An Investigation of Ply Behaviour in A Composite Laminate Plate Based on Failure Criterion

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Abstract

Fibre reinforced composites have become increasingly important over the past few years and are now the first choice for fabricating structures where low weight in combination with high strength and stiffness are required. The present work is aimed at gaining an initial understanding of the failure behaviour of fibre reinforced laminates with carbon, E-glass and Kevlar 149 fibres and epoxy resins by using Tsai-Wu failure criterion. The purpose of this investigation is to characterize the effect of ply angle sequence on the composite laminates subjected to various loadings and get the best ply design for the materials considered in this investigation. Finite element models are created with ABAQUS/CAE software. These models are used to simulate for different materials with different ply angles, as well as different loads. Graphs are plotted to compare the failure index of different materials, the best ply design for the composites investigated in this project.

Keywords: ABAQUS/CAE, FRP Composites, Tsai-Wu failure criterion.

1. Introduction

Fibre reinforced composites have become increasingly important over the past few years and are now the first choice for fabricating structures where low weight in combination with high strength and stiffness are required. Because of their low specific gravities, high strength to weight ratios and modulus to weight ratios, these composite materials are markedly superior to those of metallic materials. The fatigue strength- weight ratios as well as fatigue damage tolerances of many composite laminates are excellent. In fibrous composites, Fibre Reinforced Plastics (FRP) composites are in greatest commercial use. The important factor about FRP is that, unlike metals, the material is made at the same time as the component. This gives an increased freedom to the design process.

These composites may have thermo-set polymers (resins) or thermo-plastic polymers as matrix. The matrix plays a minor role in the tensile- load- carrying capacity of a composite structure but has major influence to the inter laminar shear as well as in-plane shear properties of the composites. Resins such as epoxies and polyesters are widely used matrix materials. Glass fibres are the most common of all reinforcing fibres for plastic matrix composites. The principal advantages of glass fibres are low cost, high tensile strength, high chemical resistance and excellent insulating properties. E- Glass and S- Glass are two varieties of Glass fibres. Carbon/ Graphite fibres have high tensile- weight ratio as well as high tensile modulus-weight ratio, very low coefficient of thermal expansion and high fatigue strength. Boron and ceramic fibres are also in use. Till date, Metal or Ceramic matrix composites have very small market share because of their cost, high processing temperatures and fabrication complexities.

2. Literature review

J. Eskandari Jam and N. Garshasbi Nia [1] developed finite element analysis on the failure behavior of laminated composite plates subjected to impulsive loads were undertaken using ANSYS These studies include the effects of parameters like size of plates, boundary conditions and fiber orientation angles. Extensive studies on convergence and validity of results based on available data have been carried out prior to the presentation of salient results of this analysis. The normal mode superposition technique is used for the analytical solutions of dynamic response. The failure analysis of the plates was calculated based on the material failure of the facings predicted from Tsai-Wu theory.

Dr. Roberto Frias and camanho P [2] presented recent developments in the numerical simulation of damage and structural collapse of advanced composite structures. The constitutive models presented are developed in the framework of Continuum Damage Mechanics and Fracture Mechanics, and can predict the onset and propagation of the different damage mechanisms occurring in composite materials.

David W.Sleight [3] developed progressive failure analysis for predicting the failure of laminated composite structures under geometrically nonlinear deformations. The progressive failure analysis uses C shell elements based on classical lamination theory to calculate the in-plane stresses. Several failure criteria, including the maximum strain criterion, Hashin's criterion, and Christensen's criterion, are used to predict the failure mechanisms and several options are available to degrade the material properties after failures.

3. Problem description

A Composite material is a material brought about by combining materials differing in composition or form on a macro scale for the purpose of obtaining specific characteristics and properties. To identify the failure mechanism and to trace the path of the failure propagation, failure criteria are used. The failure modes such as fibre breakage and matrix damage are predicted using different failure theories.

The problem is to characterize the effect of the ply sequences, material properties & type of loading on the performance of composite laminates plates. This subject is a crucial design question that appears frequently in the design of new composite products. This investigation attempts to provide initial insight behaviour of composite laminated plate by applying different loads with finite element models and predicted the behaviour of the laminates under different loading situations. Further research is needed to evaluate the effects of damage on specific applications.

