Determination of Failure of Notched and Un-Notched Composite Plates and Sensitivity Study of Lamina Strength Parameters

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Abstract— The finite element analysis simulation results of notched and un-notched composite panels are greatly affected by the values of only a certain set of material properties. The failure of composite structure and its effect on the response of the structure is modeled by Progressive Damage Models such as Multi-Continuum Theory (MCT) damage model. In the present work, notched and un-notched composite panels of various thicknesses are analyzed to determine the strength of the panels along with the failure point of matrix and fiber. Also a sensitivity study is carried out to determine the effect of strength parameters and the parameter which has major influence on the response of composite is carried out.
Keywords: MCT, Lamina Strength

I. INTRODUCTION

Composite materials play a very vital role in many fields, and there has been a wide research going on to increase the strength to weight ratio of these composites. In the present work, notched and un-notched composite panels of various thicknesses are analyzed to determine their strength at RTD (750F). Among various composite material failure criteria available for the simulation, MCT damage criterion is used for the determination of failure of the composite. Here the failure point of both matrix and fibers are determined in the analysis. The MCT model parameters are applied using Autodesk Simulation Composite Analysis and thus creating composite material properties. These properties are applied to the model created in the Abaqus through Autodesk plug-in. Simulation is then carried out in Abaqus to determine the failure point of the composite. Also, sensitivity study is carried out to determine the effect of varying the lamina strength parameters. It is done by initially increasing one strength parameter and keeping other strength parameters constant, thereby increasing all strength parameters except one and then comparing the results of analysis for these combinations. This sensitivity study determines the parameters with maximum influence on the response of the composite.

II. SENSITIVITY STUDY OF LAMINA STRENGTH PARAMETERS

Sensitivity study is the carried out to find how the results of the analysis vary with change in the strength properties of the lamina, by carrying a number of simulations with different combinations of parameters. By performing these variations and simultaneously observing the changes in the output, one can determine the factor which has greater influence on the output. Since there are several ways that a factor can be varied, the two main methods commonly used are single factor variation and the factorial analysis. Among these two, Single factor variation is normally used where one factor is varied each time and remaining factors are kept constant. The factorial analysis involves changing the factor in combination with the other factors and recording the outcome of the result.

III. MULTI-CONTINUUM THEORY (MCT) DAMAGE MODEL

This theory considers each constituent in a fiber reinforced composite material by taking into account the volume fractions of the matrix and fiber materials, the constituent strength and stiffness properties; and the model predicts the strength and stiffness properties of the entire composite laminate. The FEA material model then determines strains in the matrix and fiber material, which in turn are calculated from laminate strains determined using laminate properties and the global deformation gradient. Thermal strains can also be included in the model, but, for simplicity, they are not included in the present work. Initially, tensor A, which establishes relationship between the constituent strains and laminate strains (eqn.1), is calculated using volume fractions and stiffness matrices for the laminate (orthotropic), fiber (orthotropic), and matrix (isotropic).

$$[A] = -\frac{\phi_m}{\phi_f}([C]-[C_f])^{-1}([C]-[C_m])$$ Eqn.1

From tensor A, strains in the matrix and fiber materials are then determined using eqn.2

$$\{\epsilon_f\} = \frac{1}{\phi_f}(\{\epsilon\} - \phi_m\{\epsilon_m\})$$

$$\{\epsilon_m\} = (\phi_m[1] + \phi_f[A])^{-1}\{\epsilon\}$$ Eqn.2

Then stresses in the laminate, fiber, and matrix are then calculated by using eqn.3.

$$\{\sigma\} = [C]\{\epsilon\}$$

$$\{\sigma_f\} = [C_f]\{\epsilon_f\}$$

$$\{\sigma_m\} = [C_m]\{\epsilon_m\}$$ Eqn.3

MCT model predicts the damage based on the constituent strength properties. For this, the invariants in the fiber and matrix material, determined by the relationships given below, are related to the strength properties.

