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Flexural Fatigue Analysis of Carbon/Epoxy Angle Ply Laminates

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Abstract:- Laminated composite materials are being increasingly used in various engineering applications due to high specific strength, stiffness, low weight and corrosion resistance. These materials are selected for weight critical application due to good rating as per the fatigue failure is concerned. This investigation utilizes the suitable test-rig which is capable of generating data related to dynamic failure behaviour of laminated composite specimens. The experimental data generated from the test rig is analysed to understand the failure behaviour of laminated composites of carbon/ epoxy. The flexural fatigue tests are conducted to obtain stiffness degradation curves to interpret the failure behaviour. This paper explicitly discus and presents the influence of orientation sequence of stacking subjected to flexural fatigue. The fatigue failure process is presented in terms of the stiffness degradation verses number of load cycles.

Keywords:- *FRP, epoxy resin, signal conditioning system, load cell, data* acquisition *system, stiffness degradation*

I. INTRODUCTION

Polymers reinforced with glass fibre, carbon or Kevlar fibers are well known for their good fatigue behaviour when loading is applied in the direction of the reinforcement. But the fatigue damage, even under the simple loading condition, is complex and difficult to describe quantitatively. Aerospace, aeronautical, naval, and railway technologies require materials with good mechanical properties. However, the experience acquired in the use of homogeneous traditional materials showed their limited potential applications. Fortunately, the alternative appeared with composite materials whose properties are very interesting lightness, high directional stiffness, good resistance to fatigue, the absence of corrosion for non-metallic constituents, ease of fabrication, etc. Such materials, despite the misunderstanding of certain aspects of their behaviour, have stimulated a great interest in several industrial applications. Over the last three decades, several investigations have been carried out on the fatigue behaviour of composite materials with organic matrices (epoxy, polyester, etc.) and continuous fibers (glass, aramide, carbon, etc.) The prediction of their flexural fatigue life, however, is still difficult to achieve thus necessitating a better understanding of many damage mechanisms that may lead to total rupture [7, 9, and 10]. A great number of studies are reported in the literature on the traction and flexural fatigue of composite materials. The influence of fatigue behaviour of the components of those materials was studied by several authors [1–3]. Mandell [4] described the process of rupture in fatigue in the case of tensile tests of glass fiber composites. It was shown that rupture depends only on the properties of the fibers independently of the matrix [6]. However the fiber matrix interfacial bonding characteristics failure influences the overall failure behaviour of laminated composite material. The present work analysing the influence of matrix material on the performance of the laminates subjected to flexural fatigue.

II. EXPERIMENTAL PROCEDURE

2.1 Materials and Test specimens.

Recent increase in the use of carbon fiber reinforced polymer composites, especially for high temperature applications, has created new challenges to predict their service life. In this study carbon/epoxy composite laminates are prepared by compression moulding method. Four layers of unidirectional stitched carbon fabric of 200 GSM (Grams Per Square Meter) is stacked symmetrically with reference to the neutral axis, to obtain required thickness of 5 mm and a volume fraction of (0.55) reinforcement in the laminate. Sufficient quantity of epoxy resin mixed with 10% K_6 hardener by volume is impregnated using a rolling device. Proper measures were taken to apply uniform pressure on the laminate while closing the top plate and left for curing. Then the laminate is removed from the mould carefully.

Fig.No.1. various steps for preparation of composite laminate and UTM test

Fatigue test samples were sliced from these laminates with disk cutter of dimensions of 250 X 30 X 5 mm as shown in fig.1. These samples are prepared as per ASTM D 3039 specifications.
The following matrix materials are used to prepare angle ply composite laminates:

Matrix : Lapox L-12(Epoxy)
Hardener : K_6
Reinforcement Carbon fabric : 200 GSM
Typical diameter : 7.2 microns
Density : 1.81 g/cc
Tensile modulus : 242 GPa
Tensile strength : 4.137 GPa
Electrical conductivity: 0.00155 ohm-cm
Carbon content : 95%

III. EXPERIMENTAL SET UP FOR FLUXURAL FATIGUE

The specimen is subjected to cyclic bending stresses, as shown in the fig.2**.** The load cell which is connected to specimen through the hinged joint as shown in the fig 3.will generate voltage signal proportional to the load applied on the specimen. The voltage signal generated from the load cell is processed by the signal conditioning system and then given as input to analogue digital conversion system that is NI 6009 (data logger) coupled to computer to log the data by using LAB VIEW software. The entire experimental set up, signal conditioning, data logging system and their components are furnished in the following figure No.4, 5, 6, and 7.

