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Layerwise Damage Investigation of Ply Orientation on Strength Characteristics of Carbon Fibre Composite

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Abstract: Synthetic composites have higher strength to weight ratio and are extensively used in industrial applications. Most of the composites have orthotropic properties and their strength varies as per orientation. Carbon fibers are one of the synthetic fibres having extensively high tensile strength. Laminates having different ply orientations have different properties and strengths. Hence, to enhance strength properties, reducing layerwise damage becomes of up most important. It is not possible to investigate the layerwise damage of each ply separately by experimentation. This can be done by using ACP tool in ANSYS 19.2 software. In this project, two laminates having orientations as 0°- 45°- 0° and 0°- 30°- 60° are considered for analysis. Advance composite pre-post [ACP] tool from ANSYS software is used for simulation of these layers. From this analysis total deformation, equivalent stress and damage of each layer is determined. After getting layerwise damage, experimentation is done. Experimental tensile test is done on specimens above ply orientations to obtain force vs. deflection diagrams. Comparative analysis is made between simulation and experimental results. Results and conclusion is drawn. Experimental and simulation values differ by only 1%. This validates the simulation value of force reaction. Also from the result it can be seen that 0°- 45°- 0° laminate gives better results than that of 0°- 30°- 60° laminate. Hence, it can be concluded that Plate 1 has higher strength than Plate 2 i.e., 0°- 45°- 0° is better ply orientation than 0°- 30°- 60° ply orientation. Also it is observed that different ply orientations have different strengths.
Keywords: Layer wise, Carbon fiber, Ply orientation, ACP tool, Force reaction

I. INTRODUCTION

Carbon fibre materials (alternatively CF, graphite fiber or graphite fibre) are fibers about 5–10 micrometres in diameter and composed mostly of carbon atoms. Carbon fibers have many types advantages including high stiffness, very high tensile strength, low density, high chemical resistance, high temperature tolerance and low thermal expansion. These properties have made carbon fiber material very popular in aerospace, military, civil engineering, and motorsports, along with other sports. However, they are relatively expensive materials when compared process with similar fibers, such as glass fibers or plastic fibers.

To produce a carbon fiber material, the carbon atoms are bonded together in crystals form that are more or less aligned parallel to the long axis of the fiber as the crystal alignment gives the fibre material high strength-to-volume ratio process (making it strong for its size). Several thousand carbon fibers material are bundled together to form a tow, which may be used by itself or woven into a fabric.

Carbon fibers material are usually combined with other materials for testing to form a composite. When impregnated with a plastic process resin and baked it forms carbon-fiber-reinforced polymer material (which is often referred to as carbon fiber) which has a very high strength-to-weight ratio, and is extremely rigid although somewhat brittle. Carbon fibers are also composited material with other materials, such as graphite, to form reinforced carbon-carbon composites process, which have a very high heat tolerance.

II. LITERATURE SURVEY

A. Solis et al. investigated the effect of fibre orientation on the inter-laminar stresses near the edge of composite laminates. The study demonstrated the presence of a displacement gradient using a numerical model, it's maximum value is dependent on the orientation of the plies in the laminate. A solid correlation of the model predictions with experimental results was obtained. In order to study the dependence of the out-of-plane stresses on these two parameters, an analysis of symmetric laminates with varying stacking sequences and ply orientations was carried out. [1]

M. Russello et al. did research on electrical conductivity of carbon fibre laminates. In this paper, by using carbon nano-tubes, the electrical conductivity of thin-ply carbon fibre laminates in transverse is increased was investigated experimentally. A significant increment in the electrical conductivity and a decrement in electrical anisotropy was observed for both the material systems investigated. [2]

Mohamad Fotouhi et al. did study which exploits the potential of thin-ply carbon/glass hybrid laminates to generate high performance Quasi-Isotropic (QI) composite plates that show pseudo-ductility in all fibre orientations under tensile loading, overcoming the inherent brittleness of conventional composites. Two types of QI lay-ups with 45 and 60 intervals, i.e. [45/90/-45/0] and [60/-60/0], were utilized. The fabricated plates were then loaded in as per their fibre orientations. By changing the stacking sequence changes the stiffness of the separator and adjacent plies, this leads to changes in the pseudo-ductile characteristics such as the initiation and final failure strains. [3]

J. Cugnoni et al. did a research on aerospace grade thin-ply composites and found that thin-ply composites represent a promising approach for more improvement in the performance of carbon fibre composite structures due to their ability to delay the of cracking of matrix and delamination up to the point of fibre dominated failure. However, This raises concerns on damage tolerance. The newly developed composite is optimized further to improve damage tolerance by toughening the resin and selected interfaces. The effect of those modifications on damage tolerance are evaluated through compression strength after impact (CAI) tests and open hole tensile tests (OHT). In this research it is found that an optimized interlayer toughened thin-ply composite, based on 68 microns plies of intermediate modulus fibre can reach both outstanding strength properties with comparable or better CAI and OHT strength compared to current aerospace grade composites. [4]

Estelle Kalfon-Cohen et al., studied about synergetic effects about thin ply. Thin-ply carbon fiber laminates show superior mechanical properties, including higher initiation and ultimate strength compared to standard thickness plies and also greater flexibility. However, the increased ply count in thin-ply laminates also increases the number of ply-ply interfaces, thereby increasing the number of relatively weak and delamination-prone interlaminar regions. [5]

III. PROBLEM STATEMENT

Composite fibres exhibit strength as per fibre / ply orientation, here investigation of those layer needs to be done to avoid catastrophic failure.

