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An Investigation of Ply Behavior in A GFRP Composite Laminated Plate

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ABSTRACT: In this work, a finite element model is developed to predict the progressive fatigue damage and the life of the composite laminate with different layup Sequence on the composite laminates subjected to various loadings and gets the best ply design for the materials considered in this investigation. Finite element models are created with ABAQUS software. These models are used to simulate for glass epoxy materials with different ply angles, as well as different loads. Graphs are plotted to compare the failure index of glass epoxy materials, the best ply design for the composites are investigated in this project.

KEYWORDS: GFRP Composites, ply angles, Tsai-Wu failure criterion.

I. 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 shears 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.

II. LITERATURE REVIEW

J. Eskandari Jam and N. GarshasbiNia [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

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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.

III. 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 behavior of composite laminated plate by applying different loads with finite element models and predicted the behavior of the laminates under different loading situations. Further research is needed to evaluate the effects of damage on specific applications.

IV. METHODOLOGY

IV.I.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.

IV.II. 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, ensembles 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.

LAMINATE THICKNESS, LAYUP AND STACKING

Target stiffness depends on material properties as well as on the thickness of the laminate, the layup, its size and the boundary conditions. The stiffness in the thickness direction has a significant effect on the magnitude of the maximum contact force which of course will affect the extent of the damage induced. The stacking sequence also plays a very important role on the impact resistance of laminates. In a unidirectional laminate, since the reinforcing fibres are all oriented in the same direction, no delamination occurs. For two plates with the same thickness but with different stacking sequences, the one with the higher differences of angle between two adjacent plies will experience higher delamination areas. Increasing the thickness of each layer will also lead to increased delamination. Increasing the difference between the longitudinal and transverse moduli of the material

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Leads to higher bending stiffness mismatching and therefore increased delamination. However, damage initiation is matrix- and interface-dependent and therefore has little or no dependence on the stacking sequence. The peak load reached during impact or the energy at peak load is strongly dependent on the stacking sequence.[11] Stitching is used to introduce through the thickness reinforcement but in a different way than with weaving or braiding. The laminated structure is preserved and stitching can be performed on either a prepeg or perform. Stitching density and pattern and properties of the thread can be varied to improve delamination resistance.

IV.III. MATERIAL PROPERTIES

Mechanical properties of glass fibre-reinforced composites are dependent on the properties of the constituent materials (type, quantity, fibre distribution and orientation and void content). Beside these properties, the nature of the interfacial bonds and the mechanisms of load transfer at the interface also play an important role. If the building parts of composites differ in physical form and in chemical composition, only a weak interaction can be developed at the interface. For improving the adhesion between the matrix and the fibres, there are varieties of modification technique depending on the fibre and matrices type. One of them is the application of coupling agents, which are Able to establish chemical bonds between the fibre and the matrix due to their chemical composition. The price Of surface modifier chemicals is one of the key points in the applicability of reinforced composites.33 Polyesters Could not be applied for technological purposes without reinforcing because of low strength and brittleness, but They are intensively used for composite matrices. The GF composites are the most wide spread among fibre-reinforced materials due to their favorable mechanical and economical characteristics. For industrial applications, the E- and S-type GFs are the most commonly used because they have the most favorable cost-mechanical property relationships. Thermo set composites have been applied in 1940s in aircraft industry for the first time. Those materials were laminated polyester composites, and the first application was the cover of radar antennas because there was a need for such non-metallic materials that allowed radio waves through without distortion. The manufactured parts were found to have better weight/volume ratio than the ones made from metallic materials. Since then, thermo set composites have been applied as construction materials. Current civil aircraft applications have concentrated on replacing the secondary structure with fibrous composites, where the reinforcement material Has either been carbon, glass, Kevlar, or hybrids of those. Several authors have been studying the effect of composite hybridization on high-velocity impact behaviour.

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

Table: 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
ϑ_{12}	0.28	Y_c	128MPa
Ply Thickness:	0.0025m	S	89MPa

The lay-up sequences used for the investigation are

1. [0/45/90/_45/90/45/0]s
2. [0/45/02/_45/02/45/02/_45/0]s

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IV.IV. 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

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

$$F_{11} = -\frac{1}{X_t X_C}$$

$$F_{22} = -\frac{1}{Y_t Y_c}$$

$$F_{66} = \frac{1}{S^2}$$

In ABAQUS the additional parameter F_{12} is specified by f^* orσ_{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 $-1.0 \leq f^* \leq 1.0$ and the default value of f^* is zero.

Proper value of F_{12} can provide slightly more accurate results compared to experimental data, although the difference usually is not large.

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V.I INTRODUCTION

Finite element analysis is used to gain information about the behavior 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.

V.II 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.

