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Experimental fatigue damage investigation of E-glass 430GSM fiber composite

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Abstract

The current research is to evaluate the fatigue damage progression of unidirectional E-glass 430 GSM fiber composite material subjected to fatigue loads. Previously characterization was done to estimate the material modulus and strength of elasticity under tension, compression and shear loads. This paper discusses about the constant-amplitude tension-tension fatigue test conducted at a frequency of 4Hz under different loading conditions in order to accomplish fatigue life characteristics. Usually fatigue life is evaluated by cracks developed in the matrix material followed by delamination of material and finally the material rupture leading to composite fracture. SEM images were used to understand the failure architecture of composite and to accomplish damage evaluation and failure modes. The behavior of the material is observed to be heterogeneous under variable loads which can explain the scatter of experimental results.

Keywords: GRFP, fatigue, delamination, fracture, damage evaluation.

Introduction

Fiber composites are one of the leading composites in the areas of low weight to high strength applications. The key advantages to be noted are good stiffness, good ballastic resistance, reduction in vibration and noise, low part count etc.[1-12]. The paper discusses about the fatigue damage evaluation report on continuous SIKA E-glass woven fabric at different loading conditions at a cyclic frequency of 4 Hz as per ASTM standards. For experimentation work 430 GSM (Grams per Square Meter) fabric is imported from SIKA Corporation, USA. The main reason for selecting this fiber or in the other name the key noted advantages are optimised design, superior at production quality control, cost efficiency, extended range of weaving patterns, improved A-R property due to the addition of zirconia, adequate fiber resistance damage tolerances etc.

The review of literature showed that the durability or fatigue life of a composite material depends the experimental data[13-16]. In the past years fatigue damage evaluation[17-19] was reported under uniform stress levels which lead to repetitive catastropic failure at the site of composite application[20,21].

Recently reasonable changes have been made in ASTM standard procedure, defining that multiple stress levels should be induced under maximum loading conditions. Fatigue data will be fulfilled when complete characterisation is evaluated[16-18,21-24]. Previously characterisation work was carried out to know the values of in-plane shear modulus, longitudinal modulus, in-plane poisons ratio, transverse modulus etc. using DIC methodology[25,26].

Curtis P.T.[27] reported that the increasing usage of GFRP in primary structures is mainly because of stiffness and strength combined with very minimum density in comparision to steel. It is able to reduce the weight of the vehicle and heavy loaded trucks with 40 to 60 percent by replacing metal to FRP material. One main example for this is Boeing 747 uses 50% of CFRP and about 35% of hybrid (CGFRP) composite and 12-15% of GFRP. Similarly the roof of BMW M6 Chevrolet Corvette Z06, Lamborghini has produced their cars, with exception for door and roof structure entirely with FRP composite and it was identified that the weight of the vehicle was reduced by 40% compared a body with aluminium.

Sample Preparation: The samples were prepared using SIKA fiber as reinforcing material and Epofine 230 (CY230) mixed with Finehard 951 (HY951) in the ratio of 10:1 as matrix. The sequence of operations performed for sample preparation using vacuum bagging technology was discussed in detail. Table-1 shows the values of single layer laminate properties in the longitudinal direction of fibers. The values are recommended according to ASTM D3039 standard procedure of testing using 10 samples per test series[28-30]. Table-2 shows the specifications of Epofine 230 and Fine hard 951[31].

As per ASTM D3479 testing methodology the required sample dimensions are shown in Figure-1. The laminate obtained from bagging has sharp edges to remove such imperfections a BOSCH wood cutting machine with 230V, 50Hz, 8amps capacity was used. The blade is made up of stainless steel having external dia of 0.0254 m and internal dia of 0.0030m. Initially the FRP laminate is trimed based on the width of the specimen maintaining an allowance of 3-5mm on either side, the distance from horizontal column and cutting blade is fixed by measuring it with a steel rule. Finally the required samples were cut for the study of fatigue was shown in Figure-2.

Table-1: Properties of continuous E-Glass fiber weave.