A. Objectives

1) To decide the ply orientations for analysis.
a) Understanding different types of ply orientations of carbon fibre composite and its effect on strength characteristics of carbon fibre composite.
b) To consider two of the better ply orientations for laminate for performing layerwise damage investigation based on literature survey.
2) To perform layerwise damage investigation of carbon fibre ply using ACP tool in ANSYS software.
a) Performing simulation on the two ply orientations selected.
b) Finding out values of equivalent stress and damage for each layer/ply separately in both the laminates.
c) Comparing layerwise results of different ply orientations.
3) To obtain correlation between simulation and experimental analysis of carbon fibre laminate within 5%.
a) To compare reaction force values in simulation and experimental analysis.
b) Minimize error if its value exceeds 5%.
4) To decide which ply orientation is better between the chosen orientations.

B. Scope

1) The present system of dissertation work represents correlation between the results of simulation analysis and experimental analysis of Laminates of two different ply orientations.
2) Using Ansys Composite Pre-Post tool i.e., ACP tool in ANSYS for the layerwise damage investigation of the laminates.
3) Analysing the layers/plies in the laminate separately.
4) Validating simulation results with the experimental results.

C. Methodology

1) Cad modelling of various layer of specimens and defining material properties
2) Finite element discretization (Meshing) using ANSYS Workbench
3) Defining layer wise ply orientation angle in ACP
4) Perform Static Structural Analysis to investigate Stresses, Strains and damage of respective specimen.
5) Prepares specimens using Hand layup technique
6) Removal of Air gap using Vacuum pump during manufacturing
7) Cutting layers of specimens in uniform size for testing purpose as per standard dimension
8) Perform tensile test on UTM to get Force vs Deflection diagrams
9) Results and Discussion.
10) Validation of simulation results by experimental results.
11) Conclusion

IV. DESIGN

Computer Aided Design software uses either vector-based graphics to represent the objects of traditional drafting, or may also produce raster graphics which show the overall appearance of designed models for mechanical design. Similar to the manual drafting of the engineering and technical drawings, the CAD output must convey information, such as materials taken, processes, dimensions of the component, and tolerances, according to the application-specific conventions.

CAD can be used for designing two-dimensional (2D) curves and figures; and/or three-dimensional (3D) curves, surfaces, and solids.

Here, for designing the specimen we have taken into consideration the size and requirement of the Universal Testing Machine i.e., UTM which will be used for the testing of the specimen. From above considerations the specimen size is taken as followed -

Length = 250 mm
Width = 50 mm
Thickness = 3 mm

Using above dimensions model is designed using CATIA V5 R17 software.

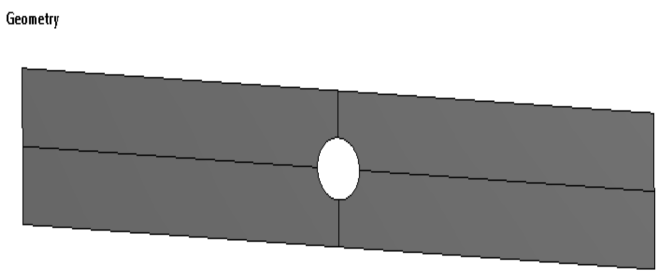


Fig. No. 1: CATIA Model of Carbon Fibre Laminar

A. Selection of Ply Orientations for Analysis

The effect of stacking sequence on laminates composite structures plays on important role for achieving required mechanical properties for in plane, flexural and buckling behavior. Ply continuity maintenance is required between the adjacent layers considered from manufacturer's point of view. Due to practical manufacturing and industrial requirements considerations, balanced and symmetric laminates with ply orientations -45, 0,45,90 degrees are considered.

There are different ply orientations carbon fibre available. Their strength varies as per the orientation of the plies. To decide the ply orientation for the analysis previous experimental data is taken into consideration. In many papers different ply orientations are used, amongst those Mohamad Fotouhi et. al.,[14] has given many orientations and found their properties by experimentation. From those better results are given by 0° and 45° ply orientations. Also 60° ply has shown good properties and results.

So by using combination of the above ply orientations two laminates having following ply orientations are decided.

For Plate 1 - 0° - 45° - 0°

And for Plate 2 - 0° - 30° - 60°

V. FINITE ELEMENT ANALYSIS

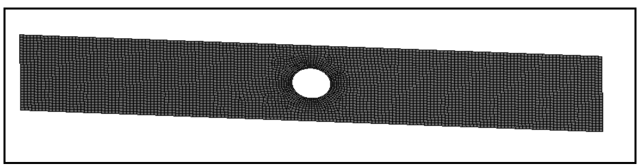
A. Mesh

ANSYS Meshing is a general-purpose and intelligent product, which gives automated high-performance result. It produces the most appropriate mesh for accurate, efficient Multi-physics solutions. A mesh well suited for a particular analysis can be generated by just a single mouse click for all parts in a model. It gives total control over the options which are used to generate the mesh for the expert user who wants to fine-tune it. The parallel processing power is automatically used to reduce the time required for the mesh generation.

