Stress and failure analysis of inter-ply hybrid laminated composite using finite element method

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Abstract - *In the present work stress analysis and failure strength of hybrid laminated composites is predicted using finite element package ANSYS. Graphite-Glass-Epoxy inter-ply hybrid composite is analyzed for different lamination schemes. Stress distribution in each layer of laminate is studied under uniaxial loading. First ply failure strength is calculated for different laminates. Various failure theories such as maximum stress, Tsai-Wu, Tsai-Hill are used to predict failure strength of laminates. Results obtained using finite element software ANSYS are compared with theoretical results*

Key Words: FEA, Hybrid Laminated Composites, Failure Strength, ANSYS, First Ply Failure, Lamina...

1. INTRODUCTION

Composites are widely used in industries as weight saving materials and now it is a challenge for us to make them cost effective. In an effort to produce economical composite components, several manufacturing techniques are being employed in the composite industry. But the fact is that, the improvement in manufacturing technology is not satisfactorily sufficient to overcome the economic hurdle. So it is quiet essential that that should be a combined effort in various prospects like material, designing, processing, tooling, manufacturing, and quality assurance.

The main reason behind the wide use of composites in fields like aerospace industry, automotive industry, sporting goods industry, ship building, marine, infrastructure etc. is due to high specific strength of composites. High specific strength of composite means high strength-to-weight ratio, which in turn results in reduced cost of material and greater efficiency. Due to rapid advancement in almost every industry, composite materials are emerging chiefly in response to unprecedented demands from technology.

Our intensive studies about fundamental nature of materials and better understanding of their structure is allowing us to develop new composite materials with improved and enhanced physical, mechanical properties.

The very steady and continuous advancements have led to the use of composite materials in more diversified applications. Near about 13% of the available engineering materials in market are composite that makes composite a more important material in today's world. New materials with unique properties that are different from their constituent ones and can easily be tailored using different types of matrix and reinforcing elements. Varying proportions of the matrix and reinforcement, changing type of matrix or the reinforcement or both of them are the ways of tailoring composites for various ambient conditions satisfactorily.

Using glass/carbon fiber in epoxy matrix, Manders [11] evaluated the tensile properties of hybrid composites fabricated over a range of glass and carbon ratio. Kretsis et al [7] presented a review on tensile, compressive, shear and flexural properties of hybrid laminated composites. He concluded that the tensile modulus of hybrid composite can be obtained from the rule of mixture, while classical laminate theory can be used to determine the flexural stress. Nonlinear behavior of thin laminated composite plates was predicted by Kam et al. [4] using a new finite element method. Kumar et al. [8] introduced a new stiffened plate element for finite element analysis of laminated composite plate with stiffeners. First ply failure load of cross ply laminated stiffened plates is predicted by performing finite element analysis. First ply failure load is calculated for uniformly distributed and sinusoidal loading conditions. A micromechanical analysis of carbon and glass fibers of a unidirectional composite using finite element method was performed by Banerjee et al [5]He composed the hybrid composites with circular fibers packed in hexagonal array. Author also studied the relative locations of two different fibers within the unit cell. Shear modulus and transverse modulus of hybrid composites are predicted using modified Tsai equations.

In the present study, Glass and Graphite fabrics with epoxy resin matrix have been used for fabricating hybrid laminates. Different fiber orientation and stacking sequences were investigated against the tensile responses of hybrid composite laminates. Stress at each layer is calculated for different ply-angles.

2. Formulation of problem/Modeling of hybrid composite

Initially, a rectangular plate has been modeled and then its failure strength has been determined using ANSYS. Results obtained from analytical solution are validated and then compared with theoretical ones.

Later on modeling of 8 layered graphite-epoxy and glass-epoxy hybrid laminated composite has been done. Since each layer can be oriented at different angles but orientation taken are (0/0/0/0)s, (0/45/0/45)s, (0/90/0/90)s, (45/-45/45/-45)s and (0/45/-45/90)s. Stress distribution at each layer for various ply orientation has been calculated using ANSYS and MATLAB as well. Finally an overall comparison of failure strength obtained through various failure theories has been made.