4. Methodology

4.1. Abaqus

Abaqus is a suite of powerful engineering simulation programs, based on the finite element method, which can solve problems ranging from relatively simple linear analyses to the most challenging nonlinear simulations. Abaqus offers a wide range of capabilities for simulation of linear and nonlinear applications. Problems with multiple components are modeled by associating the geometry defining each component with the appropriate material models and specifying component interactions. In a nonlinear analysis Abaqus automatically chooses appropriate load increments and convergence tolerances and continually adjusts them during the analysis to ensure that an accurate solution is obtained efficiently.

4.2. Shell element

Shell elements are used to model structures in which one dimension (the thickness) is significantly smaller than the other dimensions and the stresses in the thickness direction are negligible. Shell element names in Abaqus begin with the letter "S". Two types of shell elements are available in Abaqus: conventional shell elements and continuum shell elements. Conventional shell elements discretize a reference surface by defining the element's planar dimensions, its surface normal, and its initial curvature. Continuum shell elements, on the other hand, resemble three-dimensional solid elements in that they discretize an entire three-dimensional body yet are formulated so that their kinematic and constitutive behaviour is similar to conventional shell elements.

4.3. Material Properties

In the present analyses, the material properties for the various composite laminated plates are shown in the below table.

Table 1. Composite material properties of Carbon epoxy

E_1	134.75GPa		X_t	1500MPa
E_2	8.24GPa		X_c	1200MPa
$G_{12}=G_{23}=G_{31}$	7.0GPa		Y_t	50MPa
J_{12}	0.325		Y_c	250MPa
Ply Thickness:	0.0025m		S	70MPa

Table 2. Composite material properties of E-Glass epoxy

E_1	39GPa		X_t	1080MPa
E_2	8.6GPa		X_c	620MPa
$G_{12}=G_{23}=G_{31}$	3.8GPa		Y_t	39MPa
J_{12}	0.28		Y_c	128MPa
Ply Thickness:	0.0025m		S	89MPa

Table 3. Composite material properties of Kevlar 149 epoxy

E_1	87GPa		X_t	1280MPa
E_2	5.5GPa		X_c	335MPa
$G_{12}=G_{23}=G_{31}$	2.2GPa		Y_t	30MPa
J_{12}	0.34		Y_c	158MPa
Ply Thickness:	0.0025m		S	49MPa

The lay-up sequences used for the investigation are

1. $[45/-45/45/0/90]_s$
2. $[0/90/0/90/0]_s$

4.4. Failure theory used

Failure modes in laminated composites are strongly dependent on geometry, loading direction, and ply orientation. Typically, one distinguishes in-plane failure modes and transverse failure modes (associated with interlaminar shear or peel stress). Since this composite is loaded in-plane, only in-plane failure modes need to be considered, which can be done for each ply individually. The failure strength in laminates also depends on the ply layup. The effective failure strength of the layup is at a maximum if neighboring plies are orthogonal to each other. The effective strength decreases as the angle between plies decreases and is at a minimum if plies have the same direction.

The preceding biaxial strength theories suffer from various inadequacies in their description of experimental data. One obvious way to improve the correlation between theory and experiment is to increase the number of terms in the prediction equation. This increase in curve fitting ability plus the added feature of representing the various strengths in tensor form was used by Tsai and Wu. In this process, several new strength definitions are required, mainly having to do interaction between stresses in two directions.

The equation proposed by Tsai & Wu is given below

$$I_F = F_1\sigma_{11} + F_2\sigma_{22} + F_{11}\sigma_{11}^2 + F_{22}\sigma_{22}^2 + F_{66}\sigma_{12}^2 + 2F_{12}\sigma_{11}\sigma_{22} < 1.0$$

Where the Tsai-Wu coefficients are defined as

$$F_1 = \frac{1}{X_t} + \frac{1}{X_c}, \quad F_2 = \frac{1}{Y_t} + \frac{1}{Y_c}$$

$$F_{11} = -\frac{1}{X_t X_c}, \quad F_{22} = -\frac{1}{Y_t Y_c}, \quad F_{66} = \frac{1}{S^2}$$

In ABAQUS the additional parameter F12 is specified by f* or σ_{biax}.

If σ_{biax} is given

$$F_{12} = \frac{1}{2\sigma_{biax}^2}\left[1 - \left(\frac{1}{X_t} + \frac{1}{X_c} + \frac{1}{Y_t} + \frac{1}{Y_c}\right)\sigma_{biax} + \left(\frac{1}{X_t X_c} + \frac{1}{Y_t Y_c}\right)\sigma_{biax}^2\right]$$

Otherwise $F_{12} = f^* \sqrt{F_{11} F_{22}}$

Where -1.0 ≤ f* ≤ 1.0 and the default value of f* is zero.

