GLOBAL JOURNAL OF ENGINEERING SCIENCE AND RESEARCHES

FLEXURAL FATIGUE ANALYSIS OF CARBON/POLYESTER ANGLE PLY LAMINATES

Mohammed Owais Ahmed Sajjad*
*Assistant Professor, Kakatiya University, Warangal, Telangana-India

---

ABSTRACT

Composites are becoming an essential part of today's materials because they offer advantages such as low weight, corrosion resistance, and high fatigue strength, faster assembly, etc. Composites are used as materials ranging from making aircraft structures to golf clubs, electronic packaging to medical equipment, and space vehicles to home building. Composite materials have extensive engineering application where strength to weight ratio, low cost and ease of fabrication are required. They provide combination of properties such as tensile modulus, compressive strength and impact strength which cannot be realized in other materials. In recent times composites have been established as highly efficient, high performance structural materials and their use is increasing rapidly. Composites are usually used when a combination of properties of different types of fibers have to be achieved, or when longitudinal as well as lateral mechanical performances are required.

This paper explicitly discus and presents the influence of unidirectional carbon fiber and polyester polymer composite laminates. These laminates were made in $[\pm 0^0]_{10}$, $[\pm 45^0]_{10}$, $[\pm 55^0]_{10}$ and $[\pm 0^0 \& 90^0]_{10}$ degree orientations. These specimens are prepared in the laboratory using compression moulding technique. The tensile tests are performed on the composite laminates to estimate the bending load from the ultimate tensile stress. Further the composite laminates are subjected to cyclic bending load to predict the failure behaviour of angle ply composite laminates in terms of stiffness degradation

Keywords: FRP, polyester resin, signal conditioning system, load cell, data acquisition system, stiffness degradation

---

I. INTRODUCTION

Composite materials emerged in the middle of the 20th century as a promising class of engineering materials providing new prospects for modern technology. Generally speaking any material consisting of two or more components with different properties and distinct boundaries between the components can be referred to as a composite material. Moreover, the ideas of combining several components to produce a material with properties that are not attainable with the individual components have been used by man for thousands of years. Correspondingly, the majority of natural materials that have emerged as a result of a prolonged evolution process can be treated as composite materials.

The modern composite material is a system composed of two or more dissimilar materials, differing in forms, which are insoluble with each other, physically distinct and chemically not homogeneous. The resulting product's properties are much different from the properties of constituent materials. One of the materials is called reinforcement, in the form of fibre, woven fabric sheets, or particles, embedded in the other materials called matrix. Composites are used because of the overall properties of the composite which are superior to those of the individual components.

As the use of advanced fiber reinforced composites is extended to various engineering applications, extensive research has been carried out to further understand the mechanical properties of these materials so as to benefit new design and applications. It has become a common knowledge that the mechanical properties of fiber reinforced composites are dependent on the specific properties of the matrix and reinforcing fibers and, just as importantly if not more so, their interfacial properties, which ensure stress transfer between matrix and fibers. In fact, study of the mechanisms of the matrix–fiber interactions via the interface is now one of a few key issues in composite studies. Several experimental techniques have been developed to characterize the interfacial properties in a fiber reinforced composite. These include the single fiber pull out test, single fiber fragmentation test, fiber peel test and micro-indentation test.

II. EXPERIMENTAL PROCEDURE

Materials and Test specimens.

In this project, the composite laminate is prepared using compression moulding technique. Here ten plies of carbon fiber are taken in a symmetric manner i.e. (±0º, ±45º, ±55º, ±0º-90º) one over the other and polyester resin is used as an adhesive. The size of the mould taken is 30 × 30 cm. The list of ingredients used in this process is as given below in Table 1.

Table 1: Materials and test specimens

Type of resin	Polyester
Type of fiber	Carbon fiber of unidirectional type
Hardener used	Catalyst (MEKP) with Accelerator
No. of Piles per laminate	10
Nature of laminate	Symmetric type (Ex: +45,-45,-45,+45)
Method of preparation	Compression molding technique

Preparation of Specimen.

STEP 1: Initially the carbon fiber is to be cut in required shape of the size 30 × 30cms of required orientation. Five plies of positive orientation (anti-clockwise) and other five in negative orientation (clockwise) are to be prepared. A plastic sheet is used at the top and bottom of the mould in order get good surface finish for the laminate.

Fig No:1 Preparation of laminate

STEP 2: The mould has to be cleaned well after that PVA (Poly Vinyl Acetate) is applied in order to avoid sticking of the laminate to the mould. A thin plastic sheet is placed at the bottom of mould. Then a ply of positive orientation is placed over the sheet. Sufficient amount of resin which is prepared beforehand (hardener of quantity 10% of resin is to be mixed with the resin and get stirred well) is poured over the ply as shown in figure.