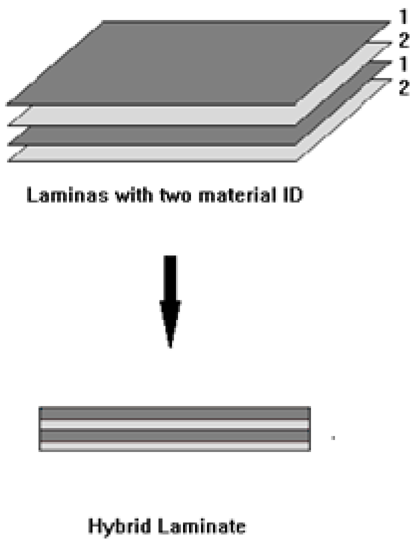

Figure1. A hybrid laminate

Table -1: Elastic and Strength Properties for Graphite-Epoxy Lamina

E_X(GPa)	126
E_Y(GPa)	11
ν_{xy}	0.28
G_{xy}(GPa)	6.6
X_t(MPa)	1950
X_c(MPa	1480
Y_t(MPa)	48
Y_c(MPa)	200
S(MPa)	79

Table 2: Elastic and Strength Properties for Glass-Epoxy Lamina

E_X(GPa)	53.48
E_Y(GPa)	17.7
ν_{xy}	0.278
G_{xy}(GPa)	5.83
X_t(MPa)	1140
X_c(MPa	570
Y_t(MPa)	35
Y_c(MPa)	114
S(MPa)	72

3. Macromechanical modeling of Laminates

Macromechanics is the study of stress-strain behavior of composites using effective properties of an equivalent homogenous material. Only the globally averaged stresses and strains are considered.

At micromechanical level where a laminate is modeled, the following assumptions are made according to the Classical Laminate Theory:

Each lamina is considered as orthotropic.

Each lamina is considered as homogenous.

ε_{yz}, ε_{xz} shear strains are assumed to be zero.

The laminate is assumed to be thin and laminate is subjected to in-plane loading $(\sigma_z = \tau_{xz} = \tau_{yz} = 0)$.

Displacements are assumed to be continuous and small, throughout the laminate $(|u|, |v|, |w| \ll |h|)$.

Each lamina is assumed to be elastic in nature.

It is assumed that no slip occurs in between the adjacent layers.

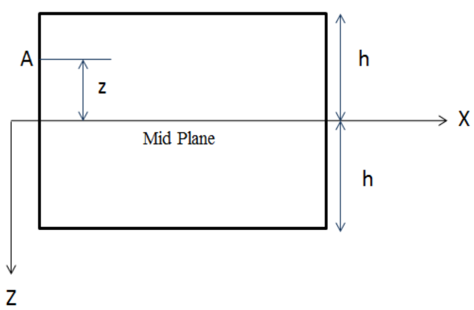

Figure2. Mid plane of a laminate

Strains in laminate can be written as

$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_{xy} \end{bmatrix} = \begin{bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \varepsilon_{xy}^0 \end{bmatrix} + z \begin{bmatrix} K_x \\ K_y \\ K_{xy} \end{bmatrix}$$

Where,

$\varepsilon_x^0, \varepsilon_y^0, \varepsilon_{xy}^0$ are the mid-plane strains of the laminate and K_x, K_y, K_{xy} are the curvatures.
'z' is the location of the point 'A' from the mid plane, where strain needs be determined.

We can calculate the global stresses, if strains are known along thickness of laminate. So from the stress-strain relationship for a lamina we have-

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} = \begin{bmatrix} \bar{Q}_{11} & \bar{Q}_{12} & \bar{Q}_{16} \\ \bar{Q}_{12} & \bar{Q}_{22} & \bar{Q}_{26} \\ \bar{Q}_{16} & \bar{Q}_{26} & \bar{Q}_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_{xy} \end{bmatrix}$$

Where,

$\bar{Q}$ is the reduced stiffness matrix corresponding the point located in lamina, along the thickness of the laminate.