V.III MESHING

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

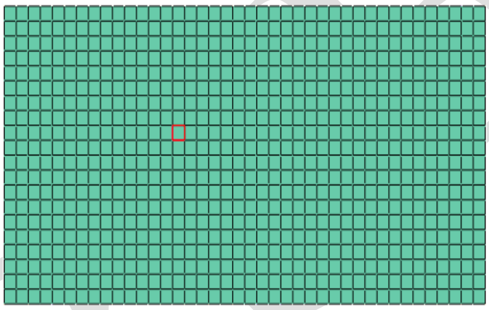

Figure V.I: Finite element model of composite plate

V.IV. 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 fig

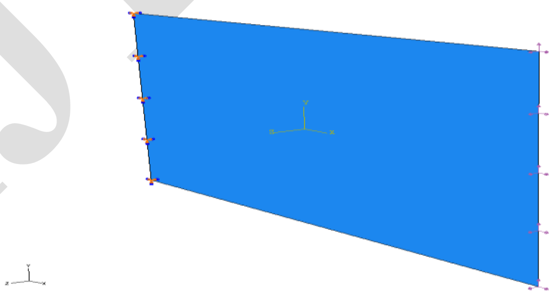

Figure V.II: Composite plate with various boundary conditions

V.V 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 here.

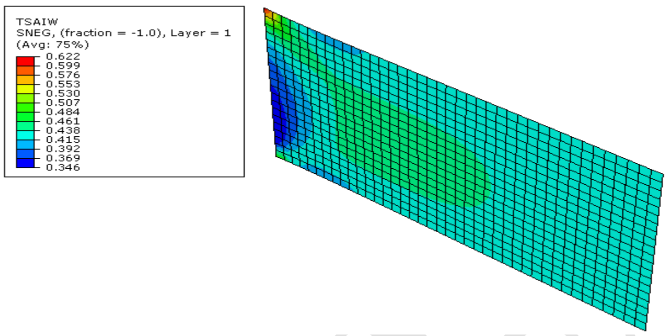

Figure V.III: Deformed shape of a composite plate based on Tsai-Wu failure criterion

V. RESULTS & DISCUSSION

The finite element analysis is done for different ply laminates, with different arrangement of lay-up sequences, material properties and loads applied to the simulation model. These simulations are repeated for different loadings which are taken by the ASME no of AS4/3501-6 the results for the simulations are extracted with the post processing tools ABAQUS. Three cases are solved by using the FEA model.

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

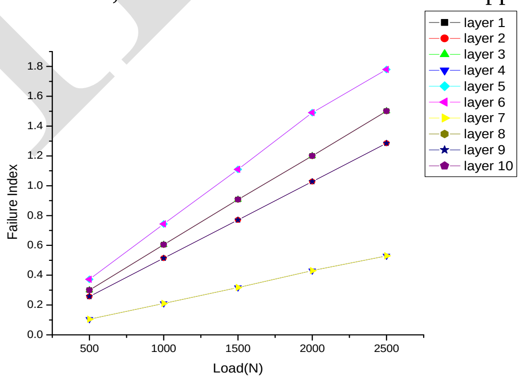

Figure VI.I: Failure index for E glass-epoxy[0/45/90/_45/90/45/0]$_s$ laminate for tensile load

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

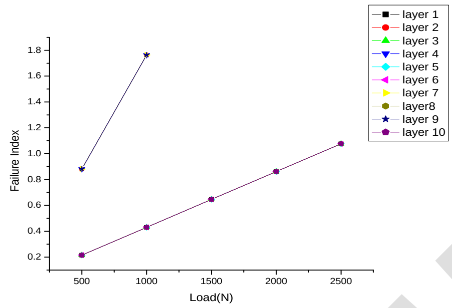

Figure VI.II: Failure index for E glass-epoxy [0/45/0$_2$/_45/0$_2$/45/0$_2$/_45/0]$_s$ laminate for tensile load

So from the above graphs we can observe that all the laminates with ply sequence [0/45/90/_45/90/45/0]$_s$ are behaving similarly and with ply sequence [0/45/0$_2$/_45/0$_2$/45/0$_2$/_45/0]$_s$ are behaving similarly. Since the loading is tension plies with 0^o angle are stronger and 90^o plies are failing soon.

Table VI.I: Load values at Failure index > 1 for tensile load

S.No.	Composite Material	Lay-up Sequence	Load (N) at Failure Index >1
1.	E glass – Epoxy	1. [0/45/90/_45/90/45/0]$_s$	1300
2.	E glass – Epoxy	2.[0/45/0$_2$/_45/0$_2$/45/0$_2$/_45/0]$_s$	700

From the above investigation we can say that E glass epoxy with layup sequence of [0/45/0$_2$/_45/0$_2$/45/0$_2$/_45/0]$_s$ has high strength than the remaining layup sequence.