Fig No:2 Mould used for preparation of laminate

STEP 3: Sufficient quantity of polyester resin mixed with 10% methyl ethyl ketone peroxide (MEKP) catalyst with accelerator by volume is impregnated using a rolling device. Enough care should be taken to avoid the air bubbles formed during rolling.

STEP 4: Then on this ply, other ply of negative orientation (clock wise) is placed, the same procedure is followed as shown in fig.no.5.4 after this, other five plies are placedto obtain required thickness of 5 mm and rolling is done.

Fig No:3 Arranging of lamina in orientations

STEP 5: After the rolling of all plies, the covering sheet (plastic sheet) is placed and the mould is closed with the upper plate. The compression is applied on the fiber- resin mixture by tightening the two mould plates uniformly. Enough care should be taken to provide uniform pressure on the laminate while fixing plates and left for curing. This explained in fig.no.4

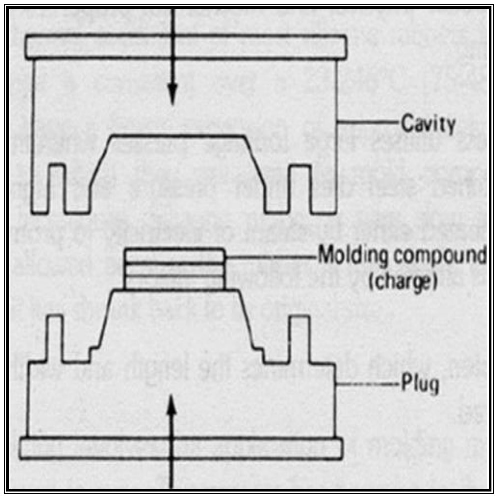


Fig No:4 Compressive moulding

STEP 6: After enough curing time (7-10 hrs.) the laminate is removed from the mould plates carefully. The laminates prepared are shown in the fig.no.5

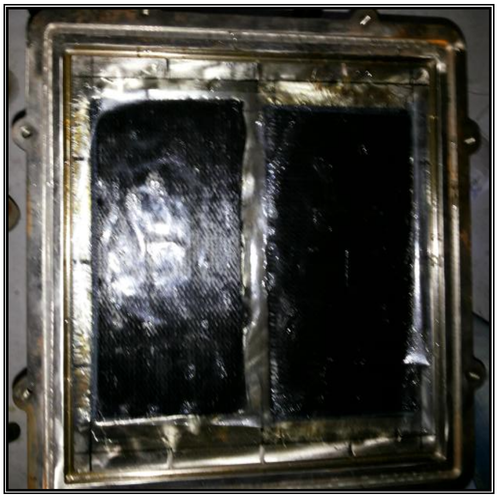


Fig No:5 Carbon polyester laminate

III. TEST PROCEDURE

Evaluation of Tensile Properties of Composite Laminates

In a broad sense, tensile test is a measurement of the ability of a material to withstand forces that tend to pull it apart and to what extent the material stretches before breaking. The stiffness of a material which represented by tensile modulus can be determined from stress-strain diagram. Tensile test is performed to and identify the ultimate strength of the laminate subjected to flexural fatigue.

Universal Testing Machine was used at cross-head speed of 3mm/min. The specimens were positioned vertically in the grips of the testing machine. The grips were then tightened evenly and firmly to prevent any slippage with gauge length kept at 50mm.

As the tensile test starts, the specimen elongates; the resistance of the specimen increases and is detected by a load cell. This load value (P) is recorded until a rupture of the specimen occurred. Instrument software provided along with the equipment records the load value (P).

Tensile properties should be considered as important design parameters for the selection of engineering materials for their desired application. Engineers have played a significant role in that they should be able to analyse and understand material behaviour and properties through these mechanical testing parameters.

Fig No:6 Tensile test performed on specimen

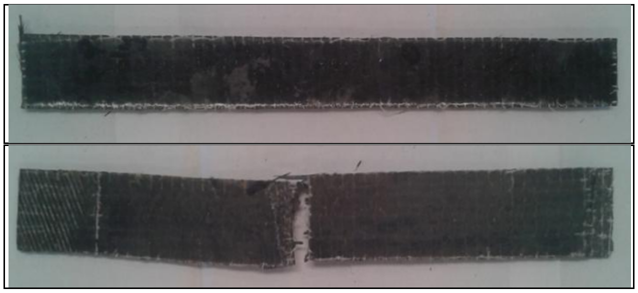


Fig No:7 Specimen before and after the tensile test

Flexural Fatigue Test-Rig design and development

The flexural fatigue failure in laminated composite materials is a very common failure mode in most of the FRP components. As reinforced polymers used in weight critical applications, often over designed to compensate fatigue failure lead to the increase in weight which in turn hampers the objective of designer. In this connection the investigation on flexural fatigue failure behaviour of laminate to be used in the component is very important. As standard equipment and test procedures are not available the need for custom built flexural fatigue testing equipment arises. The design of the flexural fatigue test rig is as shown in the figure below

