Characterization of Composite Plate Using Strain Indicator with Cyclic Loading

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Abstract- This work presents the development and testing of a composite specimen to analyze its fatigue behaviors of specimens with strain indicator and also identify the failure modes on composite specimens using Scanning Electron Microscope (SEM). A composite laminate made from glass fiber and epoxy, following ASTM standards, is subjected to cyclic loads using a laboratory scale model of fatigue testing machine. Strain values in the X, Y, and Z directions are measured during testing. By analyzing the relationship between stress and the number of loading cycles, the fatigue properties of the composite material are determined. This investigation offers valuable insights into how the material's mechanical properties change under repeated loading, ultimately leading to fatigue failure, and provides valuable data for assessing the durability and performance of composite materials under cyclic loading conditions. After post yielding, SEM as a microscopic observation is used to identify the failure modes of such as matrix cracking, fiber matrix debonding, fiber broken (crack propagation) from the tested specimens.

Index-Terms: Composite Specimen, Fatigue Test, Strain Gauge, strain Indicator, S-N curve, Scanning Electron Microscope.

I. INTRODUCTION

Conventional materials are increasingly being supplanted by composites across a wide array of applications, owing to their superior specific strength, stiffness, enhanced fatigue life, wear resistance, and corrosion resistance [1-2]. However, the tailored properties inherent in laminated composites pose a notable challenge when striving for optimal design solutions. Flexural fatigue failure is a prevalent occurrence in wind turbine components such as wind turbine rotors, leaf springs, and airplane wing structures subjected to cyclic loading.

Fatigue failure occurs when a component or structure is subjected to fluctuating loads over an extended period of time. It is a type of failure that occurs due to the initiation and propagation of cracks at a microscopic level. These cracks gradually grow and eventually lead to the failure of the component [2-5].

Fatigue failures are commonly observed in components that experience cyclic or variable loading conditions throughout their operational lifetime. The polypropylene/epoxy composite and its hybrids with glass fibre specimens were used to identify the S_N curves using flexural fatigue tests [6-7]. In the case of ductile materials, fatigue failure is not easily noticeable as the material tends to deform plastically before failure, resulting in visible signs such as necking or deformation. However, for brittle materials, fatigue failure can be more critical and less noticeable as they exhibit minimal plastic deformation prior to failure. To prevent fatigue failure, it is important to consider factors such as the applied loads, stress concentrations, material properties, design features, and operational conditions [8]. Techniques such as fatigue testing, stress analysis, and proper design practices are employed to evaluate and mitigate the risk of fatigue failure in engineering applications [9].

The present work investigates damage mechanisms in a fiber-reinforced composite plate under cyclic reversed loading [10]. Magnified views are used to identify the failure mechanisms of the composite specimen, including matrix failure, crack initiation, and fiber failure (crack propagation) in the directions of the X, Y, and Z axes, respectively, using stress vs. number of cycles to failure.

II. PREPARATION OF COMPOSITE LAMINATE

The hand lay-up manufacturing process offers several advantages, including great flexibility and suitability for a wide range of mold sizes and complex shapes [11]. The following steps involved during the manufacturing process of composite laminate using hand layup method as shown in the figure 1 (a). The mold surface is prepared by polishing it and applying a releasing agent. Unidirectional glass roving is laid down on the mold surface. A liquid thermosetting resin, such as LY 556 with hardener HY 951, is manually worked into the reinforcement using a brush or roller. The resin wets the fibers and forms the matrix that holds the composite together. After the resin has been applied, a stippling action is performed using a brush that is wetted with resin. This action helps to remove air bubbles and ensures that the resin is evenly distributed and squeezed to the top surface of the composite. After first layer formed on the surface, subsequent layers are added in the same process. Each layer consists of the reinforcement and resin, and the process is repeated until the desired thickness 5 mm, is achieved. After the required thickness has been built up, the composite is allowed to cure. After the fabrication of the laminated composites, the next step involves curing them using compression molding. The top plate of the compression molding machine is set to a pressure of 100 KPa at ambient temperature. The purpose of applying pressure is to effectively compress the laminate and ensure proper bonding between the layers. By subjecting the laminate to pressure, voids are minimized or eliminated, leading to improved overall quality and strength of the laminates. Proper curing through compression molding plays a vital role in achieving high-quality composite laminates, minimizing voids, and maximizing the material's strength and performance.