Foundation of engineering simulations is the creation of the most appropriate mesh. ANSYS Meshing knows the different types of solutions that will be used in the project and it has appropriate criteria to create the best suited mesh. ANSYS Meshing is integrated automatically with each solver which is given within the ANSYS Workbench environment. For a quick analysis or for the new and infrequent user, a usable mesh can be created with one click of the mouse. ANSYS Meshing chooses the most appropriate options based on the type of analysis and the geometry of the model. Especially convenient is the ability of ANSYS Meshing to automatically take advantage of the available cores in the computer to use parallel processing and thus significantly reduce the time to create a mesh. Parallel meshing is accessible without any extra cost or license requirements.

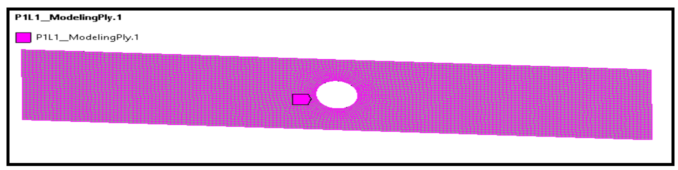
B. FEA of Carbon Fiber Ply Wise Damage Investigation 0°- 45°- 0° orientation i.e., Plate 1

Here, for this project work ACP tool i.e., ANSYS Composite Pre/Post in ANSYS 19.2 is used for analysis. It gives layer wise damage of plies of different ply orientations. Quadratic type elements are used for meshing. Element size is taken as 5 mm. Total no. of Nodes is 5101. Total no. of Elements is 4876.



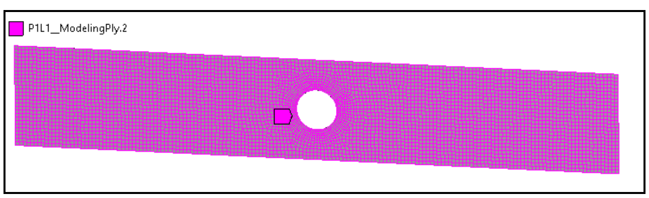
Statistics	
Nodes	5101
Elements	4876

Fig. No. 2: Meshing of Carbon Fiber Plate 1



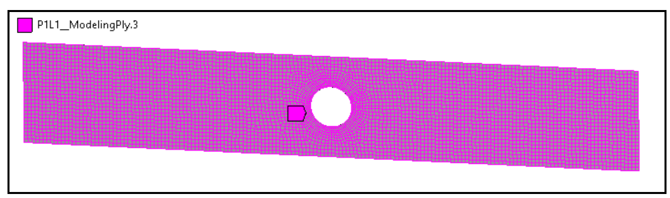
Thickness	1. mm
Angle	0. °
Number of Elements	4876.

Fig. No. 3: Meshing of Ply 1.1



Thickness	1. mm
Angle	45. °
Number of Elements	4876.

Fig. No. 4: Meshing of Ply 1.2



Thickness	1. mm
Angle	0. °
Number of Elements	4876.

Fig. No. 5: Meshing of Ply 1.3

1) Boundary Condition

Here, boundary conditions which are used are as follows -

Plate is fixed at the left end. Plate is kept free to move in the x - direction. Force is applied at the middle i.e., at the hole which is in the middle of the plate in the x - direction. Value of the force is 5180 N.

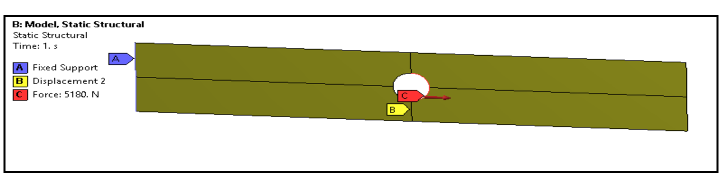


Fig. No. 6: Boundary Conditions applied to Plate 1

2) Simulation Results

a) Total Deformation

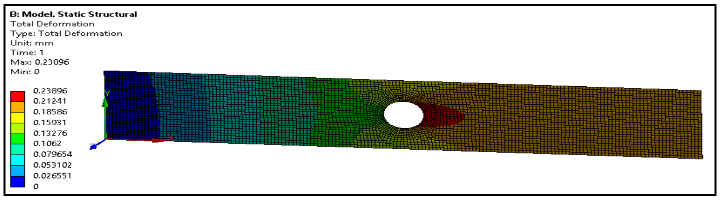


Fig. No. 7: Total Deformation of Plate 1

From the FEA, it can be seen that the total deformation of the plate 1 is 0.2389 mm.