Fig No 8 Real Time Test Rig

FRP components like windmill blades, leaf spring and most of the components used in automobile industry are generally subjected to flexural fatigue. The present work is aimed at the establishing a standard test procedure for analysing and understanding the flexural fatigue failure behaviour of composite laminates. The capability of the test-rig critically depends on the dynamic load sensing transducer and data logging system. The data generated from the test rig's data logger could be analysed to predict fatigue life characteristics of composite laminates.

The strain measuring sensing element in the load cell is of electrical type. The strain gauge is glued to the load cell. The resistance of the strain gauge is 350 ohms under unstrained conditions. These strain gauges are incorporated in the bridge circuit. The amount of strain applied on the load cell proportionally changes the resistance of the strain gauge. This change in resistance causes the bridge unbalance. This unbalanced voltage is proportional to the load applied on the specimen. The unbalanced voltage from bridge is of low magnitude which is very difficult to sense, which is fed to instrumentation amplifier.

Flexural Fatigue test rig interfacing with data logging system

The specimens are fixed vertically to a rigid platform as shown in figure 5.8. The dynamic load sensor is fixed to the specimen through a hinge as represented in the schematic diagram 5.9.The dynamic load sensor's other end is assembled to the pivot of the eccentric mechanism. The eccentricity is provided based on the deflection load calculations made from the experimental results. On rotating the eccentric mechanism by one revolution, a complete symmetrical reversible bending about the neutral axis of the laminate is induced. The deflection force is measured from the signal condition system digital display. The induced load is estimated in view of providing bending stress on the laminate, the stresses were kept 50% below the yield strength of the individual laminates. The bending loads are estimated from the tensile test results of the respective laminates $[\pm 0^{\circ}]_{10}$, $[\pm 45^{\circ}]_{10}$, $[\pm 55^{\circ}]_{10}$ and $[\pm 0^{\circ}\ -90^{\circ}]_{10}$. As the eccentric mechanism is rotating the bending load is measured in the indirect from of voltage generated from the dynamic load sensor.

The NI 6009 data logger with 8 channel analog and digital signal receiving capability has been used to log the data generated from the load sensor. The voltage generated from the load sensor is conditioned by a signal condition system and then the analog output from the signal condition systems is fed through the date logger to PC.

The LabVIEW software provided by 'National Instruments' is used to log data in the form of time versus voltage. As the cyclic loading is applied on specimen is converted in the form of a perfect sinusoidal voltage wave form is stored in the PC in the LAB VIEW file format. As the test is continuously performed on the specimen the continuous data points of voltage and time are stored in the PC. The LabVIEW software has the provision of collection of snapshot for a period of 3.33 sec. And then there is a provision of exporting the data into EXCEL format in the form of time versus voltage data points. Number of such snapshots in regular intervals of one snapshot for every 5mins is taken and exported to EXCEL file format, from the beginning of the test to end of the test. The test is stopped when the residual stiffness of the laminates is almost constant after number of cycles of fatigue loading.

Fig No:9 Data Acquisition System and Data Logging System

IV. EXPERIMENTAL PROCEDURE

The entire experiment is performed in four steps.

Step No.1:	A test coupon is collected from the laminate to perform tensile test and identify the ultimate strength of the laminate subjected to flexural fatigue.
Step No.2:	Calculation of bending load with reference to the bending stresses imposed on the laminate so that the bending stresses are equivalent of 50% of the ultimate tensile stress.
Step No.3:	Estimation of deflection with reference to the bending stresses to be imposed on the laminate considering the effective length.
Step No.4:	The deflection is adjusted by adjusting the lead screw to obtain desired deflection.

The test rig's rotating disk is rotated at 1.93rps. The cyclic load applied by the load cell link is recorded in the form of digital signal by the data logger in the form of a sinusoidal digital wave. As the number of cycles load application proceeds, the stiffness of the laminate continuously reduced. In this situation the digital data generated by the data logger is off high volume which cannot be processed to understand the stiffness degradation phenomena thoroughly. The LabVIEW software has the provision of collection of snapshot for a period of 3.33 sec. And then there is a provision of exporting the data into EXCEL format in the form of time versus voltage data points. Number of such snap shots in regular intervals of one snap shot for every 5mins are taken and exported to EXCEL file, from the beginning of the test to end of the test.