Proper value of F12 can provide slightly more accurate results compared to experimental data, although the difference usually is not large.

5. Finite element analysis

Finite element analysis is used to gain information about the behaviour of the composite laminates subjected to various loading conditions. Simple models are analyzed. FEA is used to predict the stresses and failure index induced in the laminate. These stresses and failure index can later be used to predict the life span of the composite under various loading conditions. ABAQUS finite element codes are used for the simulations.

5.1. Modeling

A 3D deformable planar shell of length 400mm and width 200mm and thickness of each layer is 2.5mm, created to represent as a composite laminated plate in ABAQUS.

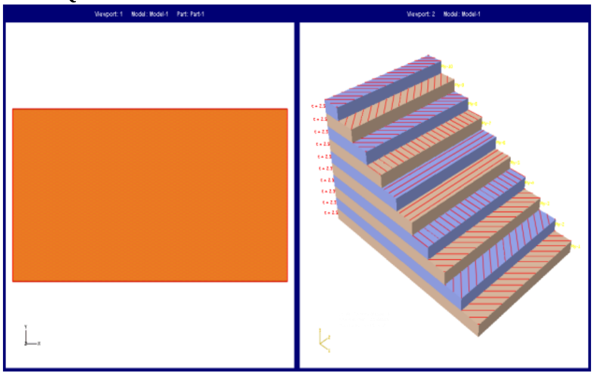

Figure 1. Shell model

5.2. Meshing

The finite element model is developed by meshing the model with S4 element type of element edge length 10mm.

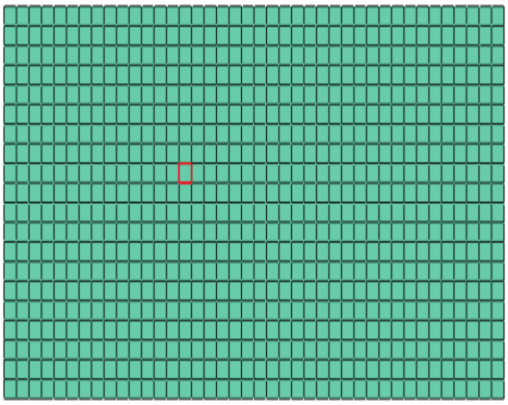

Figure 2. Finite element model of composite plate

5.3. Loading

The analysis is carried out by fixing one end of the composite plate as a cantilever and applying various types of loads such as tension, shear & transverse at the other end. The loaded model is shown in below figure.

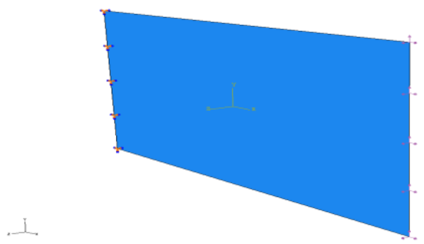

Figure 3. Composite plate with various boundary conditions

5.3. Analysis

Now the finite element model is ready to solve. The model is solved in three different cases such as tension loading, transverse loading & shear loading with varying the material properties and ply sequence. All cases are solved in static analysis. The results from this analysis were discussed in detail in the following chapter.

6. Results & discussion

The finite element analysis is done for different FRP materials, with different arrangement of lay-up sequences, material properties and loads applied to the simulation model discussed in the previous chapter. These simulations are repeated for different loadings. The results for the simulations are extracted with the post processing tools ABAQUS/CAE. Three cases are solved by using the FEA model.

6.1. Tension load

Here we took case I as tension load. These loads are applied by changing the material properties and changing the ply sequence. When this type of loads is applied on plates, the debonding between the fibres and matrix occurs and material breaks. Load vs. failure index graphs are plotted for each material and ply sequence as shown below

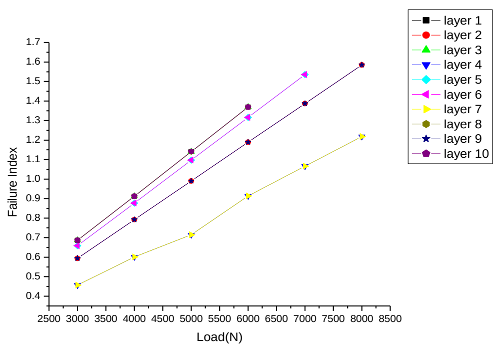

Figure 4. Failure index for carbon-epoxy [45/-45/45/0/90]s laminate for tensile load

When a steady load is applied gradually on this laminate, failure initiation occurs at 4300N approximately.