b) Equivalent Stress

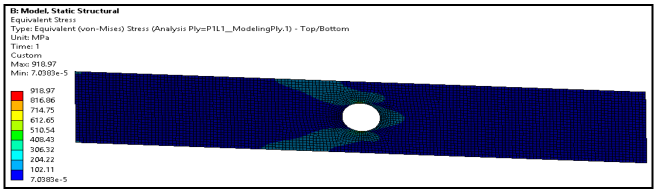


Fig. No. 8: Equivalent stress in ply 1.1

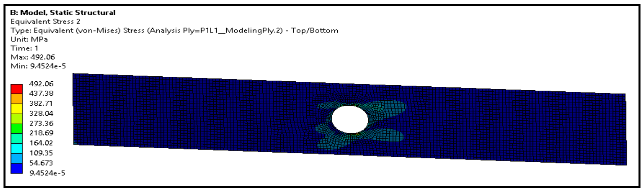


Fig. No. 9: Equivalent stress in ply 1.2

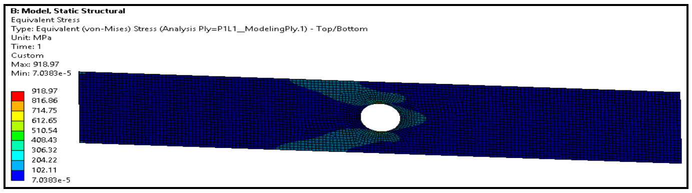


Fig. No. 10: Equivalent stress in ply 1.3

The Equivalent stress generated in the plies of different orientation is different. From above analysis, the values of the equivalent stress generated in the plies of are as follows -

i) For Ply 1 i.e., 0° Ply Maximum Equivalent Stress = 918.97 MPa

ii) For Ply 2 i.e., 45° Ply Maximum Equivalent Stress = 492.06 MPa

iii) For Ply 3 i.e., 0° Ply Maximum Equivalent Stress = 918.97 MPa

c) Damage in Plies

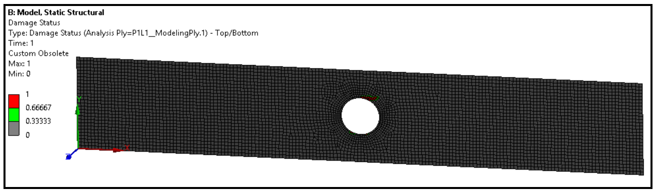


Fig. No. 11: Damage in ply 1.1

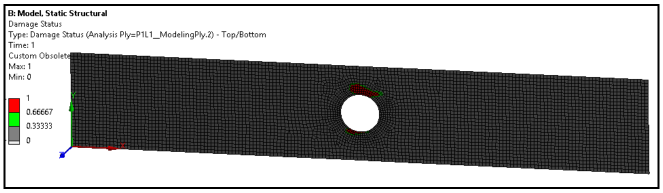


Fig. No. 12: Damage in ply 1.2

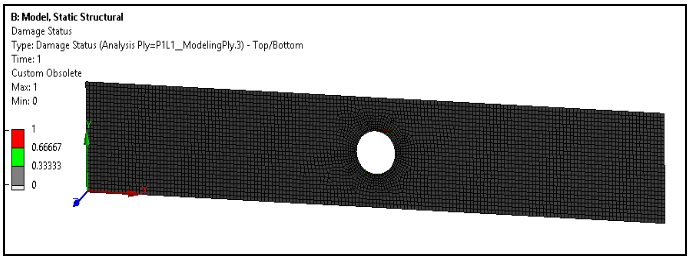


Fig. No. 13: Damage in ply 1.3

It can be seen in the above simulation results, that the damage occurs at the centre of the plate. As the tensile load is applied 45° ply is getting more damaged than the 0° ply. This shows that 0° ply is stronger when the tension is applied on it.

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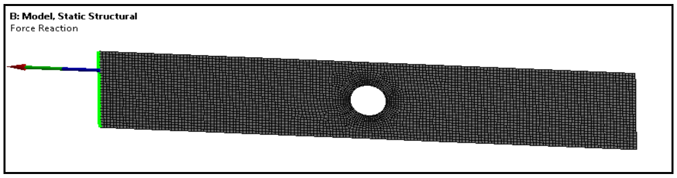
d) Reaction Force

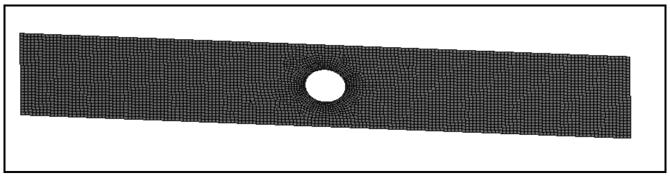


Maximum Value Over Time	
X Axis	-518. N
Y Axis	5.1835e-007 N
Z Axis	8.0188e-016 N
Total	5180. N

Fig. No. 4.1.13: Force Reaction in Plate 1

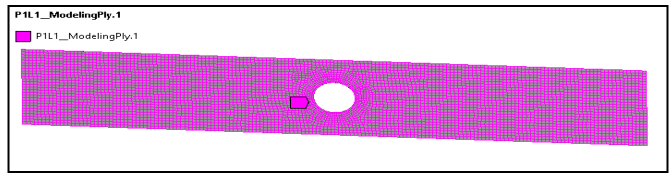
From the simulation, force reaction of the plate 1 is determined. The value of the force reaction is 5180 N.

3) *FEA of Carbon Fiber Ply Wise Damage Investigation 0°-30°-60° orientation i.e., Plate 2:* Here also same meshing is used. Quadratic type elements are used for meshing. Element size is taken as 5 mm. Total no. of Nodes is 5101. Total no. of Elements is 4876.