Type of fiber	High strength E- Glass fibers
Color	White
Fiber orientation	0^0 (unidirectional)
Weight per square yard	440g/m^2 (approx.)
Density of fiber	2.56 g/cm^3
Thickness of fiber	0.3 mm
Tensile strength of fibers (dry-single layer)	3,400 N/mm^2
Tensile modulus of fibers (dry-single layer)	76,000 N/mm^2
Break strain percentage	2.8 %
Shell life and storage conditions	2 years from production date at temp between +5^{0}C and +35^{0}C

Table-2: Specifications of Epofine - 230 and Finehard – 951.

	Characteristic	Test Method	Specification
Epofine – 230 (CY 230)	Viscosity	ASTM- D 445	1200 -1900 mPas
	Density at 25^{0}c	ASTM- D 4052	1.12 - 1.16 g/cc
Finehard – 951 (HY 951)	Viscosity at 25^{0}c	ASTM- D 445	< 20 mPas
	Density at 25^{0}c	ASTM- D 4052	0.97 - 0.99 g/cc

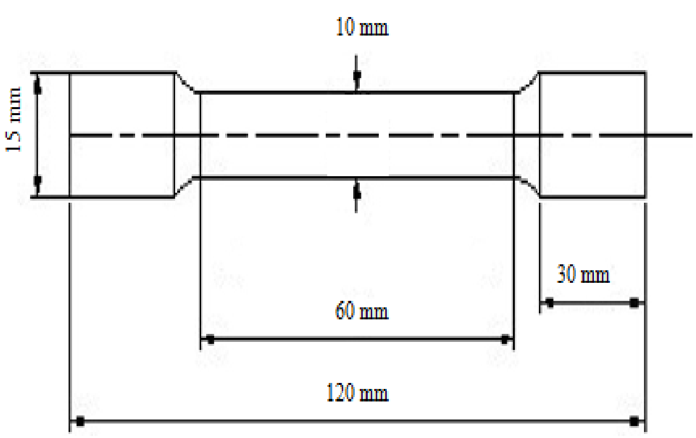


Figure-1: ASTM D3479 sample dimensions for fatigue testing of fiber composite.

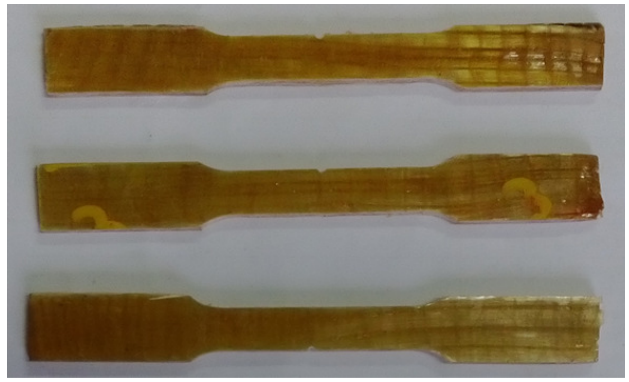


Figure-2: Dumbbell shape samples with v-notch for fatigue testing.

The thickness of the samples was maintained as 2.5 mm i.e it needed almost 8 layers of fiber as individual layer thickness is about 0.3mm.

Materials and Methods

Experimentation: The fatigue experimentation was carried out on a perfectly calibrated MTS Mechanical Testing System (servohydraulic)-model 370.10 load frame. It has 100KN load capacity and 5Hz loading frequency. The specimen is fixed in between the two wedge grips with a gripping pressure of 900 psi. A constant amplitude load is applied on the specimen at a frequency of 4Hz (4 cycles per second) at maximum loads of 10KN, 4KN, 2KN and minimum load is maintained as 1KN through out the testing. Before conducting the fatigue test it is important to know the longitudinal modulus/ modulus of elasticity and maximum tensile strength of the specimen in logitudinal direction ie. fibers are oriented in 0^o. Previously characterisation was carried out using DIC technique and conventional testing on tensile 0^o specimens. The longitudinal modulus (E11) and the maximum tensile strength (Xt) is calibrated as an average value of minimum and maximum of three speciens using DIC and MTS data. The values are tabulated in Table-3.

From the tabulated data it was identified that the value of E11 is not varied much more when calibrated by DIC and is somewhat increased from specimen 1 and 2 and it was reduced litlle bit when tested conventionally. Similarly Xt was greatly varied in both cases. The reason behind this is that the composite material has heterogeneous behavior which led to scatter of data. Figure-3 and 4 shows the variation in data regarding E11 and Xt.