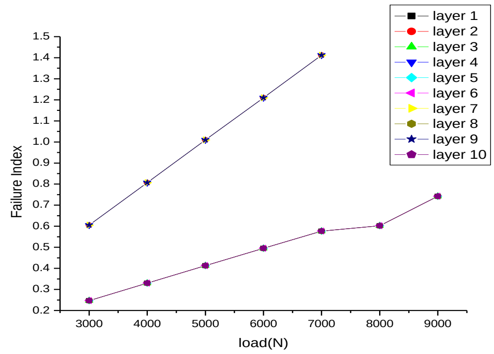

Figure 5. Failure index for carbon-epoxy [0/90/0/90/0]s laminate for tensile load

When a steady load is applied gradually on this laminate, failure initiation occurs at 4500N approximately.

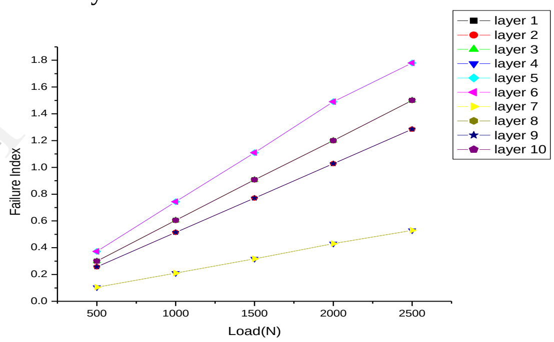

Figure 6. Failure index for E glass-epoxy [45/-45/45/0/90]s laminate for tensile load

When a steady load is applied gradually on this laminate, failure initiation occurs at 1300N approximately.

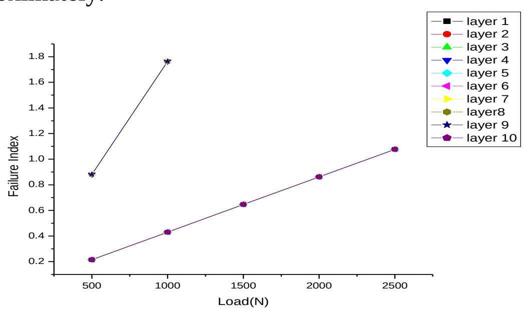

Figure 7. Failure index for E glass-epoxy [0/90/0/90/0]s laminate for tensile load

When a steady load is applied gradually on this laminate, failure initiation occurs at 700N approximately.

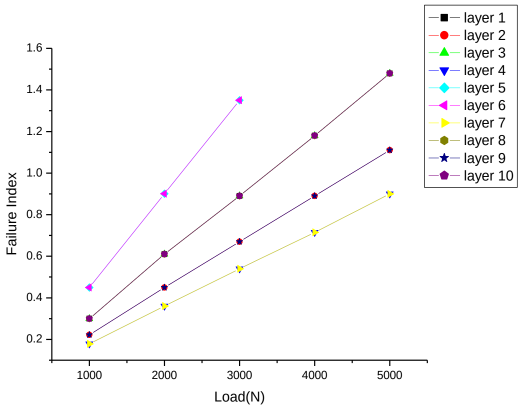

Figure 8. Failure index for Kevlar 149-epoxy [45/-45/45/0/90]s laminate for tensile load

When a steady load is applied gradually on this laminate, failure initiation occurs at 2200N approximately.

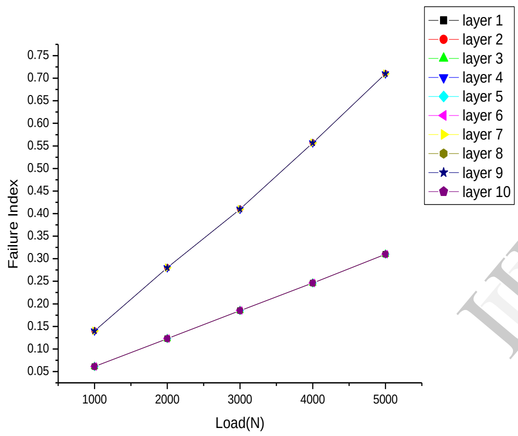

Figure 9. Failure index for Kevlar 149-epoxy [0/90/0/90/0]s laminate for tensile load