$$I_{1f} = \sigma_{11f}$$

$$I_{4f} = \sigma_{12f}^2 + \sigma_{13f}^2$$

$$I_{3m} = \sigma_{22m}^2 + \sigma_{33m}^2 + 2\sigma_{23m}^2$$

$$I_{4m} = \sigma_{12m}^2 + \sigma_{13m}^2$$ Eqn.4

Following are the equations relating the fiber invariants to the strength properties

$$\pm K_{1f} I_{1f}^2 + K_{4f} I_{4f} = 1$$

$$\pm K_{1f} = \frac{1}{\pm S_{11f}^2}$$

$$K_{4f} = \frac{1}{S_{12f}^2}$$ Eqn.5

And the equations relating the matrix invariants and the strength properties are as follows

$$\pm K_{3m} I_{3m} + K_{4m} I_{4m} = 1$$

$$\pm K_{3m} = \frac{1}{\pm S_{22m}^2 +^{\pm 22} S_{33m}^2}$$

$$K_{4m} = \frac{1}{S_{12m}^2}$$ Eqn.6

IV. SOLUTION DEPENDENT STATE VARIABLES

In a finite element model, the SDVs track required output at each integration point. The number of SDVs present in a model, determined using the flow chart, depends on many factors and is specified by *DEPVAR keyword. SDVi, where i=1,2,3, ….7,11,13,17,35, or 90, is the default naming convention for the SDVs, among which SDV1 is most useful as it tracks the composite's discrete failure state at each integration point. The MCT SDVs must be requested at the output database, as they are not automatically written to the database file. It is done by clicking Output > Field Output Requests > Edit > "Name of the output request" in the main toolbar of the step module and then the box labelled "SDV, Solution Dependent State Variables" must be checked.

V. SIMULATION OF MODEL USING ABAQUS

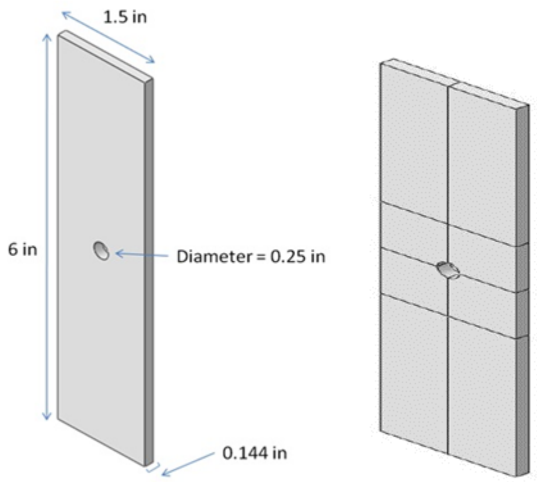

Fig. 1: Plate with Hole

The whole model is modeled using Abaqus standard/explicit. Initially a 3D deformable part viz. rectangle of length 1.5 inch, thickness of 0.144 inch and height 6 inch is modeled as shown in figure (5.1). A hole at the center of the plate with (0.75, 3) as co-ordinates and perimeter (0.75, 3.125) is then created. The plate is partitioned in order to mesh it finely near the hole. ABAQUS provides an AUTODESK plugin option for creating a composite material property using AUTODESK simulation composite analysis, which includes the directional strengths, lamina properties, fiber and matrix properties, and fiber volume fraction, with carbon low as fiber and thermoset polymer as matrix. For studying the failure of the model, MCT (Multi Continuum Theory) is used for damage initiation and for damage evolution, instantaneous degradation method is used. Composite layup property of solid element type with 24 initial ply count, which will divide the whole model into 24 plies with the rotation angles [450/00/-450/900]6 as shown in the figure (5.3) with layup percentage for 00 is 10%, 50% of 450 and 25% of 900 is created.