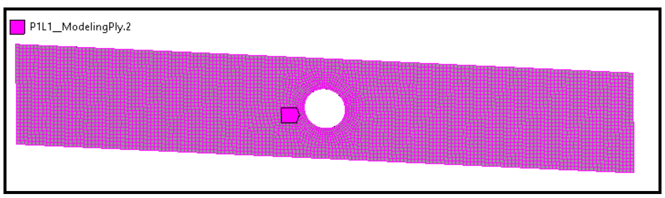
Statistics	
Nodes	5101
Elements	4876

Fig. No. 14: Meshing of Carbon Fiber Plate 2



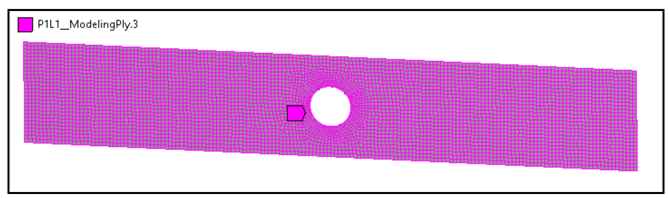
Thickness	1. mm
Angle	0. °
Number of Elements	4876.

Fig. No. 15: Meshing of PLY 2.1



Thickness	1. mm
Angle	30. °
Number of Elements	4876.

Fig. No. 16: Meshing of PLY 2.2



Thickness	1. mm
Angle	60. °
Number of Elements	4876.

Fig. No. 17: Meshing of PLY 2.3

a) *Boundary Condition:* Plate is fixed at the left end. Plate is kept free to move in the x - direction. Force is applied at the middle i.e., at the hole which is in the middle of the plate in the x - direction. Value of the force is 5180 N.

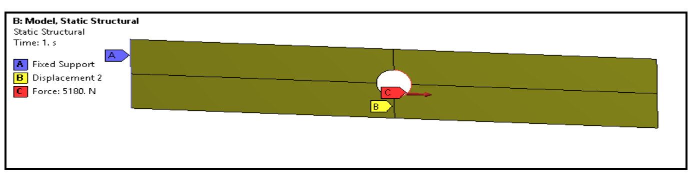


Fig. No. 18: Boundary Conditions applied to Plate 2

4) *Simulation Results*

a) *Total Deformation*

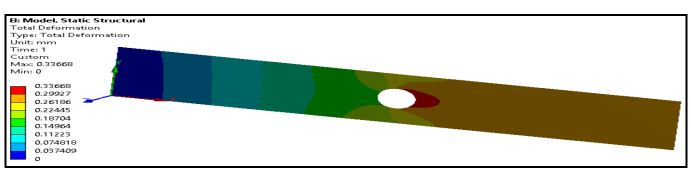


Fig. No. 19: Total Deformation of Plate 2

From the FEA, it can be seen that the total deformation of the plate 2 is 0.3366 mm.

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b) Equivalent Stress

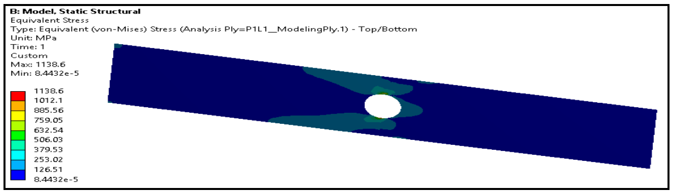


Fig. No. 20: Equivalent Stress at ply 2.1

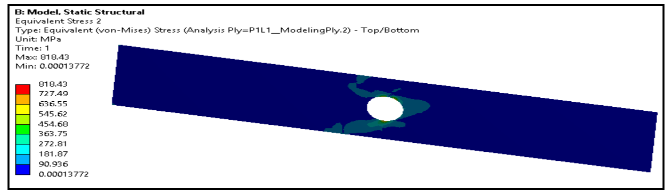


Fig. No. 21: Equivalent Stress at ply 2.2

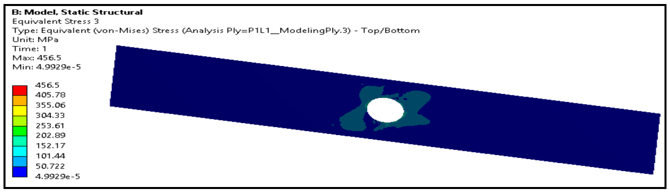


Fig. No. 22: Equivalent Stress at ply 2.2

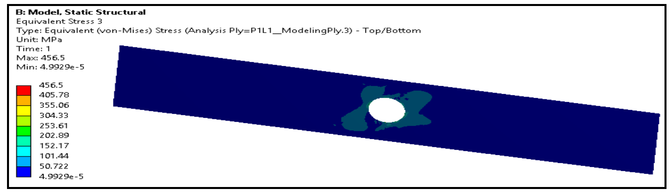


Fig. No. 23: Equivalent Stress at ply 2.3

The Equivalent stress generated in the plies of different orientation is different. From above analysis, the values of the equivalent stress generated in the plies of are as follows -

i) For Ply 2.1 i.e., 0° Ply Maximum Equivalent Stress = 1138.6 MPa
ii) For Ply 2.2 i.e., 30° Ply Maximum Equivalent Stress = 818.43 MPa
iii) For Ply 2.3 i.e., 60° Ply Maximum Equivalent Stress = 456.5 MPa