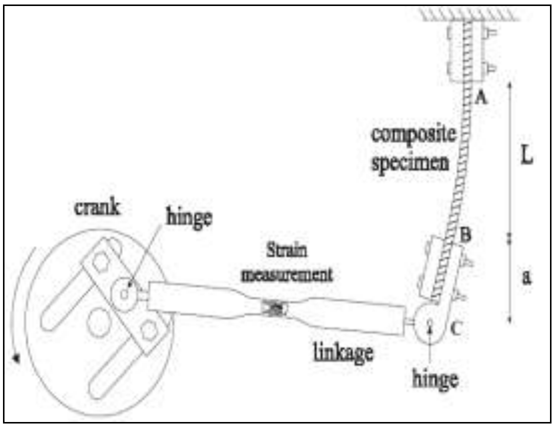

Fig.No.2: Design of critical components in the test rig

Fig.No.3: Real Time Test Rig Fabricated

3.1 Flexural Fatigue Failure Mode in Laminated Composites:

Composite material is a combination of a reinforcement fibre and polymer resin. Where the reinforcement is major load carrying member and the polymer matrix acts as the load transfer medium between fibre to fibre which are bonded to the matrix. Fatigue failure mechanism in metallic materials is completely different from the laminated composite material. Pertaining to metallic material the fatigue failure starts with initiation of crack and the crack propagates in to the depths of the material cycle by cycle. The fatigue failure in laminated composite progresses by initiating the damage of fibres starts from the top layer and bottom layer. Further it is observed that the progress of the damage from top and bottom layers stops at a particular depth and further damage is not progressed and reaches a state called "pivoting state". It is also observed that the stiffness of the laminate reduces at very fast pace latter the stiffness reduction rate reduced and further the stiffness reduction rate is almost zero. The present experimentation work conducts experiments on various laminates with the following configurations of **carbon/epoxy** with different orientations.

1. $[0^0]_4$
2. $[\pm45^0]_4$
3. $[\pm55^0]_4$
4. $[0^0, 90^0]_4$

The residual stiffness (y_0) of $\pm10^0$, $\pm20^0$, $\pm30^0$, $\pm65^0$, $\pm75^0$ is considerably low pertaining to glass epoxy laminates [5]. From this observed trend, the present experiment is carried out flexural fatigue analysis on the above mentioned laminates only to curtail the experimentation cost.

Fig.No.4: Eccentric Mechanism

Fig.No.5: Signal Conditioning System

Fig.No.6: Load cell

Fig.No.7: Wiring

3.2 Calibration and Testing of the Load Cell:

The load cell is calibrated by applying a standard weight on the load cell then response is recorded to the signal conditioning system. The standard load applied is above 50% of the desired load cell capacity. In the present case the desired load cell capacity is to measure the load up to 100 kg.

Fig.No.8: Data Logger

IV. FLEXURAL FATIGUE EXPERIMENTATION PROCEDURE:

The entire experiment is performed in four steps.

Step No.1: A test coupon is collected from the laminate to perform tensile test as per ASTM D 3039 standards 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 1.93 rps. 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 5 mins 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.

4.1 Specifications of the Flexural Fatigue Specimen:

Flexural fatigue specimens are made with specifications mentioned in reference [8]. With reference to the NASA report the thickness of the specimen is 2.5 mm and 35mm width, the effective length is 50 mm. In the present experimental work in view of accommodating the specimen with the custom-built flexural fatigue test rig, the effective length is increased to 100 mm, in the same proportion the thickness was increased to 5 mm.

4.2 Estimation of Bending Load to Be Simulated For Conducting Flexural Fatigue Analysis.

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/epoxy 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 = $\mathbf{bt^3/12}$, 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., $\mathbf{M/I = f_b/Y}$, 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.