The test is stopped when the residual stiffness of the laminates is almost constant after number of cycles of fatigue loading. It has been observed from the test, that the stiffness of the test coupon is continuously degrading due to the failure of the top and bottom layers because of cyclic loading. Once few layers of the top and bottom layers of laminate are damaged, the continuous redistribution of stress leads to the prevention of further damage because attainment of pivoting effect occurrence in the laminate. Once this state is reached further reduction in stiffens is not observed

V. CALCULATING THE BENDING LOAD IN N

Table 2 Bending Load w.r.t to orientation

S.No	Degree of orientation	Name of the Material	Cross sectional in mm^2	Ultimate stress in N/mm^2	Bending Load in N
1	$[\pm0^0]_{10}$	Carbon Polyester	150 x 30mm^2	846.72Mpa	352.8
2	$[\pm45^0]_{10}$	Carbon Polyester	150 x 30mm^2	810.72Mpa	337.512
3	$[\pm55^0]_{10}$	Carbon Polyester	150 x 30mm^2	397.72Mpa	165.3
4	$[\pm0^0\text{-}90^0]_{10}$	Carbon Polyester	150 x 30mm^2	432Mpa	180.4

The basic definition of high cyclic fatigue, the stresses induced cyclic loading should be well below the 50% of the ultimate tensile stresses (strength) of the specimen subjected to fatigue loading. The present work is focusing on flexural fatigue analysis of carbon/polyester balanced symmetric laminates. In view of simulating such stresses the following calculations provides the estimation of bending loads to be simulated on specimens.

Let M = Bending Moment = W*L (Where W is the bending load and L is the effective length of the specimen) f = Bending Stresses.

And **I** = Moment of Inertia of the specimen = **$bt^3/12$**, where '**b**' is the width of the specimen and 't' is the thickness of the specimen.

The load to be simulated is estimated from classical bending beam equation i.e., **$M/I = f_b/Y$**, Where f_b is the bending stresses to be simulated as per the definitions of high cyclic fatigue loading and **'Y'** is the half the thickness of the specimen.

VI. RESULTS AND DISCUSSIONS

In the present work the custom built flexural fatigue test rig is designed and fabricated to perform flexural fatigue experiments on laminates of $[\pm0^0]$, $[\pm45^0]$, $[\pm55^0]$, and $[\pm0^0.90^0]$ angle ply balanced symmetric laminates made of carbon/polyester at constant amplitude at a frequency of 1.93 RPS at 50% stress ratio, in view of choosing best orientation sequence for critical applications. As the flexural fatigue failure behaviour of laminates are exhibiting pattern of continuous decay of stiffness with respect to number of cycles of load application. The pattern of the stiffness degradation curve analysed origin lab software.

1. Flexural Fatigue Failure Analysis of Carbon/Polyester Angle Ply composite laminate at $[\pm0°]_{10}$ Orientation Sequence of Stacking

Fig 10 Carbon/polyester at [±0°] angle ply composite laminate test specimen.

Fig 11 Carbon/polyester at $[\pm 0^{o}]$ angle ply composite laminate specimen after tensile test

Fig 12 Carbon/polyester at $[\pm 0^{o}]$ angle ply composite laminate specimen after flexural fatigue test

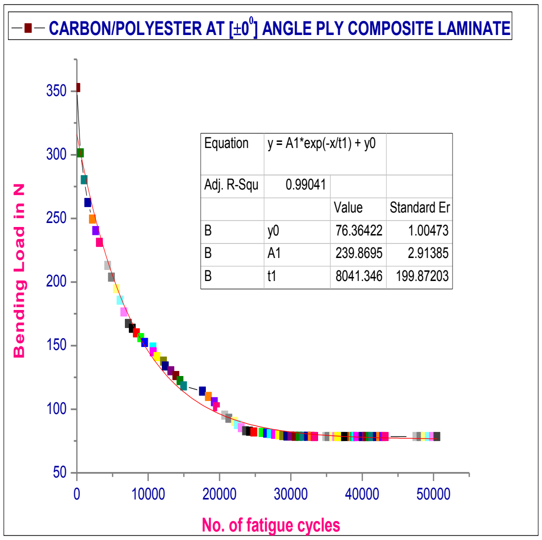


Fig 13 Stiffness degradation behaviour of $[\pm 0^{0}]_{10}$ orientation sequence of stacking of angle ply composite laminate.