c) Damage in Plies

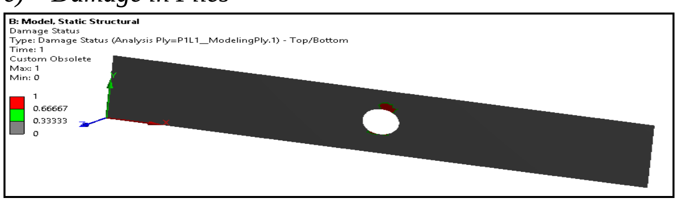


Fig. No. 24: Damage in ply 2.1

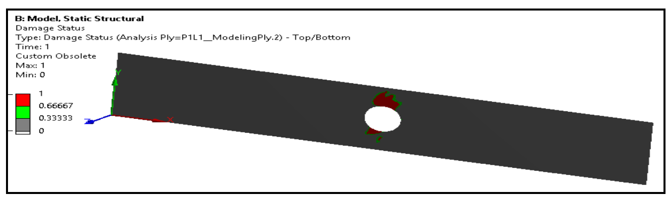


Fig. No. 25: Damage in ply 2.2

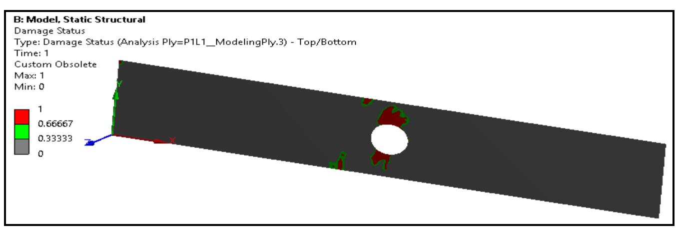
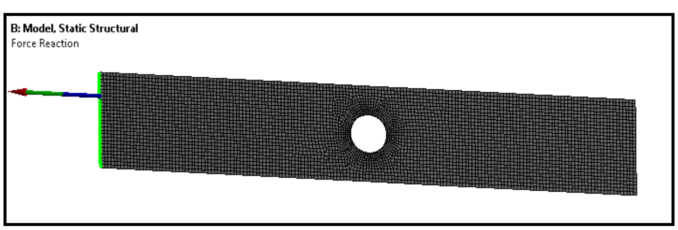


Fig. No. 26: Damage in ply 2.3

It can be seen in the above simulation results that the damage occurs at the centre of the plate. As the tensile load is applied 60° ply is getting more damaged than the 0° and 30° ply. This shows that 0° ply is strongest when the tension is applied on it.

d) Reaction Force



Maximum Value Over Time	
X Axis	-518. N
Y Axis	5.1835e-007 N
Z Axis	8.0188e-016 N
Total	5180. N

Fig. No. 27: Force Reaction in Plate 2

From the simulation, force reaction of the plate 2 is determined. The value of the force reaction is 5180 N.

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VI. FABRICATION

Specimens are prepared using hand layup technique. 1 mm thick sheet of carbon fibre having 0° orientation is taken. Steel Plate is taken and wax is applied on its surface. This steel plate is used as mould in the fabrication procedure. 1 plate/laminate is cut in required dimensions viz., Length = 250 mm and Width = 50 mm. Then epoxy resin is applied on its surface. Second layer of the plate is kept at 45° to the initial or first layer. Again epoxy resin is applied on the surface of the ply. Third i.e., last layer is again kept at 0°. Pressure is applied on the plate in order to make the bond strongly. This way the three layers/plies are combined. Air gap is Removed using vacuum pump during manufacturing. Similar procedure is carried out for preparing second specimen, which is the laminate having ply orientation as 0°-30°-60°.

Fig. No. 28: Fabricated Plate

VII. EXPERIMENTAL ANALYSIS

Tensile testing is a very common testing technique which is used to establish the tensile force or crush resistance of a material and the ability of the material to recover after a specified tensile force is applied and even held over a defined period of time. Tensile tests are used to determine the material behaviour under a load. The maximum stress a material can bear over a period of time under a load (constant or progressive) is determined. Tensile testing is often done to a break (rupture) or to a limit. When the test is performed to a break, break detection can be defined as per the type of material being tested. When the test is performed to a limit, either a deflection limit or load limit is used.

Tensile test is carried out on the specimen to a break. We applied tension at the given point as shown in the fig. for applying tension a hole is drilled on the laminar. A bolt is put through the hole and tension is applied in one direction i.e., pull is applied on the specimen.