Using equation (1.6) and equation (1.7) for the laminate, we get

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} = \begin{bmatrix} \bar{Q}_{11} & \bar{Q}_{12} & \bar{Q}_{16} \\ \bar{Q}_{12} & \bar{Q}_{22} & \bar{Q}_{26} \\ \bar{Q}_{16} & \bar{Q}_{26} & \bar{Q}_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \varepsilon_{xy}^0 \end{bmatrix} z + \begin{bmatrix} \bar{Q}_{11} & \bar{Q}_{12} & \bar{Q}_{16} \\ \bar{Q}_{12} & \bar{Q}_{22} & \bar{Q}_{26} \\ \bar{Q}_{16} & \bar{Q}_{26} & \bar{Q}_{66} \end{bmatrix} \begin{bmatrix} K_x \\ K_y \\ K_{xy} \end{bmatrix}$$

Relation between Force and Moments in laminate are given by-

$$\begin{bmatrix} N_X \\ N_Y \\ N_{XY} \\ M_X \\ M_Y \\ M_{XY} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{13} & B_{11} & B_{12} & B_{13} \\ A_{21} & A_{22} & A_{23} & B_{21} & B_{22} & B_{23} \\ A_{31} & A_{32} & A_{33} & B_{31} & B_{32} & B_{33} \\ B_{11} & B_{12} & B_{13} & D_{11} & D_{12} & D_{13} \\ B_{21} & B_{22} & B_{23} & D_{21} & D_{22} & D_{23} \\ B_{31} & B_{32} & B_{33} & D_{31} & D_{32} & D_{33} \end{bmatrix} \begin{bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \varepsilon_{xy}^0 \\ K_x \\ K_y \\ K_{xy} \end{bmatrix}$$

Where,
$[A]$ is extensional stiffness matrix, in which in-plane forces are related to in-plane strains.
$[D]$ is bending stiffness matrix, in which the resulting bending moments are related to the laminate curvatures.
$[B]$ is coupling matrix which couples the force and moment terms to the mid-plane strains and mid-plane curvatures.
And,

$$\begin{bmatrix} N_X \\ N_Y \\ N_{XY} \end{bmatrix} = \int_{-h/2}^{h/2} \begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} dz$$

$$\begin{bmatrix} M_X \\ M_Y \\ M_{XY} \end{bmatrix} = \int_{-h/2}^{h/2} \begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} z dz$$

Where,
N_X, N_Y are the normal forces per unit laminate width.
N_{XY} is the shear force per unit laminate width.
M_X, M_Y are the bending moment per unit laminate width.
M_{XY} is the twisting moment per unit laminate width

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4. Failure theories

Failure of ductile material is predicted mainly using the yield criteria. Tresca and Rankine are commonly used failure theories to predict the failure of ductile materials. Here four types of theories are used for determining the failure strength of a hybrid laminate. These are explained below.
Maximum Stress Failure Theory: Tresca and Rankine are commonly used failure theories to predict the failure of ductile materials. According to these theories, failure will occur when the value of maximum stress exceeds the failure value of stress in uniaxial tensile test. If any one of the following conditions are violated the lamina is considered to be failed-

$$-(\sigma_1^C)_{ult} < (\sigma_1) < (\sigma_1^T)_{ult}$$
$$-(\sigma_2^C)_{ult} < (\sigma_2) < (\sigma_2^T)_{ult}$$
$$-(\tau_{12})_{ult} < \tau_{12} < (\tau_{12})_{ult}$$

Maximum Strain Failure Theory: This theory is based on max. Strain theory of St. Venant. According to this theory lamina fails when values of strains in material axis exceed limiting values of strains.
Lamina is considered to be failed if any one of the following conditions violate-

$$-(\varepsilon_1^C)_{ult} < (\varepsilon_1) < (\varepsilon_1^T)_{ult}$$

$$-(\varepsilon_2^C)_{ult} < (\varepsilon_2) < (\varepsilon_2^T)_{ult}$$

$$-(\gamma_{12})_{ult} < \gamma_{12} < (\gamma_{12})_{ult}$$

Tsai-Wu Failure theory: This is interactive failure theory used for isotropic materials and is based on the strain energy. According to Tsai-Wu failure theory a lamina is considered to be safe, only when it satisfies the expression given below-

$$H_1\sigma_1 + H_2\sigma_2 + H_6\tau_{12} + H_{11}\sigma_2^2 + H_{66}\tau_{12}^2 + 2H_{12}\sigma_1\sigma_2 < 1$$