Creating Composite Material

$^+$S11 = 3.144E+5 psi (2168 MPa)	$^+$S22= 7086 psi (48.86 MPa)	$^+$S33=7086 psi (48.86 MPa)
$^-$S11 = -2.100E+5 psi (-1448 MPa)	$^-$S22= -2.881E+4 psi (-198.6 MPa)	$^-$S33=-2.881E+4 psi (-198.6 MPa)
S12 = 2.244E+4 psi (154.7 MPa)	S13 = 2.244E+4 psi (154.7 MPa)	S23 = 7250 psi (49.99 MPa)

Table 1: Strength properties at Room Temp Dry

E_{11} = 1.810E+7 psi (1.248E+5 MPa)	E_{22} = 1.219E+6 psi (8405 MPa)	E_{33} = 1.219E+6 psi (8405 MPa)
ν_{12} = 0.309	ν_{13} = 0.309	ν_{23} = 0.400
G_{12} = 6.130E+5 psi (4.226E+6 MPa)	G_{13} = 6.130E+6 psi (4.226E+6 MPa)	G_{23} = 4.354E+5 psi (3002 MPa)

Table 2: Lamina Properties

Material properties are created using AUTODESK Simulation Composite Analysis and then they are managed in the ABAQUS using AUTODESK Plug-in. Both, unidirectional and woven composite material properties along with lamina strengths, lamina elastic constants can be created using composite material manager. There are four different unit systems available viz. (lb/in/R, N/m/K, N/mm/K, lb/ft/R).

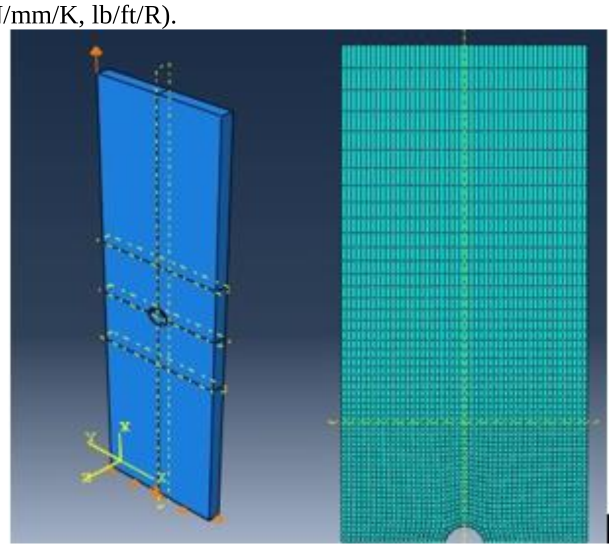

Fig. 2: Applied Boundary conditions and Meshing

VI. RESULT AND DISCUSSION

A. Plate with Hole:

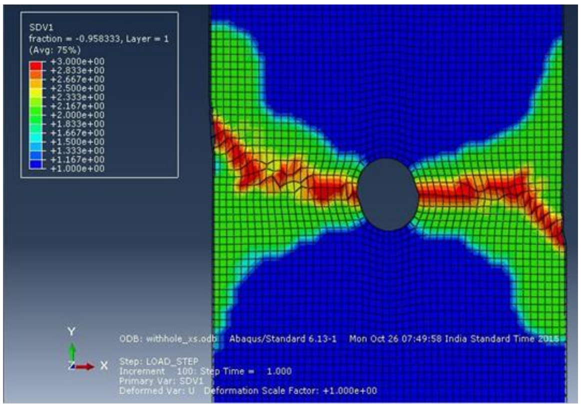

Fig. 3: SDV1 Output from ABAQUS

Figure 3 shows the final visualization of the composite laminate, consists of three regions coloured red, green and blue. Blue region indicates part has not failed, green indicates matrix failure and red indicates matrix and fiber failure. Field output for this simulation involves the solution dependent state variables (SDV). For unidirectional composites with instantaneous degradation there are seven state variables among them SDV1 is considered.