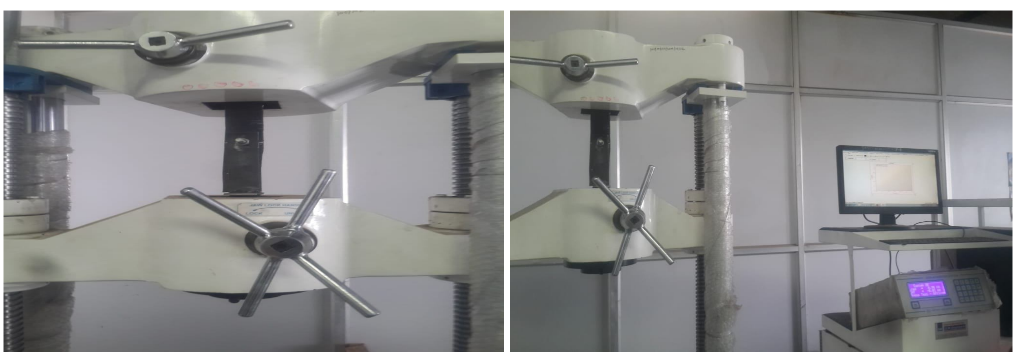

Fig. No. 29: Experimental setup

A. Experimental Results

Fig. No. 30: Plate 1 after tensile test

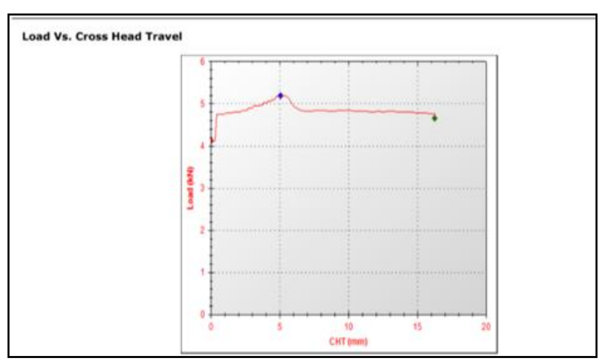

Fig. No. 31: UTM testing Graph for Plate 1

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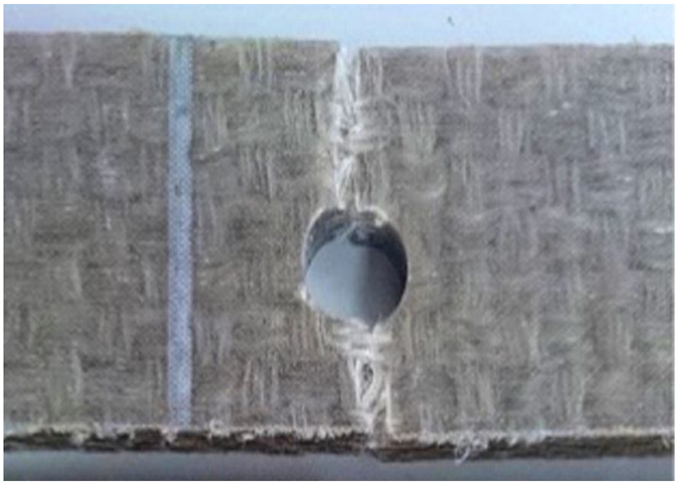

Fig. No. 32: Plate 2 after tensile test

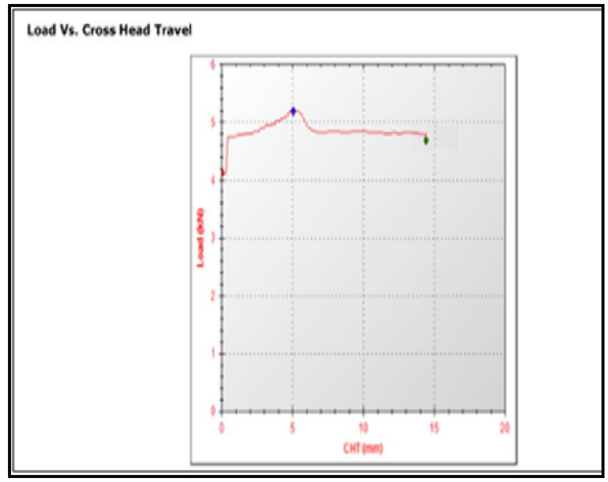

Fig. No. 33: UTM testing Graph Plate 2

Results obtained from experimental testing is that the force reaction of the carbon fibre laminate is 5200 N for 0°-45°-0° laminate. The force reaction of the carbon fibre laminate is 5170 N for 0°-30°-60° laminate.

VIII. RESULTS

Results obtained are as follows -

A. For 0°-45°-0° laminate

The carbon fiber ply damage investigation is found out. The force reaction after the FEA is 5180 N & that of the force reaction after the experimental testing is 5200 N. Both the values are same so, validation is done.

1) Maximum Total Deformation is 0.2389 mm.
2) Maximum Equivalent Stress in ply of 0° is 918.97 Mpa.
3) Maximum Equivalent Stress in ply of 45° is 492.06 Mpa.
4) Maximum Equivalent Stress in ply of 0° is 918.97 Mpa.

B. For 0°-30°-60° laminate

The carbon fiber ply damage investigation is found out. The force reaction after the FEA is 5180 N & that of the force reaction after the experimental testing is 5170 N. Both the values are same so, validation is done.

1) Maximum Total Deformation is 0.3366 mm.
2) Maximum Equivalent Stress in ply of 0° is 1138.6 Mpa.
3) Maximum Equivalent Stress in ply of 30° is 818.43 Mpa.
4) Maximum Equivalent Stress in ply of 60° is 456.5 Mpa.