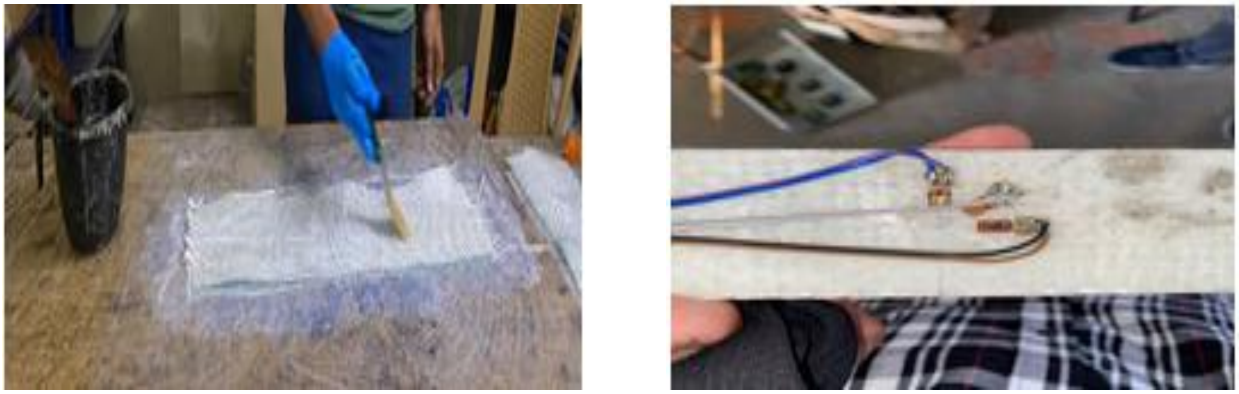

Figure 1: (a) FABRICATION OF COMPOSITE LAMINATE (b) STRAIN GAUGE ORIENTATION

The dual ends of the strain gauges are then connected to the Strain gauge indicator (Single/ Three Channel Strain gauge indicator), in order to derive the strain data along the surface of the test specimen as shown in the figure 1 (b).

III. EXPERIMENT SETUP FOR TESTING WITH STRAIN INDICATOR

This study aims to conduct a critical examination of various properties through experimental testing to clarify the fatigue failure behavior, resulting from cyclic loads applied to composite laminates [12]. The three axes of X, Y, Z Strain gauge is attached with Composite laminate for testing as shown in the figure 2. The strain gauge is connected to a strain indicator to apply the cyclic loading as shown in the figure 3. While conducting the testing, strain indicator displays strain values for different cyclic loading such as 5 x 10^4, 10 x 10^4, 15 x 10^4 etc. During this study, it was noted that subjecting the composite specimen to cyclic loading resulted in the formation of fatigue cracks, leading to a reduction in stiffness particularly at the fixed end of the composite. This change was reflected in the voltage output acquired from the strain measuring bridge circuit. The experiment setup employed to replicate the desired reversed cyclic bending load applied to the horizontally fixed composite laminate (like cantilever beam). Load cells were employed to capture the bending load signals, which were continuously processed through a signal conditioning system to amplify the signals, facilitating data acquisition for further analysis using stain indicator.