Before conducting the experiment a small v-notch of negligible depth is made at the center of the specimen as predefined stress concentration because the material is brittle. Probably the crack initiation starts from this zone. The fatigue loading conditions are illustrated in Figure-3. The loading conditions are based on specification of machine and ASTM C1360. Figure-4 shows one complete cycle of fatigue load. The frequency of loading is 4Hz i.e. 4 cycles/sec.

Table-3: Evaluated material properties for tensile 0^{o} specimens.

Property	Evaluation method	Specimen1	Specimen2	Specimen3	Avg. of mim. and max. values
Longitudinal modulus (E11)-Gpa	DIC	50.284	50.245	51.93	51.0875
	MTS	46.557	47.523	47.093	47.04
Maximum Tensile Strength (Xt)- Mpa	DIC	1012.3	1082.86	1037.466	1047.583
	MTS	919.32	983.956	942.513	948.596

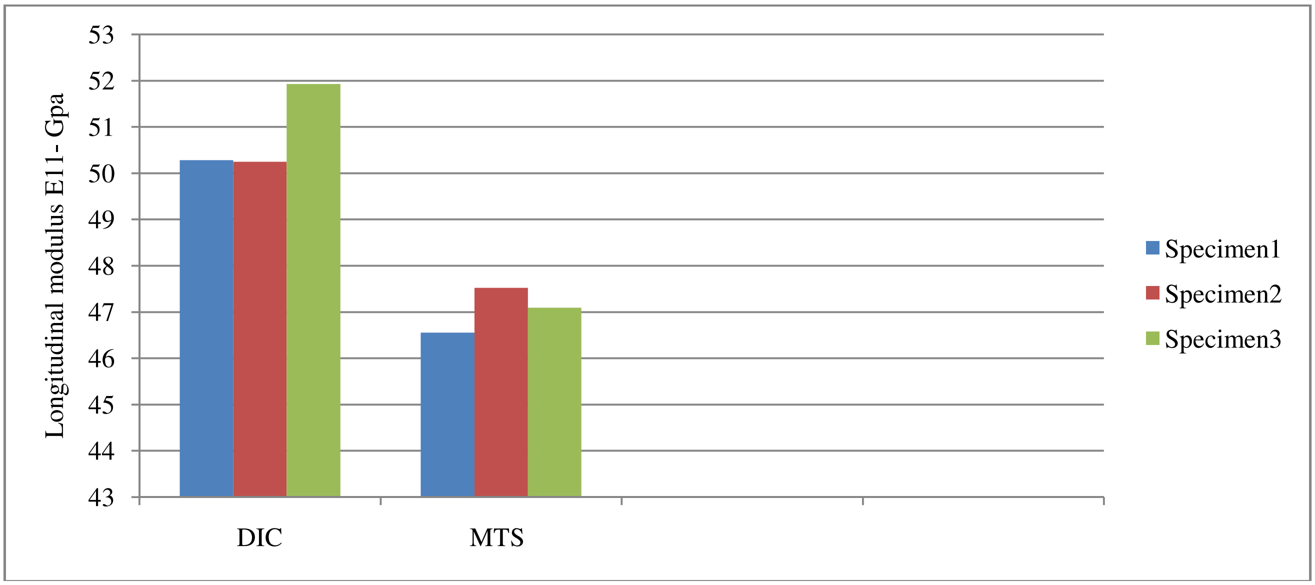


Figure-3: Variation of E11 data in DIC and MTS.