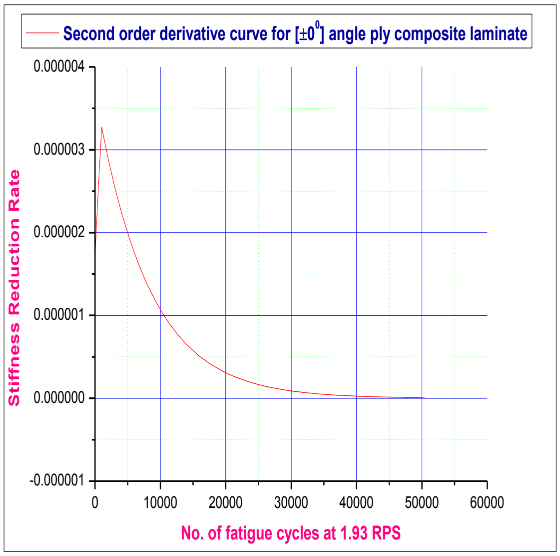


Fig 14 Second order differential curve for $[\pm 0^{0}]$ orientation sequence of stacking of angle ply composite laminate.

The second order differential equation of stiffness reduction per cycle (plotted on Y–axis) with respect to number of fatigue cycles is determined and plotted in Fig 6.5, and it is observed that stiffness reduction per cycle is appeared that it is linearly increasing mode up to 1,500 cycles. Further the stiffness reduction is steadily reduced up to 45,000 cycles. Further it is observed that there is no variation in the stiffness after 45,000 cycles and more. This state is considered as pivoting state.

2. Flexural Fatigue Failure Analysis of Carbon/Polyester Angle Ply composite laminate at [±45°]$_{10}$ Orientation Sequence of Stacking

Fig 15 Carbon/polyester at [±45°] angle ply composite laminate test specimen

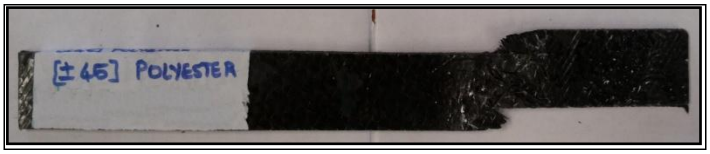


Fig 16 Carbon/polyester at [±45°] angle ply composite laminate specimen after tensile test.

Fig 17 Carbon/polyester at [±45°] angle ply composite laminate specimen after flexural fatigue test.

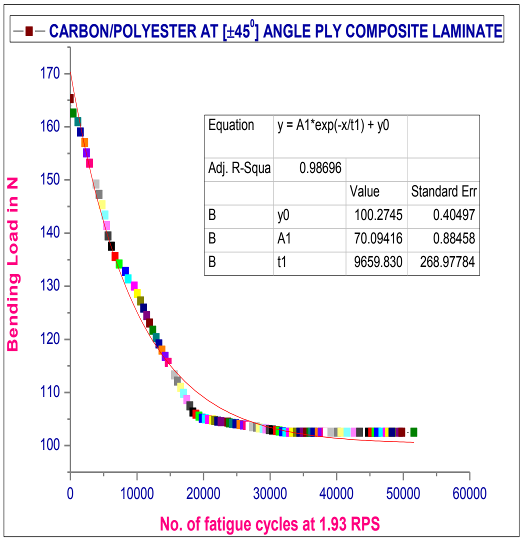


Fig 18 Stiffness degradation behaviour of [±45^0]$_{10}$ orientation sequence of stacking of angle ply composite laminate

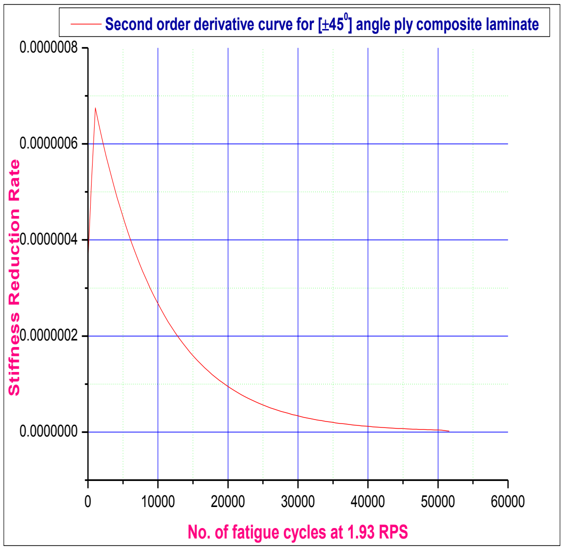


Fig 19 Second order differential curve for [±45^0] orientation sequence of stacking of angle ply composite laminate.