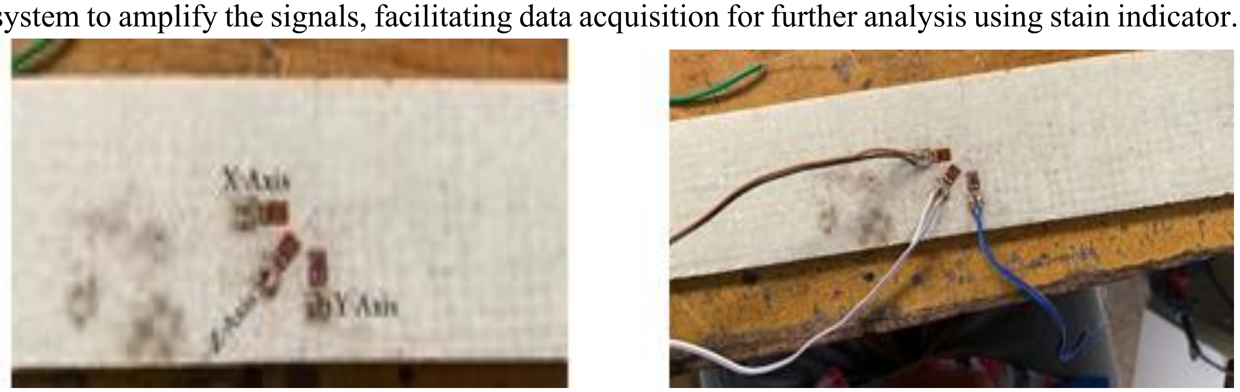

Figure 2: X, Y, Z axis Strain gauge Attached with Composite laminate

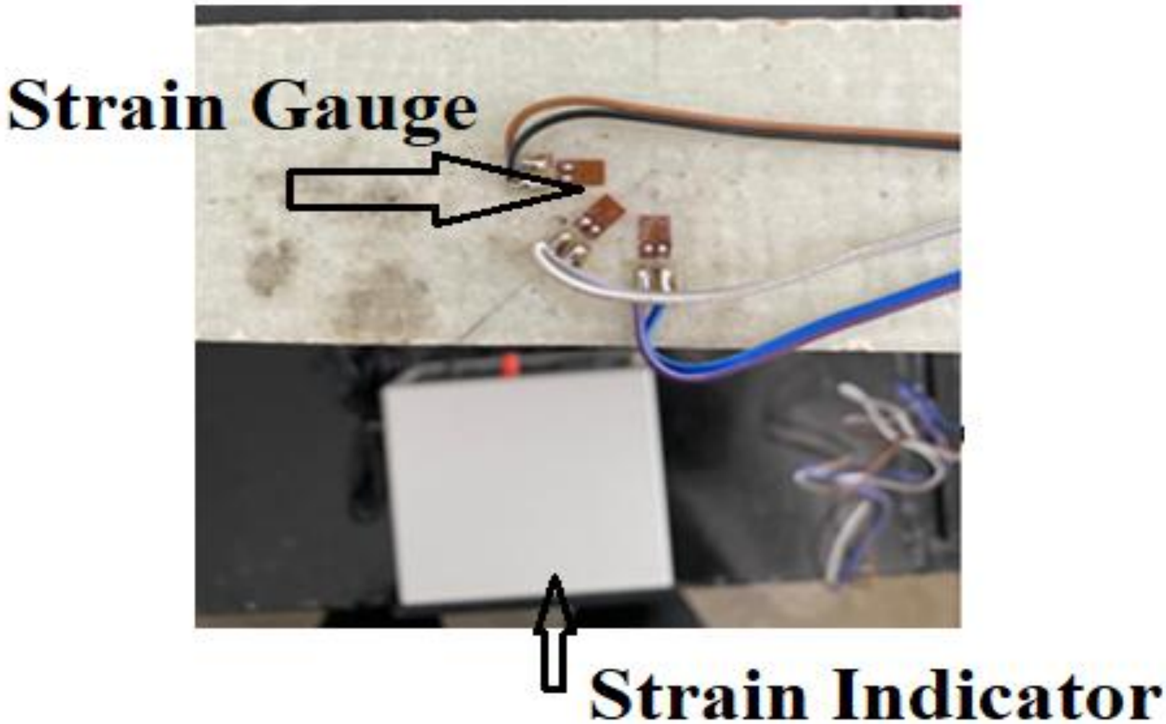

Figure 3: Embedded Strain Gauge with Test Setup

IV. RESULTS AND DISCUSSION

The process of characterizing a composite plate using a strain indicator with cyclic loading involves subjecting the plate to repetitive loading and unloading cycles while monitoring strain levels through strain indicators. Each loading cycle should induce strain in the composite plate, with strain indicators continuously measuring the strain responses [13-14]. The collected data are analyzed to understand the stress-strain relationships, fatigue life, and observed failure modes due to cyclic loading for composite plate [15-16]. For each 5 x 10^4 cycles, the strain values are measured in the directions of x, y, z axes respectively.

Table 1: Strain Values of X, Y, Z axes during Fatigue Test for 5 cycles

	X-Axis		Y-Axis		Z axis	
	Strain Values		Strain Values		Strain Values	
No of Cycles x 10^4	Max	Min	Max	Min	Max	Min
1	296	-390	64	-42	139	-176
2	323	-323	62	-38	137	-165
3	265	-296	61	-41	145	-165
4	323	-367	65	-40	149	-162

5	367	-356	65	-41	144	-169
Average	314.8	-346.4	63.4	-40.4	142.8	-167.4
Stress=E1*μ_s	5178.46	-5698.28	1042.93	-664.58	2349.06	-2753.73
Stress=E2*μ_s	1736.752	-1911.09	349.7778	-222.887	787.8276	-923.546
Stress=E3*μ_s	1736.752	-1911.09	349.7778	-222.887	787.8276	-923.546

Table 2: Strain Values of X, Y, Z axes during Fatigue Test for 10 cycles

	X-Axis - Strain Values		Y-Axis- Strain Values		Z axis- Strain Values	
No of Cycles x 10^4	Max	Min	Max	Min	Max	Min
1	320	-374	74	-40	147	-175
2	332	-327	67	-44	138	-166
3	333	-345	72	-44	144	-167
4	328	-322	77	-49	142	-177
5	327	-333	78	-41	157	-171