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	$[\pm 0]_4$	Carbon Epoxy	$1.50*10^2$ mm^2	852 Mpa	532.5
2	$[\pm 45]_4$	Carbon Epoxy	$1.50*10^2$ mm^2	475 Mpa	296.875
3	$[\pm 55]_4$	Carbon Epoxy	$1.524*10^2$ mm^2	368 Mpa	230
4	$[\pm 0^0,90^0]_4$	Carbon Epoxy	$1.505*10^2$ mm^2	285 Mpa	178.125

Table.1: Estimation of Bending Load

4.3 Numerical Modelling of Stiffness Degradation Curve:

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.

4.3.1 CARBON/EPOXY LAMINATE

1) At 0^0 orientation

Fig.No.4.31: Specimen before tensile test

F

ig.No.4.32: Specimen after tensile test

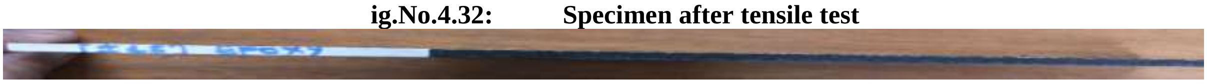

Fig.No.4.33: Specimen after Flexural fatigue test

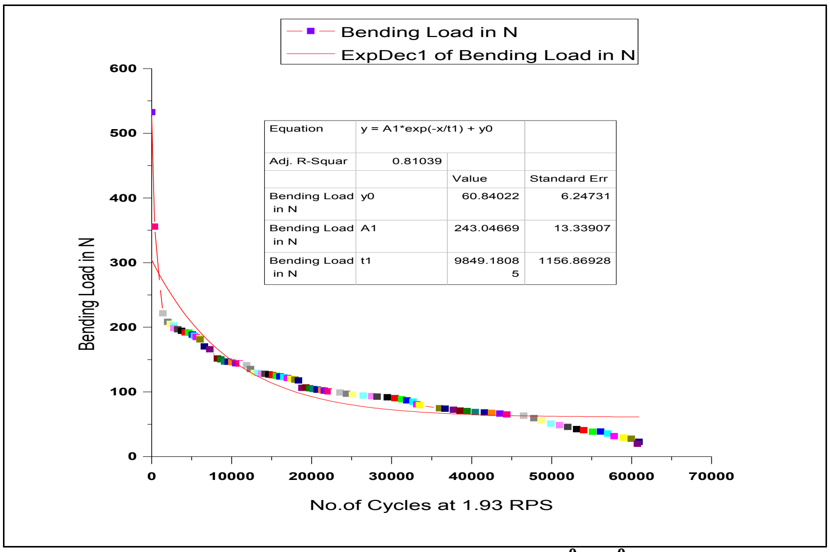

Figure 4.34 Stiffness degradation behaviour of [± 0^0, 90^0]$_4$ orientation Laminate with angle ply orientation sequence of stacking