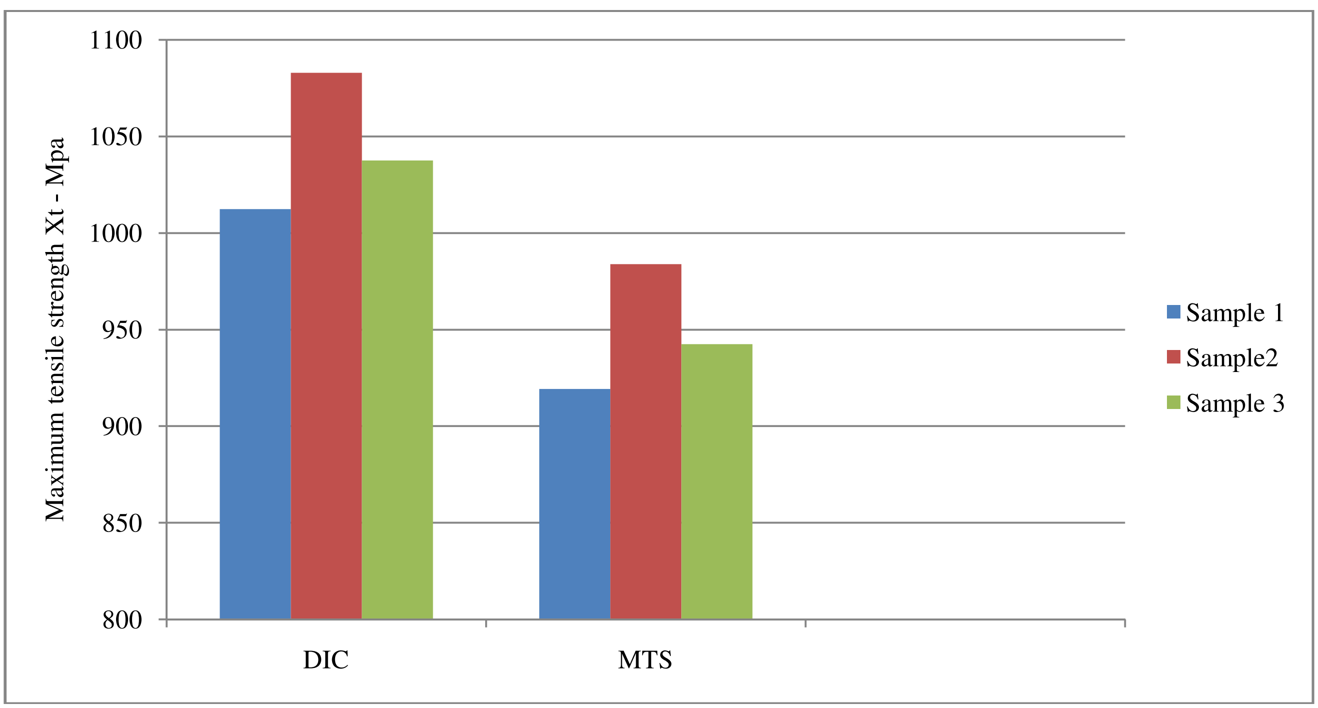


Figure-4: Variation of Xt data in DIC and MTS.

Table-4: Fatigue loading conditions.

Sample No.	Load Applied (KN)		Load range (KN)
	Max.	Min.	
1	+10	+1	9
2	+4	+1	3
3	+2	+1	1

In the figure, σmin is minimum tensile stress, σmax is maximum tensile stress, σm is mean tensile stress, σr is tensile stress range, σ a is stress amplitude, R is stress ratio, A is amplitude ratio.

The loading is applied until final failure or fracture takes place. There exists 4 stages in fatigue failure i. Initiation of crack, ii. Crack deepening, iii. Crack growth iv. Fracture. Crack initiation is identified by crack nucleation length of 0.025mm (0.001 inch)[38-40].

The parameters required for fatigue life prediction were calculated and tabulated in 5 and failure cycles are also listed from experimentation. Considering Stress = Load/Cross sectional area, where Cross sectional area = (10mm*2.5mm = $25mm^2$).

Results and discussion

Test results: After conducting the tests, the results obtained are plotted as follows.