Tsai-Hill Failure Theory: Tsai-Hill failure theory is based on distortion energy theory for isotropic materials. According to this theory a lamina is considered fail when it does not satisfy the expression given below-

$$(G_2 + G_3)\sigma_1^2 + (G_1 + G_3)\sigma_2^2 + (G_1 + G_2)\sigma_3^2 - 2G_3\sigma_1\sigma_2 - 2G_2\sigma_1\sigma_3 - 2G_1\sigma_3\sigma_2 + 2G_4\tau_{23}^2 + 2G_5\tau_{13}^2 + 2G_6\tau_{12}^2 < 1$$

5. Modeling and Analysis of laminate

Structural analysis is used to predict the behaviour of engineering structures under the application of various loads. Structural analysis is generally conducted using analytical methods, experimental methods and numerical methods.
Among many numerical techniques, finite element analysis (FEM) is the most versatile numerical technique for solving engineering problems.
The most distinguishing feature of the finite element method is discretization of a given domain into a set of simple sub-domains called finite elements or nodes.

Steps Involve in Finite Element Analysis (ANSYS):
Once the element type has been selected the material properties, layer orientation, and layer thickness must be defined within each element. In ANSYS these properties are set using real constants. Real constants are user-defined element characteristics, which represent the configuration of the elements. The first step is to define the materials that will be used in the model. Possible materials are accessed through the material models section of ANSYS. In dialog window, the orthotropic mechanical properties can be set for any number of materials. In the real constant dialog window, the preliminary option is to define the number of layers in the model. Once the number of layers is specified, the composition of each individual layer is defined. Each layer can be represented by any one of the material models that have been defined. The layer orientation is defined as the direction of the layer coordinate system relative the global coordinate system, and the orientation is defined by entering the angle between the x-axes of each coordinate system. Finally the thickness of each individual layer can be defined to meet the specifications of the composite.
Steps used in modelling and analysis of hybrid laminated composites using ANSYS-

- Pre-processing
- Specify element types to be used
- Specify options for element behaviour
- Specify real constants
- Specify material model
- Specify material properties
- Create geometry
- Specify meshing options
- Mesh model
- Apply boundary conditions
- Solve problem
- Post processing (reviewing results)