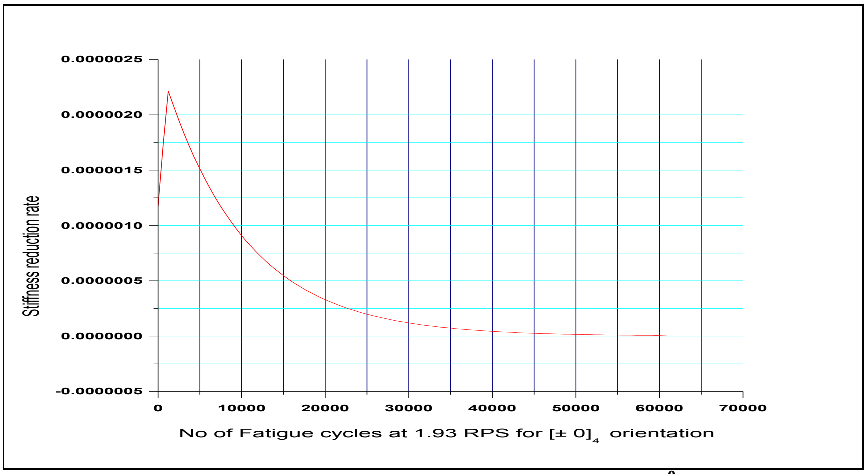

Figure 4.35: second order differential curve of [± 0^0]$_4$ orientation

2) At 0^0, 90^0 orientation

Fig.No:4.36 Specimen before tensile test

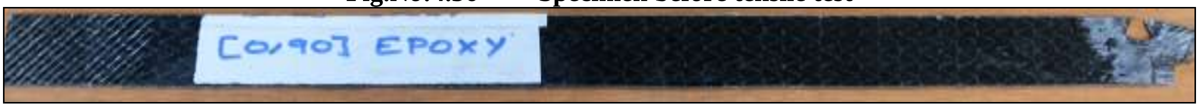

Fig.No:4.37 Specimen after tensile test

Fig.No:4.38: Specimen after Flexural fatigue test

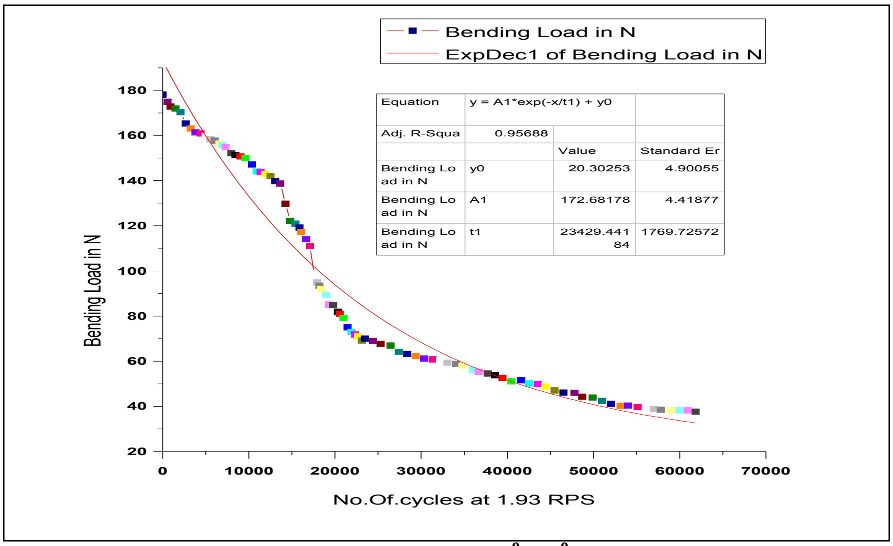

Figure 4.39 Stiffness degradation behaviour of [± 0^0, 90^0]$_4$ orientation Laminate with angle ply orientation sequence of stacking