VI.II TRANSVERSE LOAD

In the case 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 V$_s$ failure index graphs are plotted for each material and ply sequence as shown below

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

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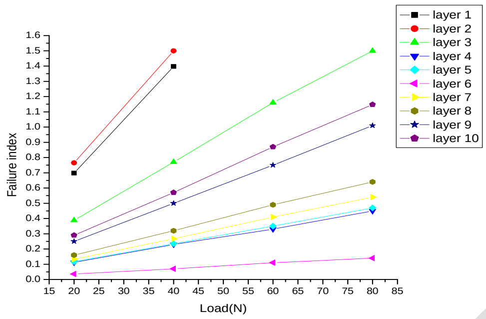

Figure VI.III: Failure index for E glass -epoxy [0/45/90/_45/90/45/0]$_s$ laminate for transverse load

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

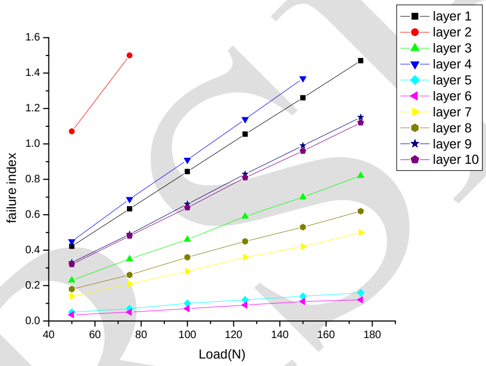

Figure VI.IV: Failure index for E glass -epoxy [0/45/0$_2$/_45/0$_2$/45/0$_2$/_45/0]$_s$ laminate for transverse load

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

From the above graphs we can observe that each ply is behaving of its own since it is a transverse loading. In most of the cases in transverse loading, second ply is failing first. Middle plies are showing more strength than outer plies.

Table VI.II : Load values at Failure index > 1 for Transverse load

S.No.	Composite Material	Lay-up Sequence	Load (N) at Failure Index >1
1.	E glass – Epoxy	1.[0/45/90/_45/90/45/0]$_s$	30
2.	E glass – Epoxy	2.[0/45/0$_2$/_45/0$_2$/45/0$_2$/_45/0]$_s$	40

From the above investigation we can say that the best ply sequence design for transverse loading is E glass epoxy with ply sequence [0/45/0$_2$/_45/0$_2$/45/0$_2$/_45/0]$_s$

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VI.III 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's delamination occurs strength of the laminate decreases. Load V_s failure index graphs are plotted for each material and ply sequence as shown below

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

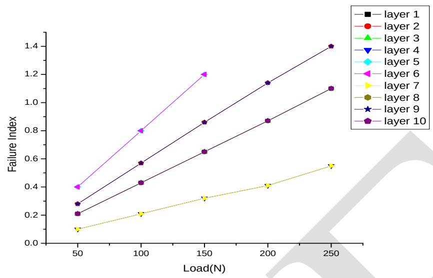

Figure VI.V: Failure index for E glass -epoxy $[0/45/90/\_45/90/45/0]_s$ laminate for shear load

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

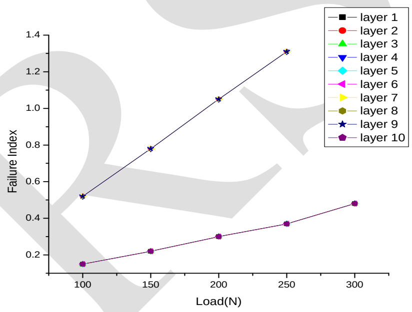

Figure VI.VI: Failure index for E glass -epoxy $[0/45/0_2/\_45/0_2/45/0_2/\_45/0]_s$ laminate for shear load

So from the above graphs we can observe that all the laminates with ply sequence $[0/45/90/\_45/90/45/0]_s$ are behaving similarly and with ply sequence $[0/90/0/90/0]_s$ are behaving similarly. Since the loading is shear plies with 90^o angle are stronger and 0^o plies are failing soon.

Table VI.III: Load values at Failure index > 1 for Shear load

S.No.	Composite Material	Lay-up Sequence	Load (N) at Failure Index >1
1.	E glass – Epoxy	1.$[0/45/90/\_45/90/45/0]_s$	110
2.	E glass – Epoxy	2.$[0/45/0_2/\_45/0_2/45/0_2/\_45/0]_s$	170

Form the above graphs for shear loading we can observe that for E glass epoxy with $[0/45/0_2/\_45/0_2/45/0_2/\_45/0]_s$ has high strength compared to remaining laminates.

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VII.CONCLUSION

The present work is aimed at gaining an initial understanding of the ply behavior of fiber reinforced laminates with E-glass 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 behavior.
- E glass epoxy with $[0/45/0_2/\_45/0_2/45/0_2/\_45/0]_s$ has best performance under shear loading and transverse loadings

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