SDV1	Failure
1	No Failure
2	Matrix Failure
3	Fiber and Matrix Failure

Table 3: Values of SDV1

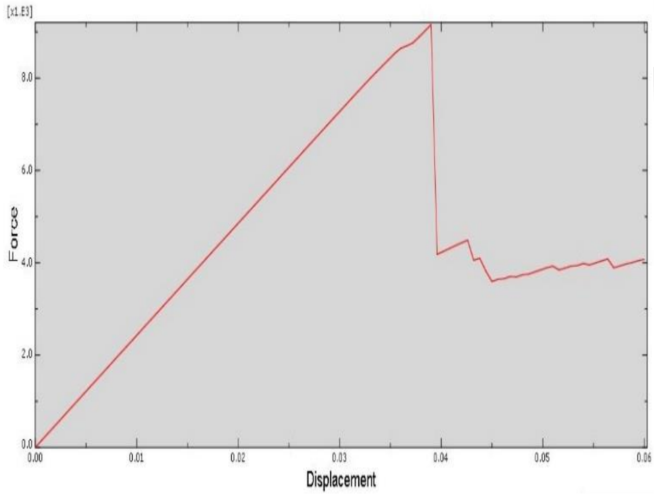

Fig. 4: Graph 6.1 Force (lb.) vs. Displacement (inch) for Plate with Hole

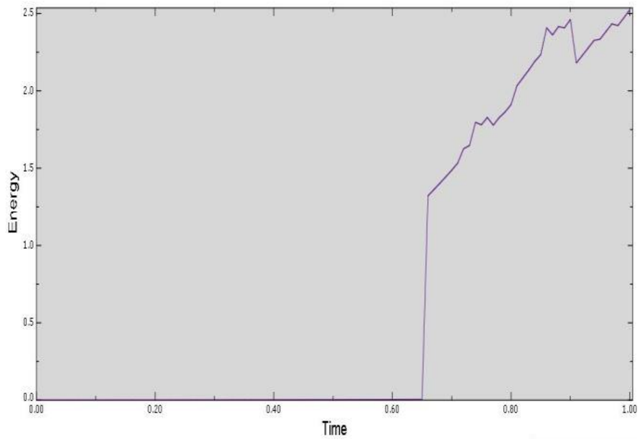

Fig. 5: Graph 6.2 Artificial Strain energy for Plate with Hole

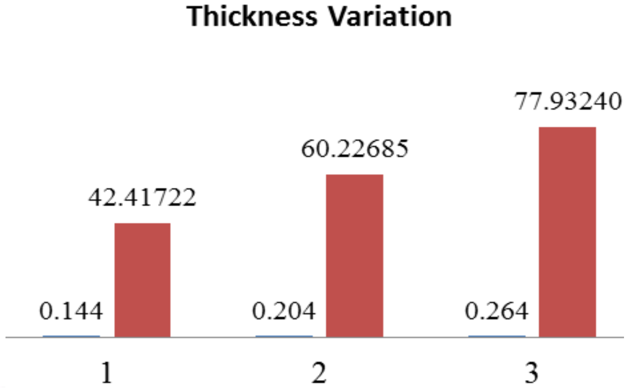

Fig. 6: Graph 6.3 Variation of Strength with thicknesses for Plate with Hole

The graph 6.3 shows the effect of lamina strength parameters on the failure stress.

Each parameter is increased by 20% and correspondingly failure stress is noted. Among these parameters, S11 is found to have more dominance over the remaining parameters

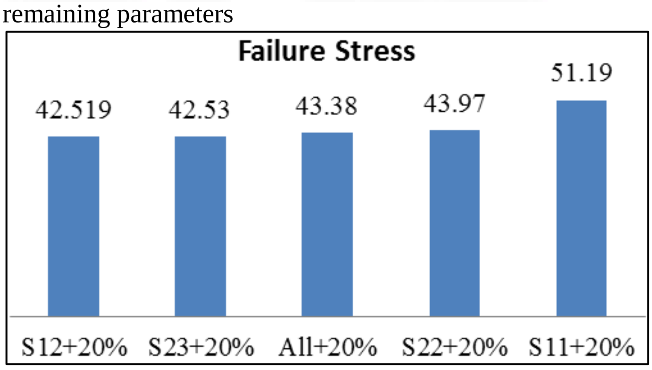

Fig. 7: Graph 6.4 Variation of Strength with Lamina Strength Parameters for Plate with Hole