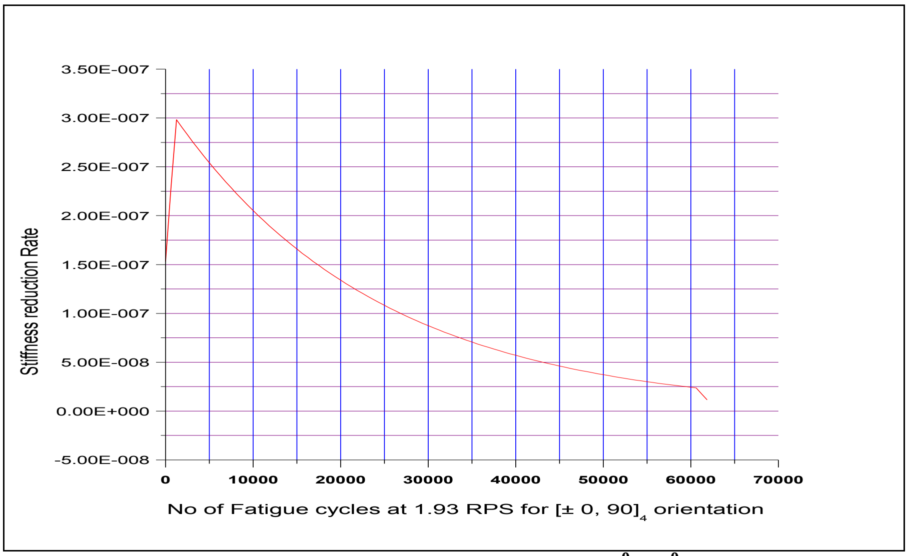

Figure 4.40: second order differential curve of [± 0^0, 90^0]$_4$ orientation

3) At [±45^0]$_4$ Orientation

Fig.No:4.41 Specimen before tensile test

Fig.No:4.42 Specimen after tensile test

Fig.No.4.43: Specimen after Flexural fatigue test

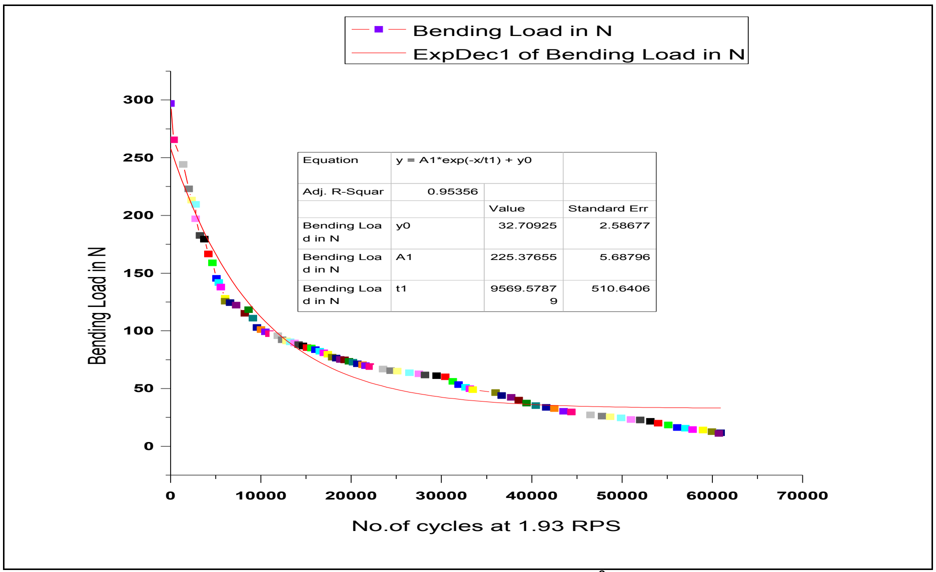

Figure 4.44 Stiffness degradation behaviour of [± 45^0] orientation Laminate with angle ply orientation sequence of stacking