When a steady load is applied gradually on this laminate, failure initiation occurs at 6500N approximately

Table 4. Load values at Failure index > 1 for Tensile load

S. No.	Composite Material	Lay-up Sequence	Load (N)
1	Carbon Epoxy	$[45/-45/45/0/90]_s$	4300
2	Carbon Epoxy	$[0/90/0/90/0]_s$	4500
3	E glass Epoxy	$[45/-45/45/0/90]_s$	1300
4	E glass Epoxy	$[0/90/0/90/0]_s$	700
5	Kevlar149 Epoxy	$[45/-45/45/0/90]_s$	2200
6	Kevlar149 Epoxy	$[0/90/0/90/0]_s$	6500

From the above investigation we can say that Kevlar 149 epoxy with layup sequence of [0/90/0/90/0]s has high strength than the remaining layup sequence.

6.2. Transverse load

In the case II we take the same material properties and same ply angles as in the above case. Since it is a transverse loading with a minimum loading the material tends to fail. When these types of loads are applied on the composite plate's maximum damage occurs to the matrix and fails quickly. Load vs. failure index graphs are plotted for each material and ply sequence as shown below

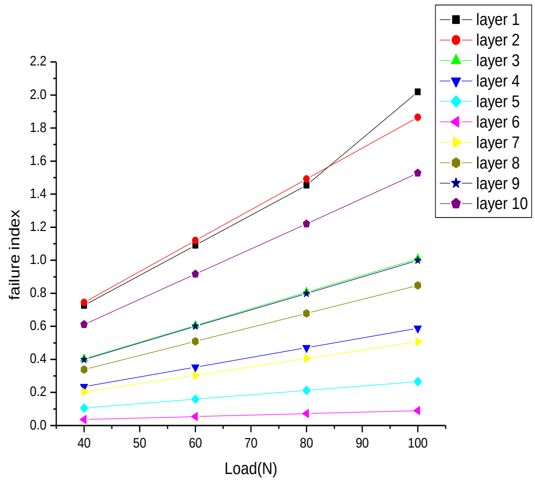

Figure 10. Failure index for carbon-epoxy [45/-45/45/0/90]s laminate for transverse load

When a steady load is applied gradually on this laminate, failure initiation occurs at 55N approximately.

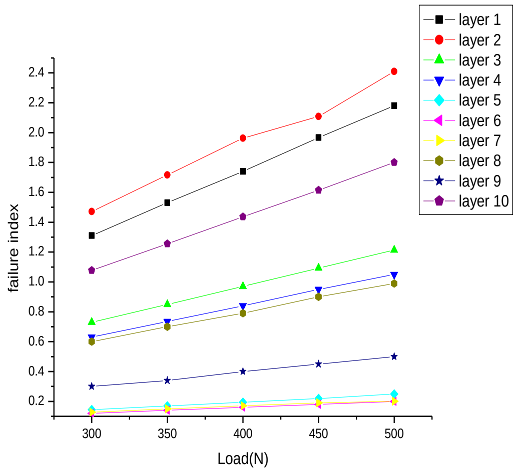

Figure 11. Failure index for carbon-epoxy [0/90/0/90/0]s laminate for transverse load

When a steady load is applied gradually on this laminate, failure initiation occurs at 250N approximately.

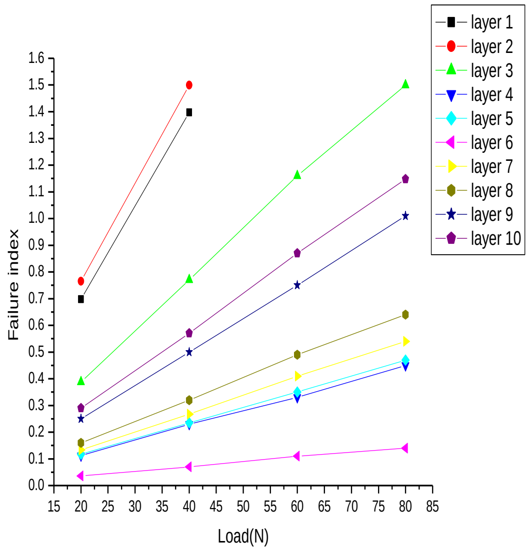

Figure 12. Failure index for E glass-epoxy [45/-45/45/0/90]s laminate for transverse load

When a steady load is applied gradually on this laminate, failure initiation occurs at 30N approximately.