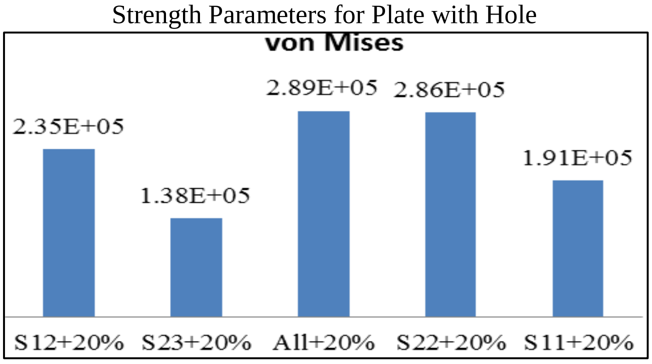

Fig. 8: Graph 6.5 Variation of von Mises Stress with Lamina Strength Parameters for Plate with Hole

B. Plate Without Hole:

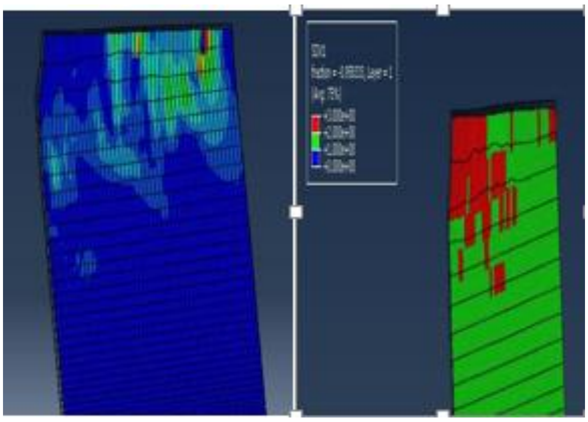

Fig. 9: Failed Part SDV1 Output from ABAQUS

Figure 9 shows the simulation result obtained from the ABAQUS, showing the failed composite plate.

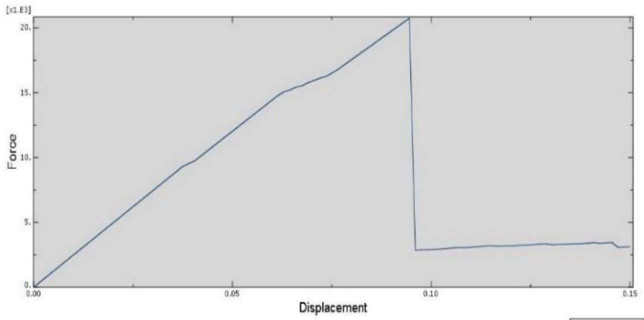

Fig. 10: Graph 6.6 Force (lb.) vs. Displacement (inch) for Plate without

The graph 6.6 reveals the failure of the composite part; a positive slope initially indicates the damage initiation and then a sudden drop in the force at certain point indicates the failure point of the composite.