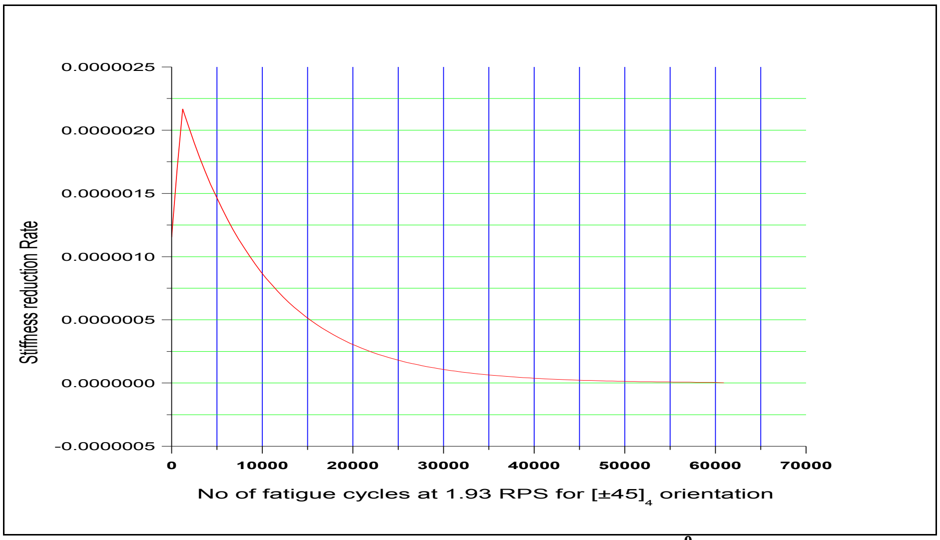

Figure 4.45: second order differential curve of [±45^0]$_8$ orientation

4) At [±55^0]$_4$ Orientation

Fig.No:4.46: Specimen before tensile test

Fig.N0:4.47 Specimen before tensile test

Fig.N0:4.48 Specimen after Flexural fatigue test

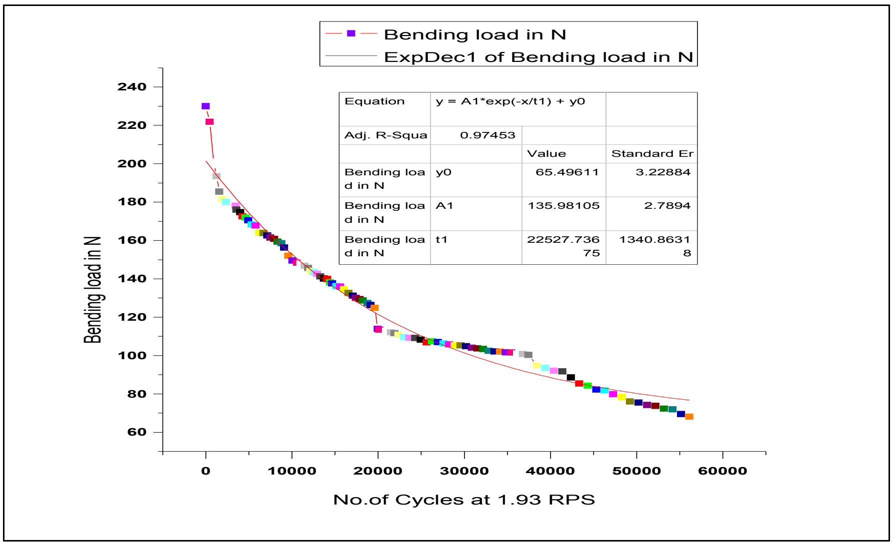

Figure 4.49 Stiffness degradation behaviour of [± 55^0]$_4$ orientation Laminate with angle ply orientation sequence of stacking