The second order differential equation of stiffness reduction per cycle (plotted on Y–axis) with respect to number of fatigue cycles is determined and plotted in Fig 6.10, and it is observed that stiffness reduction per cycle is appeared that it is linearly increasing mode up to 1,500 cycles. Further the stiffness reduction is steadily reduced up to 44,500 cycles. Further it is observed that there is no variation in the stiffness after 44,500 cycles and more. This state is considered as pivoting state.

3. Flexural Fatigue Failure Analysis of Carbon/Polyester Angle Ply composite laminate at [±55°]$_{10}$ Orientation Sequence of Stacking

Fig 20 Carbon/polyester at [±55°] angle ply composite laminate test specimen

Fig 21 Carbon/polyester at [±55°] angle ply composite laminate specimen after tensile test

Fig 22 Carbon/polyester at [±55°] angle ply composite laminate specimen after flexural fatigue test

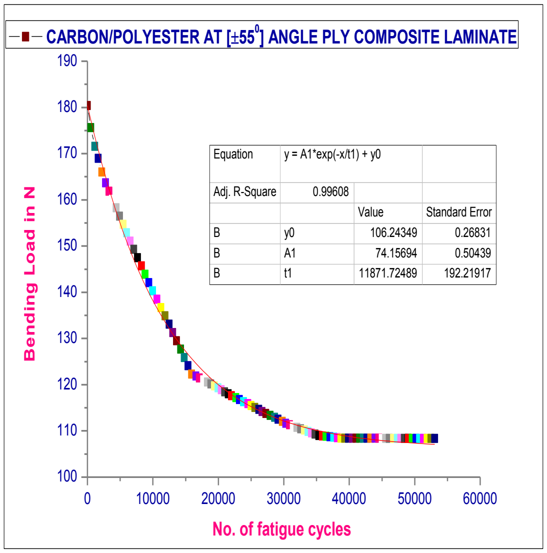


Fig 23 Stiffness degradation behaviour of [±55^0]$_{10}$ orientation sequence of stacking of angle ply composite laminate

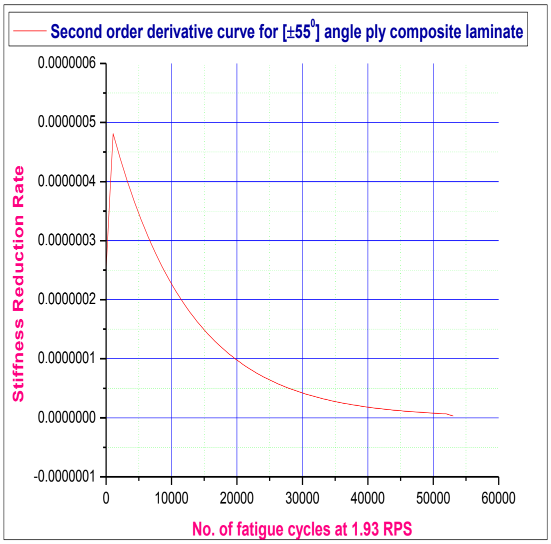


Fig 24 Second order differential curve for [±55^0] orientation sequence of stacking of angle ply composite laminate.

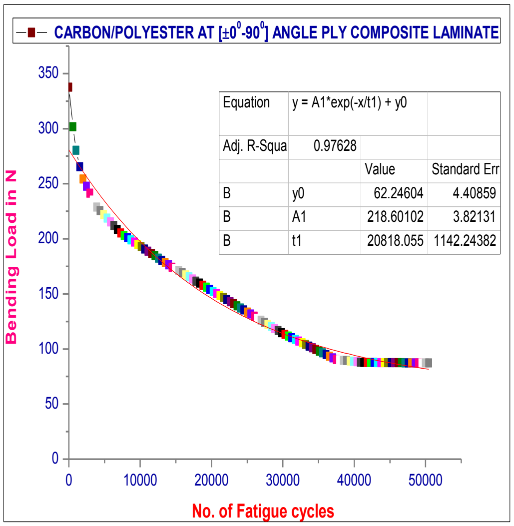
The second order differential equation of stiffness reduction per cycle (plotted on Y–axis) with respect to number of fatigue cycles is determined and plotted in Fig 6.15, and it is observed that stiffness reduction per cycle is appeared that it is linearly increasing mode up to 1,500 cycles. Further the stiffness reduction is steadily reduced up to 49,800 cycles. Further it is observed that there is no variation in the stiffness after 49,800 cycles and more. This state is considered as pivoting state.