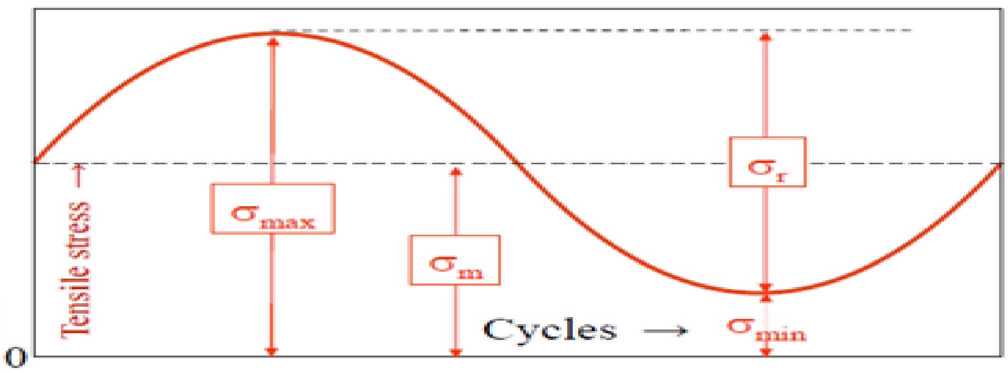
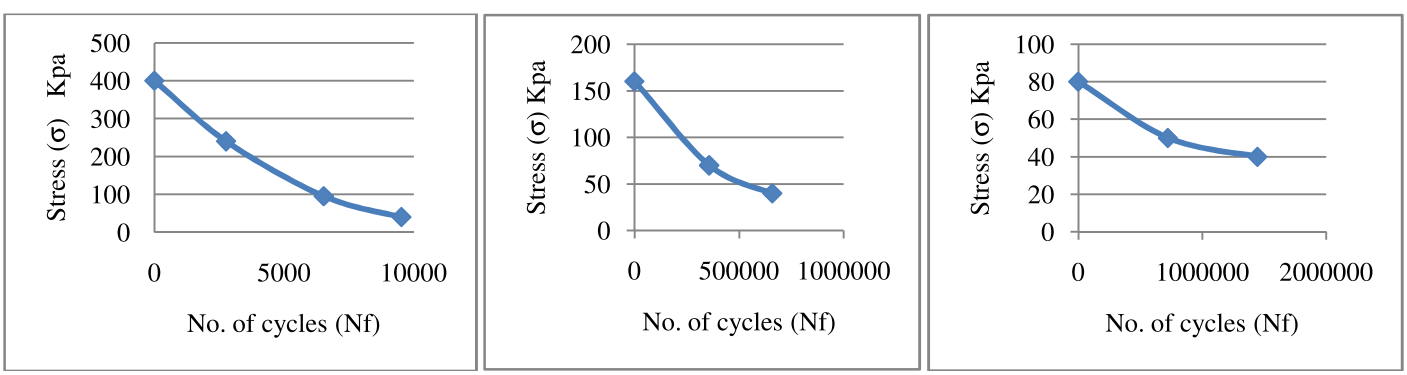


Figure-5: Complete cycle of Tension- Tension fatigue (R from 0 to 1).

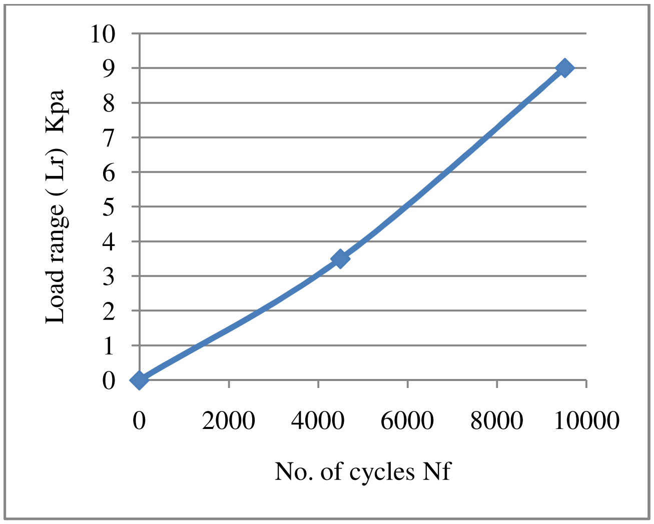
Table-5: Fatigue load calculations.

Sample No.	Tensile Load Applied (KN)		σmax Kpa	σmin Kpa	σr Kpa	σa Kpa	σa Kpa	R	A	Total no. of cycles
	Max.	Min.								
1	+10	+1	400	40	360	180	220	0.1	0.8181	9,522
2	+4	+1	160	40	120	60	100	0.25	0.6	6,86,392
3	+2	+1	80	40	40	20	60	0.5	0.333	1,445,254