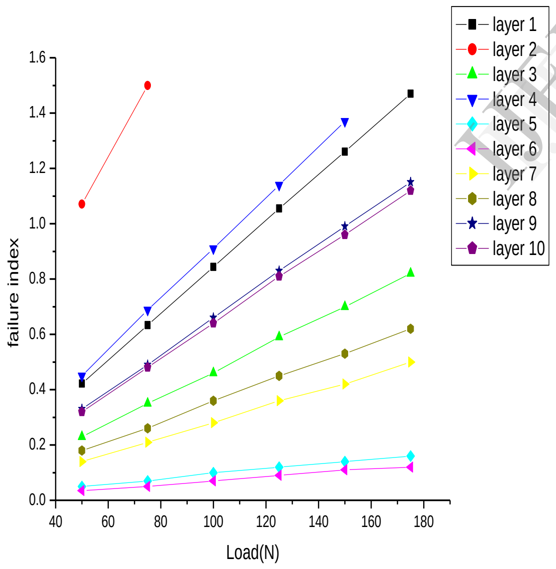

Figure 13. Failure index for E glass-epoxy [0/90/0/90/0]s laminate for transverse load

When a steady load is applied gradually on this laminate, failure initiation occurs at 40N approximately.

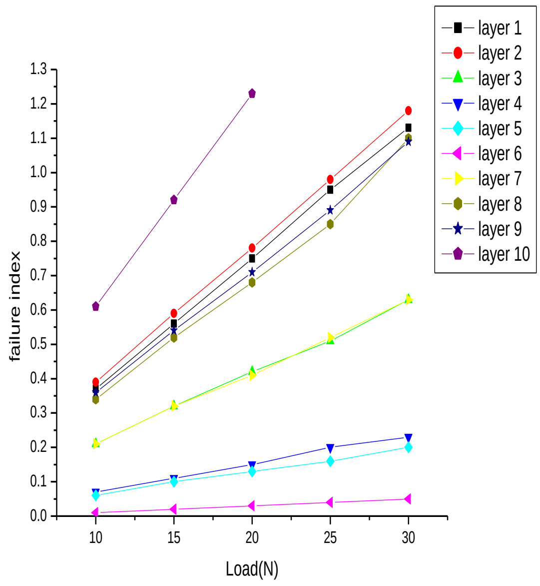

Figure 14. Failure index for Kevlar 149-epoxy [45/-45/45/0/90]s laminate for transverse load

When a steady load is applied gradually on this laminate, failure initiation occurs at 15N approximately.

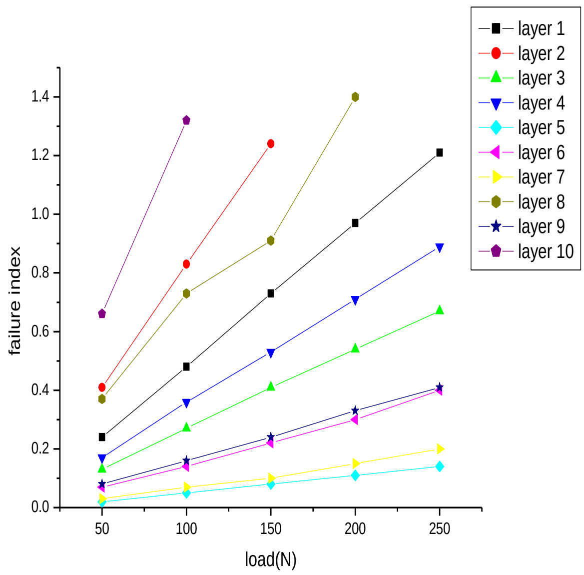

Figure 15. Failure index for Kevlar 149-epoxy [0/90/0/90/0]s laminate for transverse load

When a steady load is applied gradually on this laminate, failure initiation occurs at 75N approximately.

Table 5. Load values at Failure index > 1 for Transverse load

S. No.	Composite Material	Lay-up Sequence	Load (N)
1	Carbon Epoxy	$[45/-45/45/0/90]_s$	55
2	Carbon Epoxy	$[0/90/0/90/0]_s$	250
3	E glass Epoxy	$[45/-45/45/0/90]_s$	30
4	E glass Epoxy	$[0/90/0/90/0]_s$	40
5	Kevlar149 Epoxy	$[45/-45/45/0/90]_s$	15
6	Kevlar149 Epoxy	$[0/90/0/90/0]_s$	75

From the above investigation we can say that the best ply sequence design for transverse loading is carbon epoxy with ply sequence [0/90/0/90/0]s.