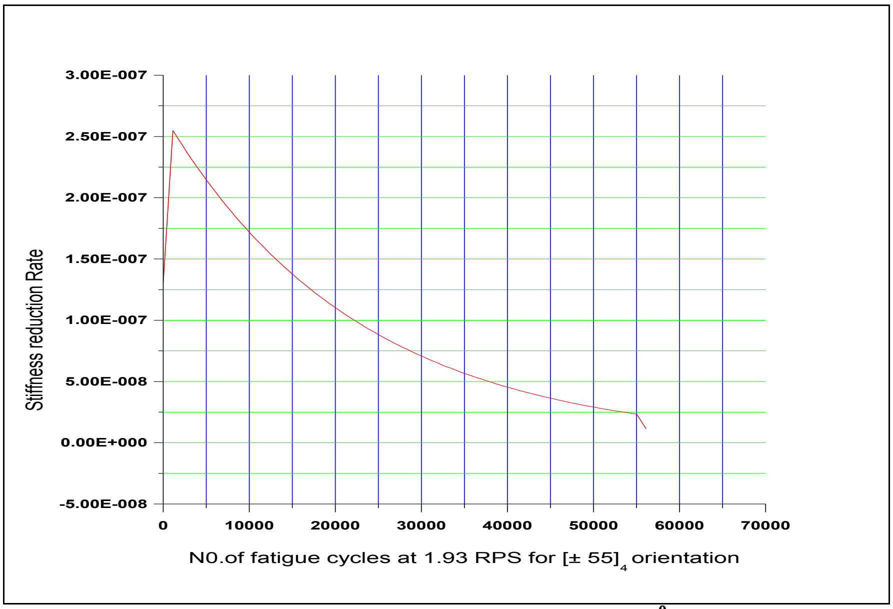

Figure 4.50: second order differential curve of [±55^0]$_4$ orientation

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

5) Consolidated flexural fatigue results

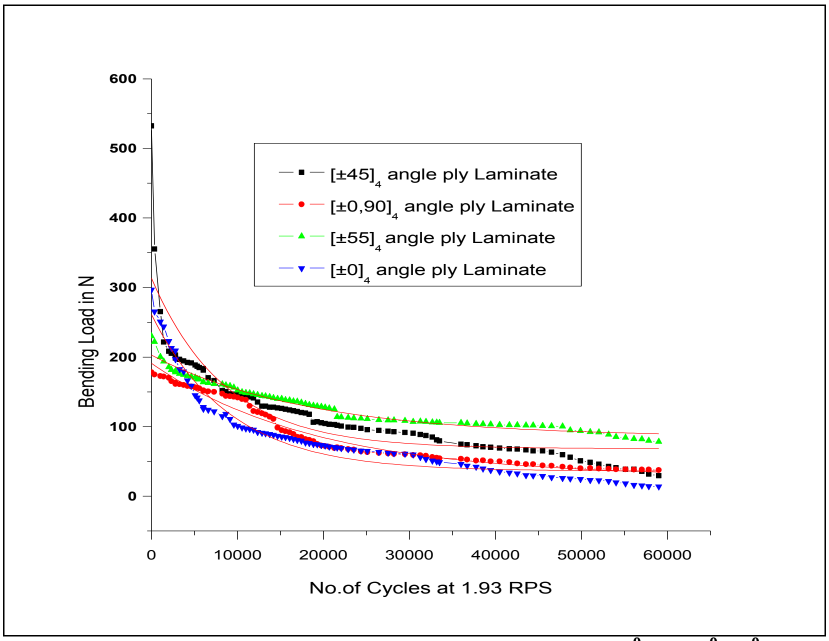

Figure 4.50: Consolidated flexural fatigue test results of $[\pm 0^0]_4$, $[\pm 0^0.90^0]_4$, $[\pm 45^0]_4$, and $[\pm 55^0]_4$ angle ply laminates

V. RESULTS AND DISCUSSIONS

In the author's point of view flexural fatigue occurrence is very common in most of the fibre reinforced plastic components like leaf spring, wind turbine blades and even most of the automotive components. Hence this aspect has been considered as a critical property to be investigated. In the literature the information regarding flexural fatigue aspects of laminated composites is very limited and there is no standardized testing procedure available, very few researchers like Van Paepegem published few papers on flexural fatigue aspects of laminated composites made of glass epoxy. He carried out experiments on $\pm 0^0$, $\pm 90^0$ and $[\pm 45]_8$ cross ply laminates and published result regarding the flexural fatigue failure behaviour. In the present work the custom built flexural fatigue test rig is designed and fabricated to perform flexural fatigue experiments on laminates of $[\pm 0^0]_4$, $[\pm 45^0]_4$, $[\pm 55^0]_4$ and $[\pm 0^0.90^0]_4$ cross ply balanced symmetric laminates made of glass epoxy at constant amplitude at a frequency of 1.57 RPS at 50% stress ratio, in view of choosing best orientation sequence for critical applications.

VI. CONCLUSIONS

1. The $[\pm 0^0]_4$ orientation laminate is possessing high tensile strength, but the stiffness reduction rate is very high in the orders of 0.0000020 N/s^2 to 0.0000022 N/s^2 till 250 cycles. Later the stiffness reduction rate is reduced to 0.0000022 N/s^2 to 0.0000001 N/s^2 up to 35,000 cycles. Then further reduction is not observed from 35,000 cycles to 60,000 cycles.
2. The $[\pm 0^0, 90^0]_4$ orientation laminate is possessing high tensile strength, but the stiffness reduction rate is very high in the orders of 0.0000015 N/s^2 to 0.0000025 N/s^2 till 200 cycles. Later the stiffness reduction rate is reduced to 0.0000025 N/s^2 to 0.0000005 N/s^2 up to 55,000 cycles. Then further reduction is not observed from 55,000 cycles to 60,000 cycles.
3. The $[\pm 45^0]_4$ orientation laminate is possessing high tensile strength, but the stiffness reduction rate is very high in the orders of 0.0000012 N/s^2 to 0.0000021 N/s^2 till 175 cycles. Later the stiffness reduction rate is reduced to 0.0000021 N/s^2 to 0.0000001 N/s^2 up to 45,000 cycles. Then further reduction is not observed from 45,000 cycles to 60,000 cycles.
4. The $[\pm 55^0]_4$ orientation laminate is possessing high tensile strength, but the stiffness reduction rate is very high in the orders of 0.0000014 N/s^2 to 0.0000025 N/s^2 till 150 cycles. Later the stiffness reduction rate is reduced to 0.0000030 N/s^2 to 0.0000005 N/s^{2}Up to 50,000 cycles. Then further reduction is not observed from 50,000 cycles to 60,000 cycles.
5. From the experimental investigation, Flexural fatigue failure behaviour of $[\pm 55^0]_4$ angle ply laminated composite exhibited better results. The results clearly establish that the $[\pm 55^0]_4$ laminate exhibited very slow stiffness reduction rate when compared to the other specimens and the residual bending load (residual stiffness) is also maximum i.e. 65.496 N. Hence it can be recommended that the angle ply with balanced symmetric layup with $[\pm 55^0]_4$ stacking is good for flexural fatigue critical applications such as wind turbine blades, Air craft wing, auto motive leaf spring constructions.

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