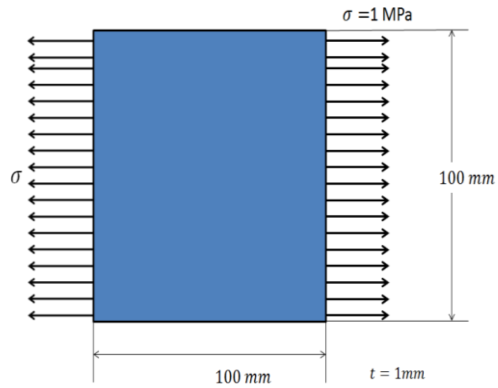

Figure 3. A 100x100 meshed rectangular section with axial loading

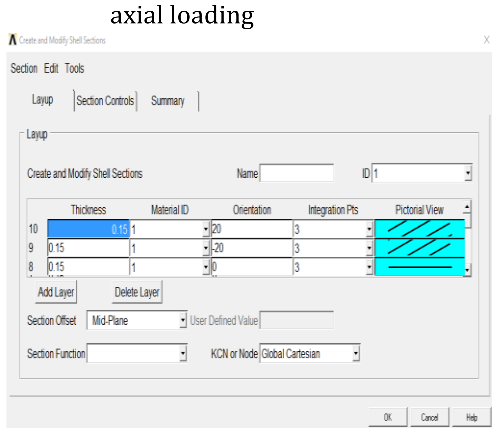

Figure4. Creating and modifying shell sections

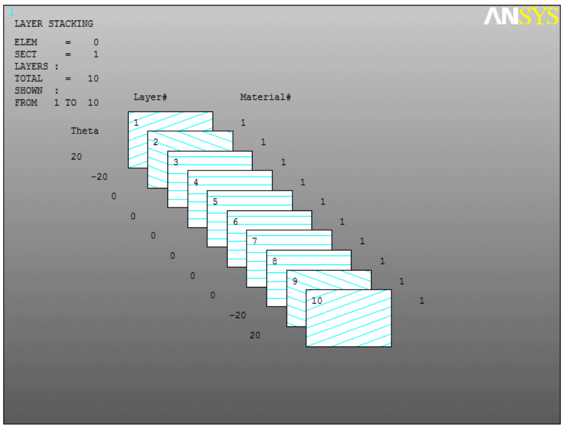

Figure5. Layer stacking at different orientation

5. Results and discussion

1. (0Gr/0Glass/0Gr /0Glass)s Unidirectional

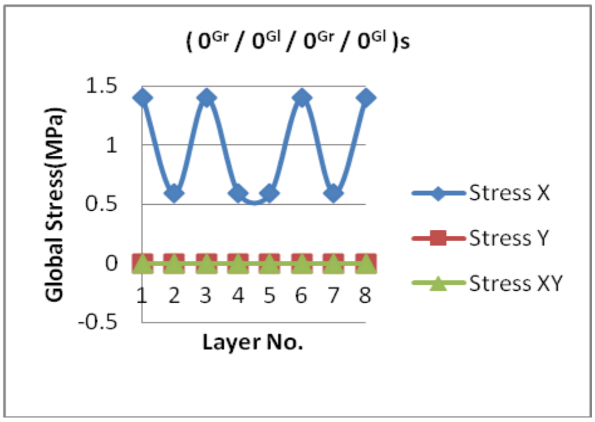

Figure 6. variation of global stresses with layers for (0Gr / 0Gl / 0Gr / 0Gl)s laminate

When graphite-glass-epoxy hybrid laminated composite is subjected to uniaxial loading (in the direction of fibers) it is observed that graphite-epoxy layers are subjected to higher stresses in comparison to glass-epoxy layers. The reason is that graphite-epoxy layers have higher longitudinal Young's modulus compared to that of glass-epoxy layers. Hence for same value of strain, higher values of stresses will associate with graphite-epoxy layers. From table1, it is observed that failure stress of 1388 MPa obtained using Tsai-Wu failure criteria lies between failure strength of graphite-epoxy and glass-epoxy lamina.

Table3. Failure Stress

Failure Criteria	Theoretical (MATLAB)	FEA (ANSYS)
Maxi Stress	1388.9	1388
Maxi Strain	1403.1	
Tsai Wu	1388.4	1388
Tsai Hill	1389	

2. (0Gr/45Gl/0Gr/45Gl)s ply

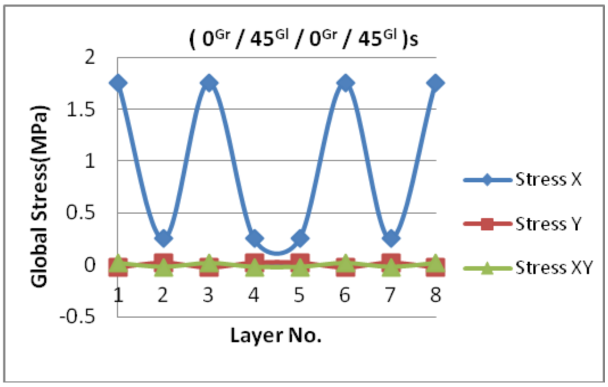

Figure 7. Variation of global stresses with layers for (0Gr / 45Gl / 0Gr / 45Gl)s laminate

Similarly in this configuration, graphite-epoxy layer has higher value of stresses in comparison to glass-epoxy layer due to same reason explained above. So layer of glass-epoxy is going to fail first as they are oriented at 45 degree to loading direction. Here 2,4,5,7 are the critical layers. From table2, it can be concluded that, the failure stress of laminate has a drastic decrement from 1388 MPa (in case of Unidirectional laminate) to 273 MPa as in this case. The values of stress in Y direction and shear stress are lying near to zero.

Table 4.Failure Stress

Failure Criteria	Theoretical (MATLAB)	FEA (ANSYS)
Maxi Stress	303.753	303
Maxi Strain	348.134	
Tsai Wu	272.991	273
Tsai Hill	273.09	

3. (0Gr/90Gl/0Gr/90Gl)s Cross ply

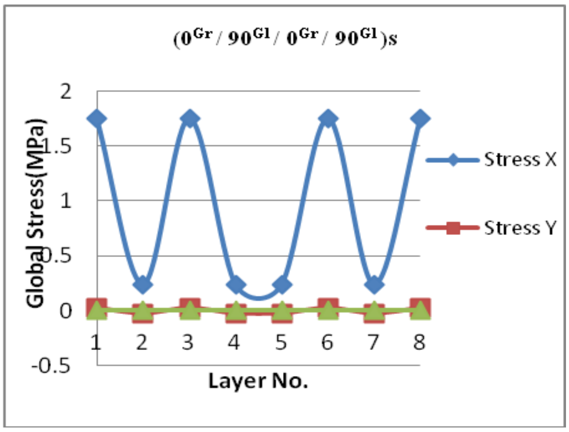

Figure 8. Variation of global stresses with layers for (0Gr / 90Gl / 0Gr / 90Gl)s laminate