6.3. Shear load

We will repeat the same procedure as done in the above two cases. But here we will apply the shear load. When this type of load is applied in composite plate delamination occurs, strength of the laminate decreases. Load vs. failure index graphs are plotted for each material and ply sequence as shown below

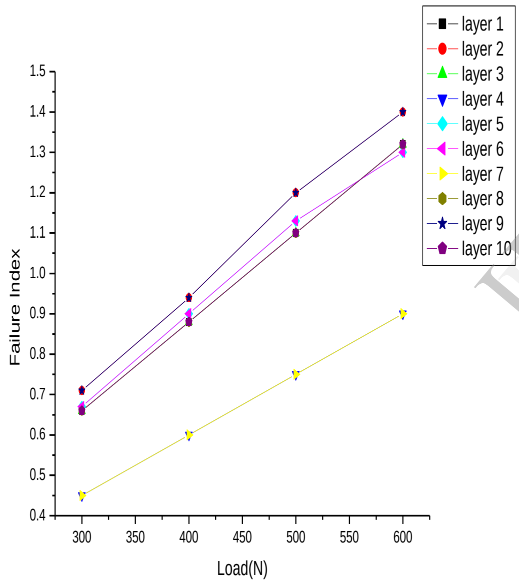

Figure 16. Failure index for carbon-epoxy [45/-45/45/0/90]s laminate for shear load

When a steady load is applied gradually on this laminate, failure initiation occurs at 400N approximately.

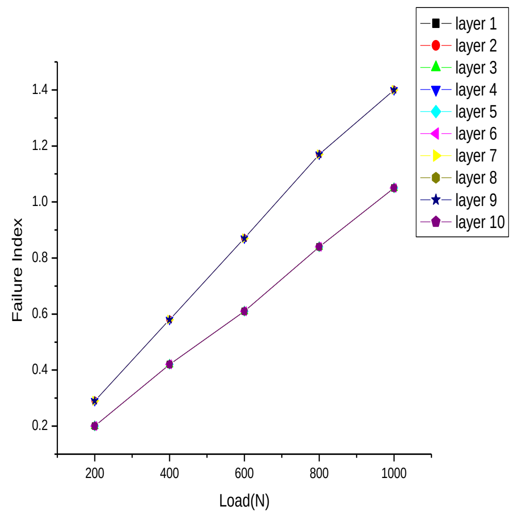

Figure 17. Failure index for carbon-epoxy [0/90/0/90/0]s laminate for shear load

When a steady load is applied gradually on this laminate, failure initiation occurs at 650N approximately.

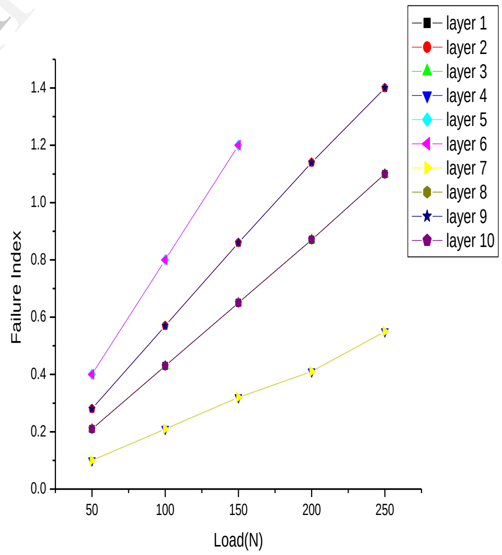

Figure 18. Failure index for E glass-epoxy [45/-45/45/0/90]s laminate for shear load

When a steady load is applied gradually on this laminate, failure initiation occurs at 110N approximately.

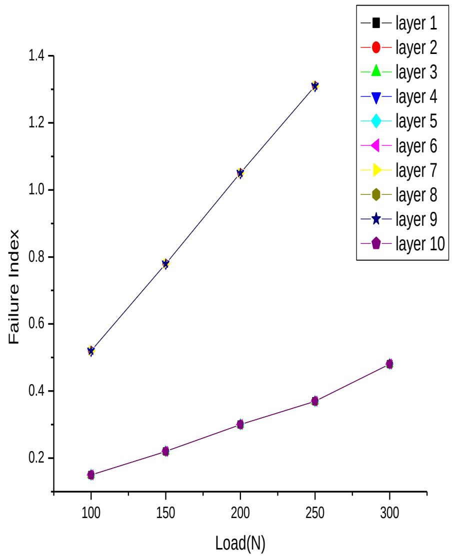

Figure 19. Failure index for E glass-epoxy [0/90/0/90/0]s laminate for shear load

When a steady load is applied gradually on this laminate, failure initiation occurs at 170N approximately.

