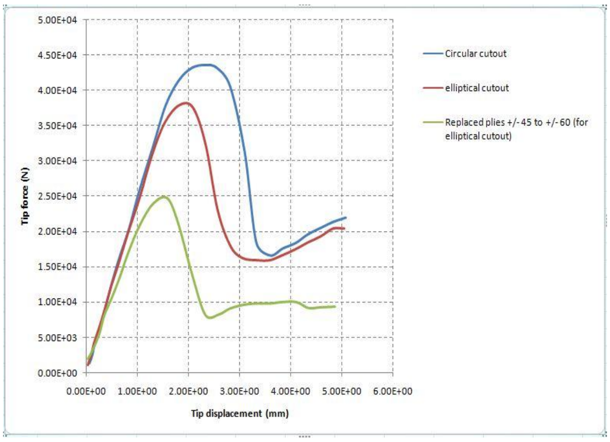

Fig 12. Effect of hole shape and ply orentations

VIII. CONCLUSION

The FEM in general and commercial FEA software MSC NASTRAN in particular is demonstrated in this investigation for accurate stress analysis and progressive failure analysis of laminated composite panels with circular and elliptical cutouts. A nonlinear analysis (combined geometric and material nonlinearty) is essential and linear analysis is approximate.

The problem becomes more complex for laminated composite plates and shell type structures, however the present proposed methodology can handle these complxities. This is identified for future works.

The present study is limited to static loads. For laterl impact by hard/ soft/ bodies at various velocities the problem is highly nonlinear and transient dynamic prediction of impact damage propagation and verification deservs in depth study.

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