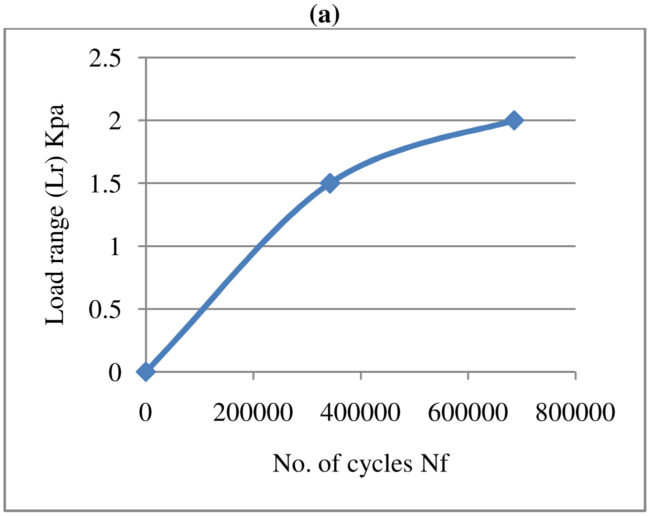


(a) (b) (c)

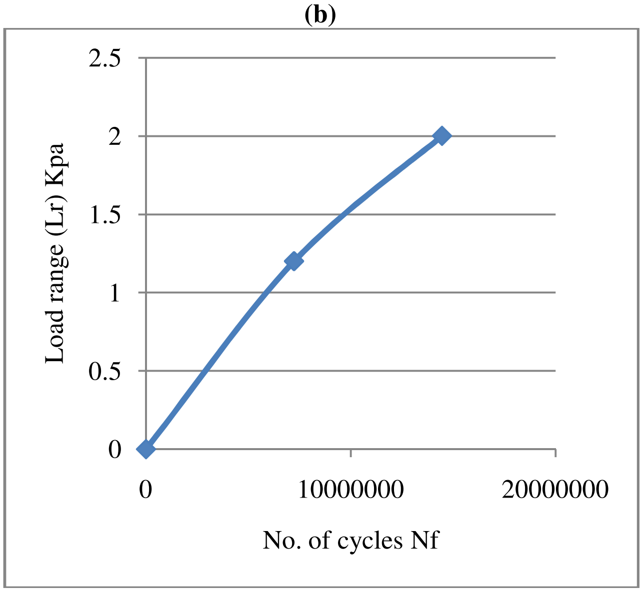
Figure-6: S-N Values for (a) sample 1 (b) sample 2 and (c) sample 3.



(a)



(b)



(c)

Figure-7: Lr-Nf Values for (a) sample 1 (b) sample 2 and (c) sample 3.

From Figure-6 ultimate strengths are identified as 400KPa, 160KPa and 80KPa, where as the endurance limit stress or endurance strength are noted below 40 Kpa for all the three samples. The reason behind this is the maximum loads are varied but minimum load is maintained constantly throughout the cycle and also the maximum endurance limit stress is 40KPa.

From the observation fatigue specimens are maintained to have constant infinite life. The point to be noted here is the maximum fatigue lives of specimens are 9522, 686392 and 1445254 respectively. Maximum fatigue life or fatigue limit is determined by the final fracture.

The fatigue strength at any point on the curve is represented by concerned fatigue strength or stress when the point is extended horizontally at a given cycle. From extensive survey of literature if the maximum fatigue life is below 10^3 cycles it is a low cycle fatigue and if it is above they are high cycle fatigue. Experimental results showed that under the application of maximum tensile load the specimen1 failed at low cycle fatigue and specimen 2 and 3 are considered to be high cycle fatigues. Figure-7 load ratio shows direct proportionality with fatigue cycles since when the specimen is subjected to low load it has high fatigue life and vice versa case is also true.

SEM analysis: Figure-8a and b shows the length wise SEM images of specimen with maximum stress range 400 KN. It was observed that there was neck failure and brittle fracture of fibers. Also in some areas there was good adhesion between fiber and epoxy. There also exists cohesive and adhesive fractures and small dimple patterns of epoxy. Figure-8 c and d shows the transverse fracture pattern under maximum tensile stress of 160KN.

The primary mode of failure delamination of laminate due to complete matrix debonding and fibers pull out with small debris leading to crack propagation. Figure-8e and f shows the longitudinal failure images for the specimen with max stress of 80KN. Due to continuous low cyclic loading there exists multiple fractures at maximum locations showing the sensitive damage parts as there is no delamination failure in the specimen the material withstood up to maximum number of cycles.