4. Flexural Fatigue Failure Analysis of Carbon/Polyester Angle Ply composite laminate at [±0° -90°]$_{10}$ Orientation Sequence of Stacking

Fig 25 Carbon/polyester at [±0º-90º] angle ply composite laminate test specimen

Fig 26 Carbon/polyester at [±0º-90º] angle ply composite laminate specimen after tensile test

Fig 27 Carbon/polyester at [±0º-90º] angle ply composite laminate specimen after flexural fatigue test



Equation	y = A1*exp(-x/t1) + y0		
Adj. R-Squa	0.97628		
		Value	Standard Err
B	y0	62.24604	4.40859
B	A1	218.60102	3.82131
B	t1	20818.055	1142.24382

Fig 28 Stiffness degradation behaviour of $[\pm 0\text{-}90^{0}]_{10}$*orientation sequence of stacking of angle ply composite laminate.*

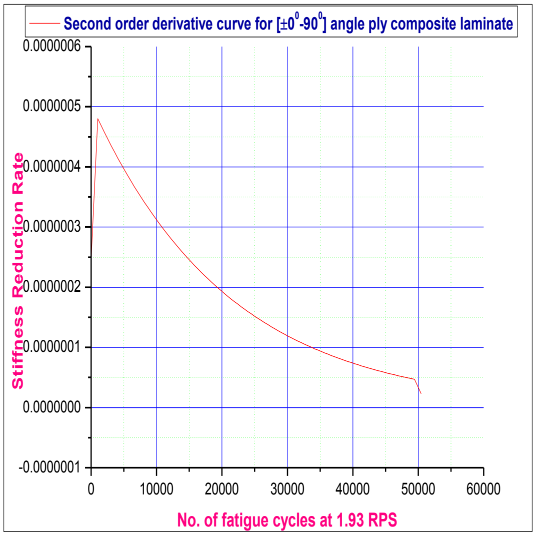


Fig 29 Second order differential curve for $[\pm 0^0\text{-}90^0]$ orientation sequence of stacking of angle ply composite laminate.

The second order differential equation of stiffness reduction per cycle (plotted on Y–axis) with respect to number of fatigue cycles is determined and plotted in Fig 6.20, and it is observed that stiffness reduction per cycle is appeared that it is linearly increasing mode up to 1,500 cycles. Further the stiffness reduction is steadily reduced up to 49,900 cycles. Further it is observed that there is no variation in the stiffness after 49,900 cycles and more. This state is considered as pivoting state.

Consolidated flexural fatigue failure behaviour of angle ply composite laminates

This curve follows the trend of the following equations

$$\mathbf{Y = Y_0 + A_1 e^{-x/t}}$$

Where,

Y is the instantaneous stiffness of the laminate

Y_0 Represents the stiffness of the laminate (where further reduction in stiffness was not observed due to pivoting state occurrence in the specimen.)

A_1 is the constant obtained by the software from regression analysis

X Represent number of fatigue cycles the specimen undergone

1/t Represents the stiffness decay constant

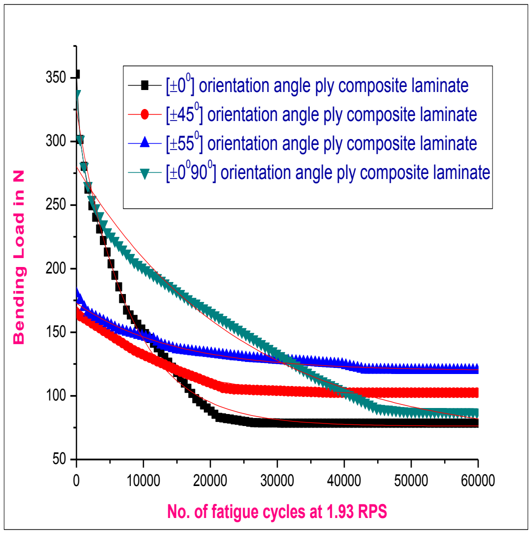


Fig 30 Consolidated flexural fatigue test results of [±0^0], [±0^0.90^0], [±45^0], and [±55^0] angle ply orientation sequence of stacking

Angle ply orientation sequence of stacking versus residual stiffness after pivoting

Table 3: Angle ply orientation sequence of stacking versus residual stiffness after pivoting.