6	333	-342	71	-44	155	-169
7	322	-344	88	-56	151	-162
8	312	-332	74	-52	142	-166
9	333	-357	77	-48	148	-177
10	340	-378	72	-50	141	-172
Average	328	-345.4	75	-46.8	146.5	-170.2
Stress=E1*μ_s	5395.6	-5681.83	1233.75	-769.86	2409.925	-2799.79
Stress=E2*μ_s	1809.576	-1905.57	413.775	-258.196	808.2405	-938.993
Stress=E3*μ_s	1809.576	-1905.57	413.775	-258.196	808.2405	-938.993

Table 3: Strain Values of X, Y, Z axes during Fatigue Test for 15 cycles

S.No	X-Axis		Y-Axis		Z axis	
No Of Cycles x10^4	Maximum	minimum	Maximum	minimum	Maximum	minimum
1	328	-345	71	-42	142	-171
2	312	-333	72	-41	138	-169
3	333	-324	67	-44	144	-167
4	320	-322	77	-49	147	-177
5	327	-327	78	-40	151	-175
6	333	-342	74	-44	155	-166
7	322	-344	88	-56	157	-162
8	332	-332	74	-52	142	-166
9	333	-357	77	-48	148	-177
10	340	-328	72	-50	141	-172

11	336	-323	69	-44	144	-168
12	333	-342	77	-42	142	-174
13	327	-332	72	-44	152	-176
14	322	-333	78	-42	147	-174
15	332	-330	74	-40	152	-172
Average	328.6667	-334.267	74.66667	-45.2	146.8	-171.067
Stress=E1*μ_s	5406.567	-5498.69	1228.267	-743.54	2414.86	-2814.05
Stress=E2*μ_s	1813.254	-1844.15	411.936	-249.368	809.8956	-943.775
Stress=E3*μ_s	1813.254	-1844.15	411.936	-249.368	809.8956	-943.775

The current study investigates damage mechanisms in a fiber-reinforced composite plate subjected to cyclic reversed loading. Magnified views were employed to identify failure mechanisms such as matrix failure, crack initiation, and fiber failure (crack propagation) along the X, Y, and Z axes, respectively, as depicted in Figure 4. Characterizing the composite plate with strain indicators during cyclic loading revealed an increase in stress levels, correlating with a decrease in the material's cyclic endurance before failure [17-19].