Conclusion

The conclusions drawn from the experiments conducted on GFRP composites to study the fatigue strength are as follows. The specimens subjected to maximum stress failed at low cycle and the specimens subjected to low stress failed at high cycle.

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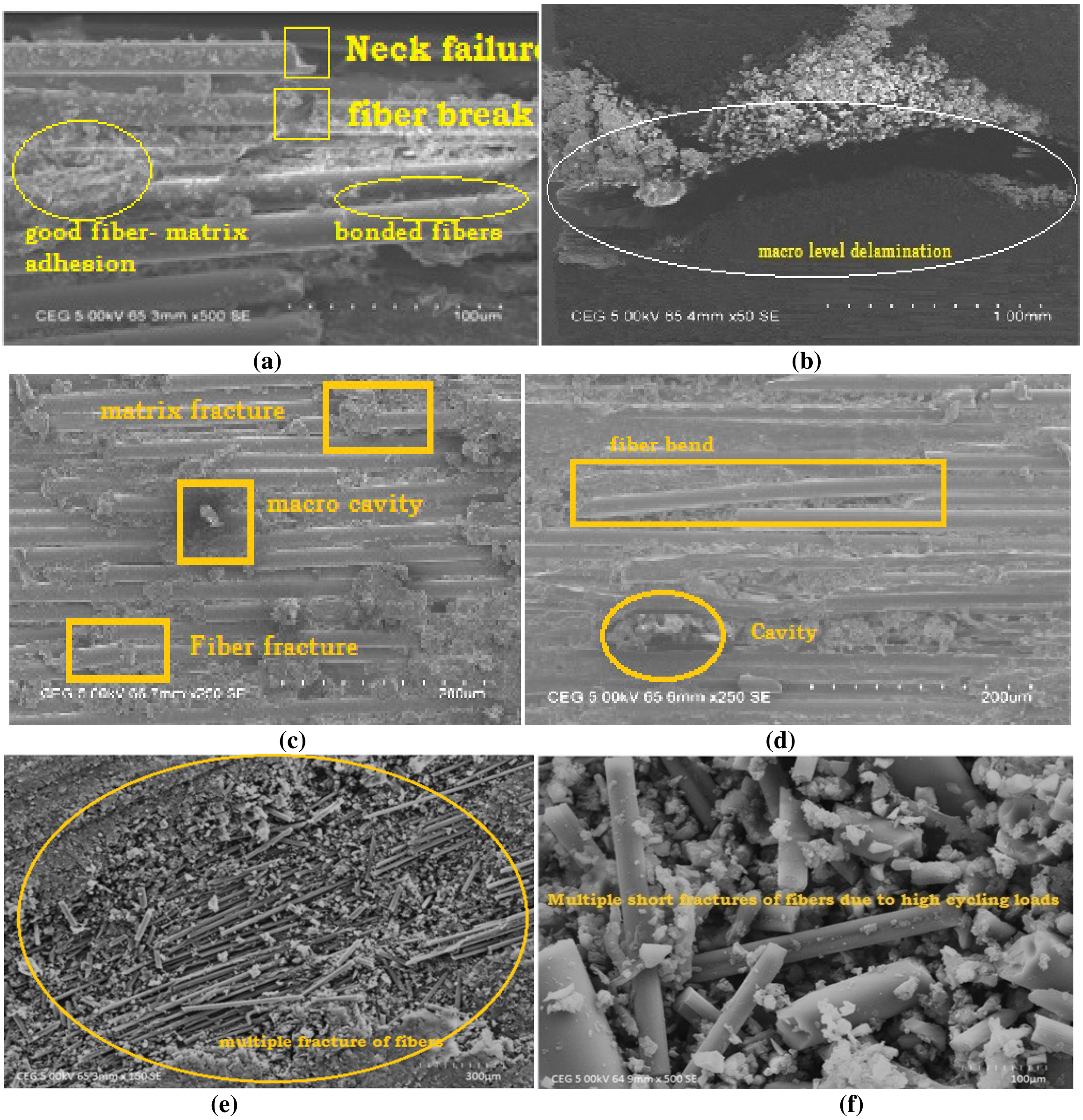

Figure-8: Failure analysis of the specimens through SEM images.

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