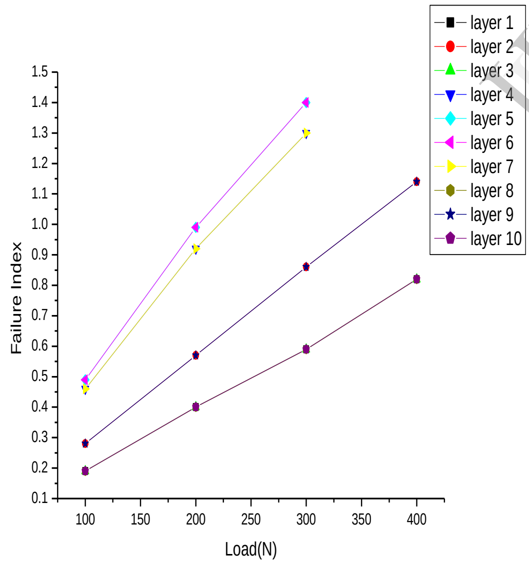

Figure 20. Failure index for Kevlar 149-epoxy [45/-45/45/0/90]s laminate for shear load

When a steady load is applied gradually on this laminate, failure initiation occurs at 200N approximately.

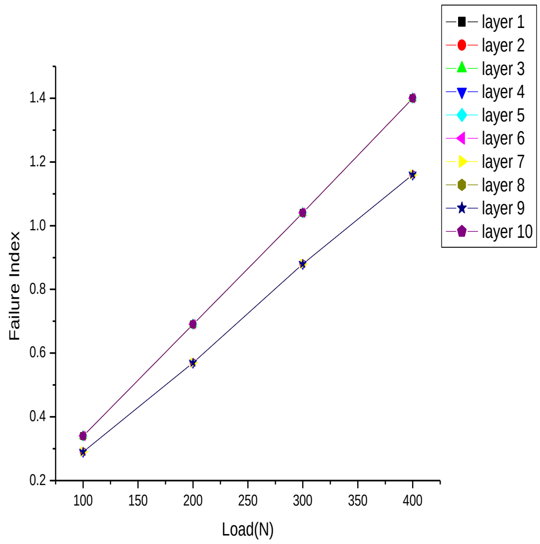

Figure 21. Failure index for Kevlar 149-epoxy [0/90/0/90/0]s laminate for shear load

When a steady load is applied gradually on this laminate, failure initiation occurs at 250N approximately.

So from the above graphs we can observe that all the laminates with ply sequence [45/-45/45/0/90]s are behaving similarly and with ply sequence [0/90/0/90/0]s are behaving similarly. Since the loading is shear plies with 90° angle are stronger and 0° plies are failing soon.

Table 5. Load values at Failure index > 1 for Shear load

S. No.	Composite Material	Lay-up Sequence	Load (N)
1	Carbon Epoxy	[45/-45/45/0/90]$_s$	400
2	Carbon Epoxy	[0/90/0/90/0]$_s$	650
3	E glass Epoxy	[45/-45/45/0/90]$_s$	110
4	E glass Epoxy	[0/90/0/90/0]$_s$	170
5	Kevlar149 Epoxy	[45/-45/45/0/90]$_s$	200
6	Kevlar149 Epoxy	[0/90/0/90/0]$_s$	250

Form the above investigation for shear loading we can observe that for carbon epoxy with [0/90/0/90/0]s has high strength compared to remaining laminates.

7. Conclusions

The present work is aimed at gaining an initial understanding of the ply behaviour of fiber reinforced laminates with carbon, E-glass and Kevlar fibers and epoxy resins. From the results of this work the following conclusions can be drawn.

- The behavior of the composite changes with the application of the different loading conditions
- The ply angle sequence of a composite material greatly affects on its failure behaviour.

- Carbon epoxy with [0/90/0/90/0]s has best performance under shear loading and transverse loadings
- Kevlar 149 epoxy with [0/90/0/90/0]s has best performance under tension loading.

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