S.No	Angle ply orientation sequence of stacking	Residual stiffness after pivoting
1	[±0^0]	76.36422
2	[±45^0]	100.2745
3	[±55^0]	106.2434
4	[±0^0-90^0]	62.24604

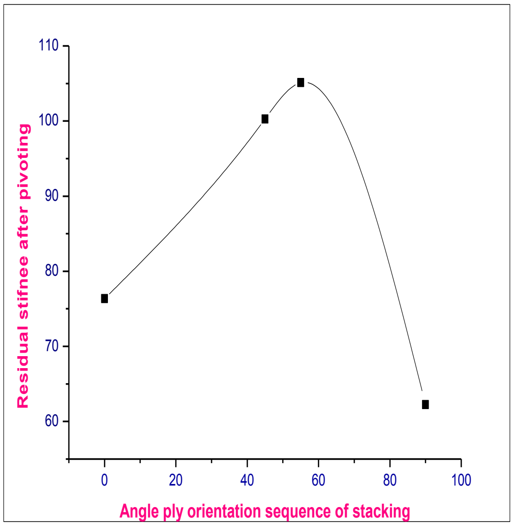


Fig 31 Angle ply orientation sequence of stacking versus residual stiffness after pivoting.

VII. CONCLUSIONS

a) It is observed from stiffness degradation curves that there is maximum damage occurred in the first few cycles of flexing, this is observed in almost all the laminates.

b) From these experimental results, it can be inferred that there is a significant influence of the orientation sequence of stacking on the flexural fatigue failure behaviour. It also observed that, the ten ply [$\pm 45^0$] orientation to ten ply [$\pm 55^0$] orientation sequence of stacking has significant fatigue life irrespective of the matrix and fiber.

c) The stiffness reduction rate is continuously increasing with respect to number of fatigue cycles up to the first few thousand cycles near to 15,00.

d) Then the stiffness reduction rate suddenly starts reducing linearly up to few tens of thousands of cycles are 40,000 cycles.

e) Further the stiffness reduction rate is reducing non-linearly till pivoting state is arrived. The pivoting state is observed near 55,000 cycles.

f) After the pivoting state the stiffness reduction rate tends to zero.

g) Among the various laminates tested, the stiffness reduction ratio i.e. ($\frac{Y_0}{Y}$) is significantly low, between ten ply [$\pm 45^0$] to ten ply [$\pm 55^0$] orientation sequence of stacking when compared to the other laminates, irrespective of the fiber and matrix.

REFERENCES

1. *Isaac M. Daniel, Emmanuel E. Gdoutos, Deformation and Failure of Composite Structures, Journal of Thermoplastic Composite Materials 2003; 16; 345.*
2. *Jean-Marc Scanzi and Bruno Hilaire "All-Thermoplastic Composite Sandwich Panels – Part II: Modeling of Bending Behavior" Journal of Sandwich Structures and Materials 2004; 6; 423.*
3. *NirmalSaha, Amar Nath Banerjee, "Flexural behavior of unidirectional polyethylene-carbon fibers-PMMA hybrid composite laminates," J. App. Poly. Sci. vol.60, 1996, pp. 139-142.*
4. *Y.Li, K.J.Xian, C.L. Choy, MeiliGuo, Zuoguang Zhang; "Compressive and flexural behavior of ultra-high-modulus polyethylene fiber and carbon fiber hybrid composites," Comp. Sci. & Tech., vol.59, 1999, pp. 13-18.*

5. *Rohchoon Park, Jyongisk Jang; "Stacking Sequence effect of aramid*-UHMPE *hybrid composites by flexural test method," Polymer Testing, vol. 16, 1997, pp. 549-562.*
6. *P.D.Bradley, S.J. Harris, Strategic reinforcement of hybrid carbon fibers reinforced polymer composites, J. Mater. Sci.12 (1977), pp. 2401-2410.*
7. *Dr. Jawad Kadhim Uleiwi, Experimental Study of Flexural Strength of Laminate Composite Material, Eng. & Technology, Vol.25, Suppl.of No.3, 2007, pp 454-466.*
8. *WEN-PIN LIN, HSUAN-TEH HU, Parametric Study on the Failure of Fiber- Reinforced Composite Laminates under Biaxial Tensile Load, Journal of composite materials, Vol. 36, No. 12/2002, pp 1481-1503.*
9. *Amjad J. Aref and Wael I. Alnahhal, Experimental Evaluation of a Hybrid FRP*-*Concrete Bridge Superstructure System under Negative Moment Flexural Loads, Jordan Journal of Civil Engineering, Volume 1, No. 4, 2007, pp 336- 343.*
10. *M. Davallo, H. Pasdar and M. Mohseni, Effects of Laminate Thickness and PlyStacking Sequence on the Mechanical Properties and Failure Mechanism of Unidirectional Glass-Polyester Composites, International Journal of ChemTech Research, CODEN(USA): IJCRGG ISSN : 0974-4290, Vol.2, No.4, Oct-Dec 2010, pp 2118-2124.*