Table 5.Failure Stress

Failure Criteria	Theoretical (MATLAB)	FEA (ANSYS)
Maxi Stress	143.098	143.69
Maxi Strain	142.239	
Tsai Wu	143.692	143
Tsai Hill	143.685	

4. (45Gr/-45Gl/45Gr/-45Gl)s Angle ply

Figure(9) shows stresses in different layers of angle ply laminates. Variation in longitudinal and transverse stress is almost constant but shear stresses have opposite values for +45 and -45 layer.

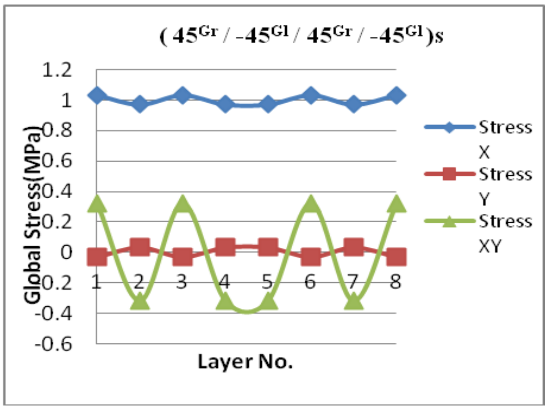

Figure 9. Variation of global stresses with layers for (45Gr / -45Gl / 45Gr / -45Gl)s laminate

Table 6.Failure Stress

Failure Criteria	Theoretical (MATLAB)	FEA (ANSYS)
Maxi Stress	153.510	148.78
Maxi Strain	153.415	
Tsai Wu	116.288	116.292
Tsai Hill	119.296	

5. (0Gr/45Gl/-45Gr/90Gl)s

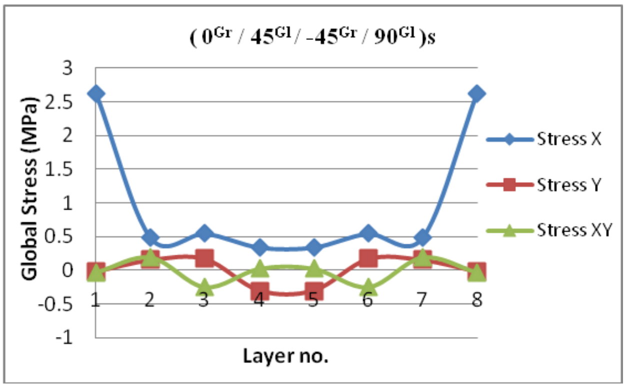

Figure 10. Variation of global stresses with layers for (0Gr / 45Gl / -45Gr / 90Gl)s laminate

Figure(10) shows variation of global stresses with layers of quasi-isotropic laminate. Magnitude of stress in X direction has highest value compare to stress in Y direction and shear stress in XY plane. Layers which are orientated along the direction of loading have maximum value of stress in X direction whereas stresses in Y direction and shear stresses are zero. Layers which are oriented at 45 are subjected to higher shear stresses compare to other layers.

Table 7.Failure Stress

Failure Criteria	Theoretical (MATLAB)	FEA (ANSYS)
Maxi Stress	102.374	102.375
Maxi Strain	94.612	
Tsai Wu	98.510	98.512
Tsai Hill	102.226	

6. Conclusion

In present study hybrid laminates with different stacking sequences has been observed. Global stresses and first ply failure stress for each laminate are obtained through FEA (ANSYS) and graphically presented. Failure strength of laminate at different orientation is calculated using different failure theories. Under uniaxial loading uniaxial laminates shows highest strength whereas quasi-isotropic laminates shows minimum failure strength. Strengths of laminates with different stacking sequences can be written as- **Unidirectional > Symmetric > Cross ply >Angle ply> Quasi-isotropic.**

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BIOGRAPHIES

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