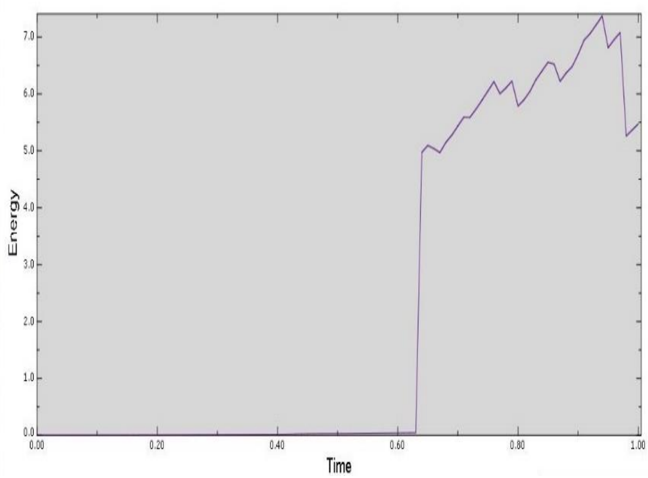

Fig. 11: Graph 6.7 Strain energy for Plate without Hole

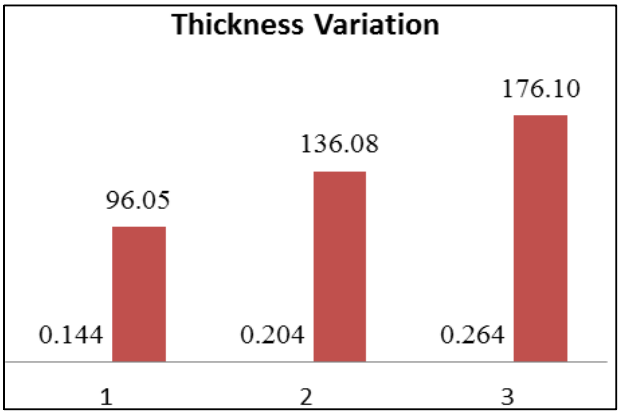

Fig. 12: Graph 6.8 Variation of Strength with thicknesses for Plate without Hole

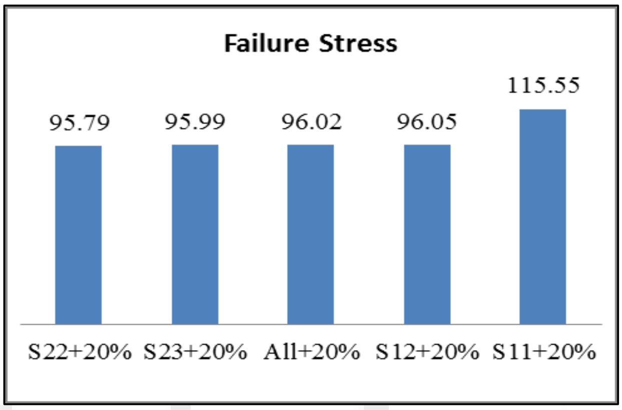

Fig. 13: Graph 6.9 Variation of the Strengths with the change in strength parameters for Plate without Hole

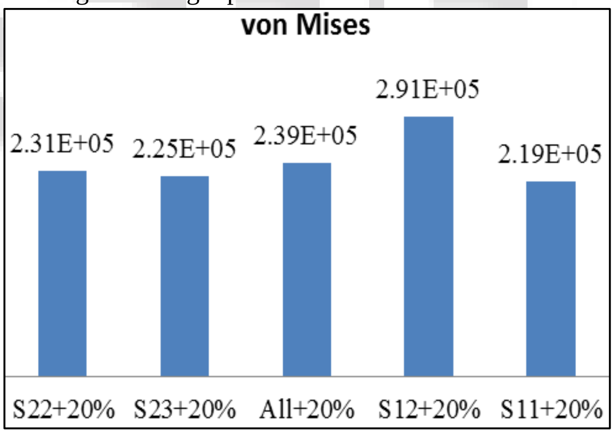

Fig. 14: Graph 6.10 Variation of the von Mises Stress with the change in strength parameters for Plate without Hole

VII. CONCLUSION

Conclusion from the present work can be made that after comparing the simulation results for both notched and un-notched composite plates, the un-notched specimen have greater strength compared to the notched specimen. The stress required to fail the un-notched specimen is comparatively high then the other specimen. The sensitivity study reveals the influence of lamina strength parameters on the outcome. Among them longitudinal tensile strength has greater effect on output compared to remaining strength parameters

VIII. Scope for Future Work

In this work carbon/epoxy properties are used for simulation and in future, simulation is carried out for different composite materials. The present work is simulated for strength properties at room temperature dry (750), extension can be done with cold temperature dry, elevated temperature dry and elevated temperature wet. Simulation can be carried out for fatigue load

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