C. Comparison of Experimental and FEA Results

Table No. 1: Comparison between Experimental and simulation results

Plate No.	Ply orientation	Simulation Result Force Reaction (N)	Experimental Result Force Reaction (N)
1	0°-45°-0°	5180	5200
2	0°-30°-60°	5180	5170

IX. CONCLUSION

Following conclusions were made from the results and work done -

A. Based on literature survey two laminates/plates of different ply orientations were considered for the analysis purpose viz., 0°- 45°- 0° and 0°- 30°- 60° named Plate 1 and Plate 2 correspondingly.

B. Layerwise damage investigation of carbon fiber was performed using ACP tool in ANSYS and following conclusions are made from the results –

C. Deformation of the Plate 1 is less that Plate 2 for same load. Also, equivalent stress and damage varies as per ply orientation even in the same plate.

D. Strength of the carbon fibre varies because of the combination of other plies.

E. Experimental results are compared with the simulation results for the validation purpose. The experimental and FEA force reaction values differ by only 1%. Hence, Validation of force reaction of the laminate in the tensile loading is done by experimental testing.

F. From above results it can be stated that Plate 1 has higher strength than Plate 2 i.e., 0°- 45°- 0° is better ply orientation than 0°- 30°- 60° ply orientation.

X. FUTURE SCOPE

A. To investigate the effect of various orientation angles to study ply-wise damage.

B. To investigate optimized angle orientation for obtaining maximum reaction force.

C. To study the effect of thickness on strength of ply oriented carbon fibre joint.

XI. ACKNOWLEDGMENT

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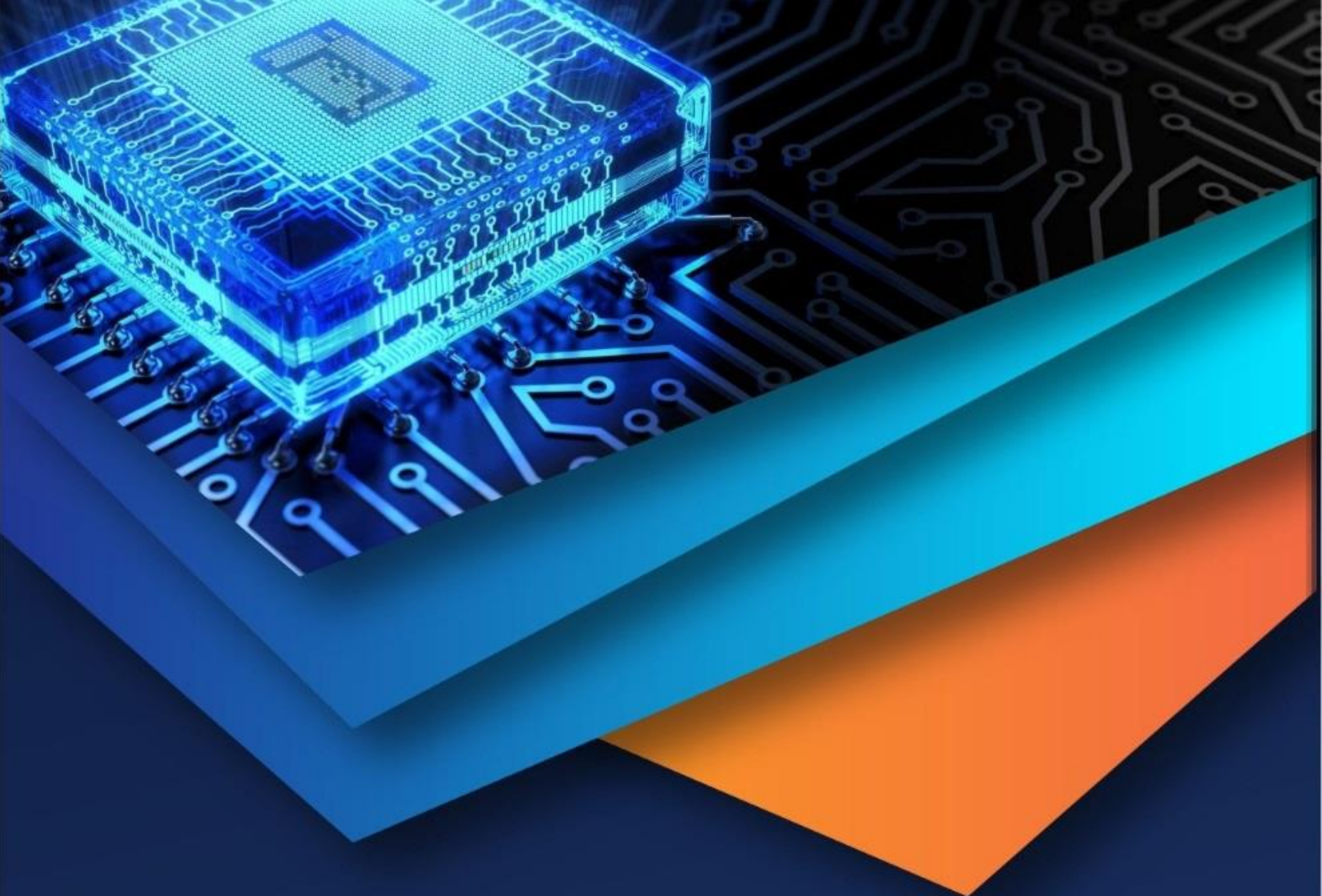

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