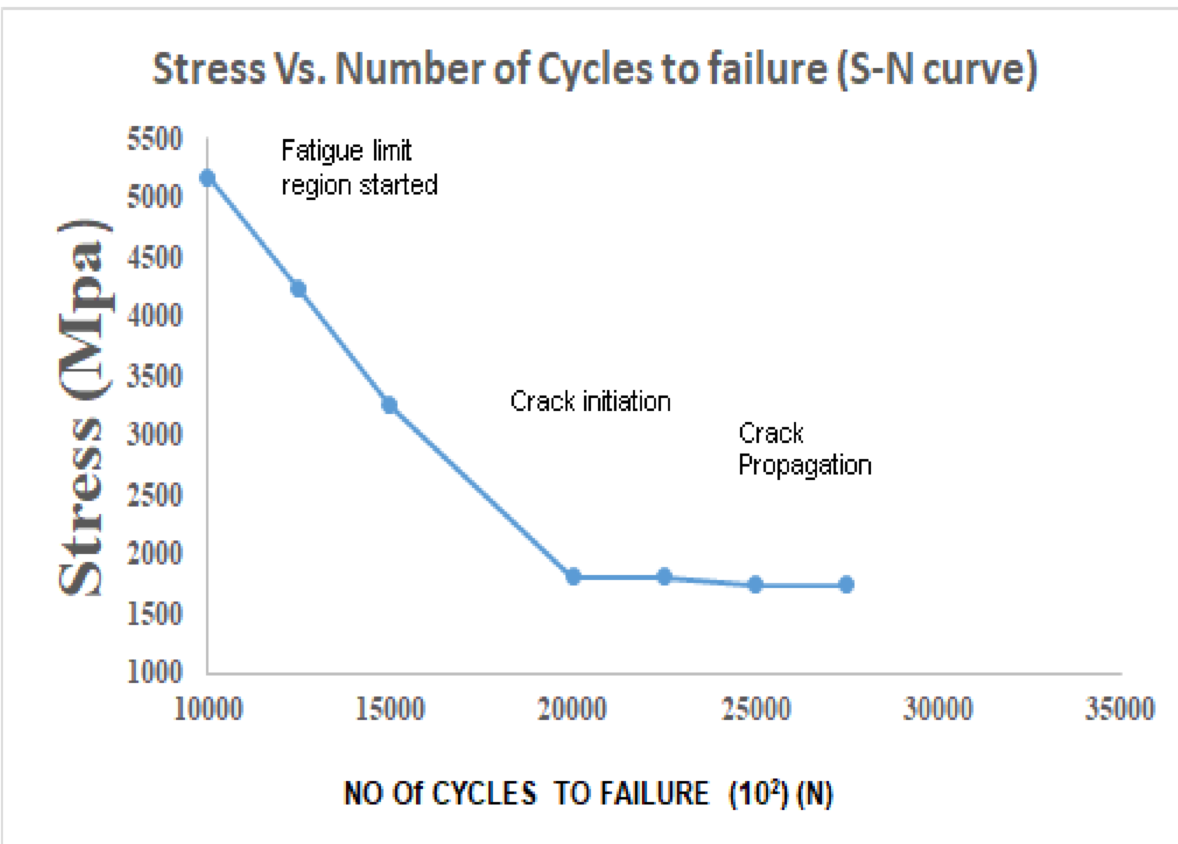

Figure 4: Failure stages of Composite Specimen using S-N Curve

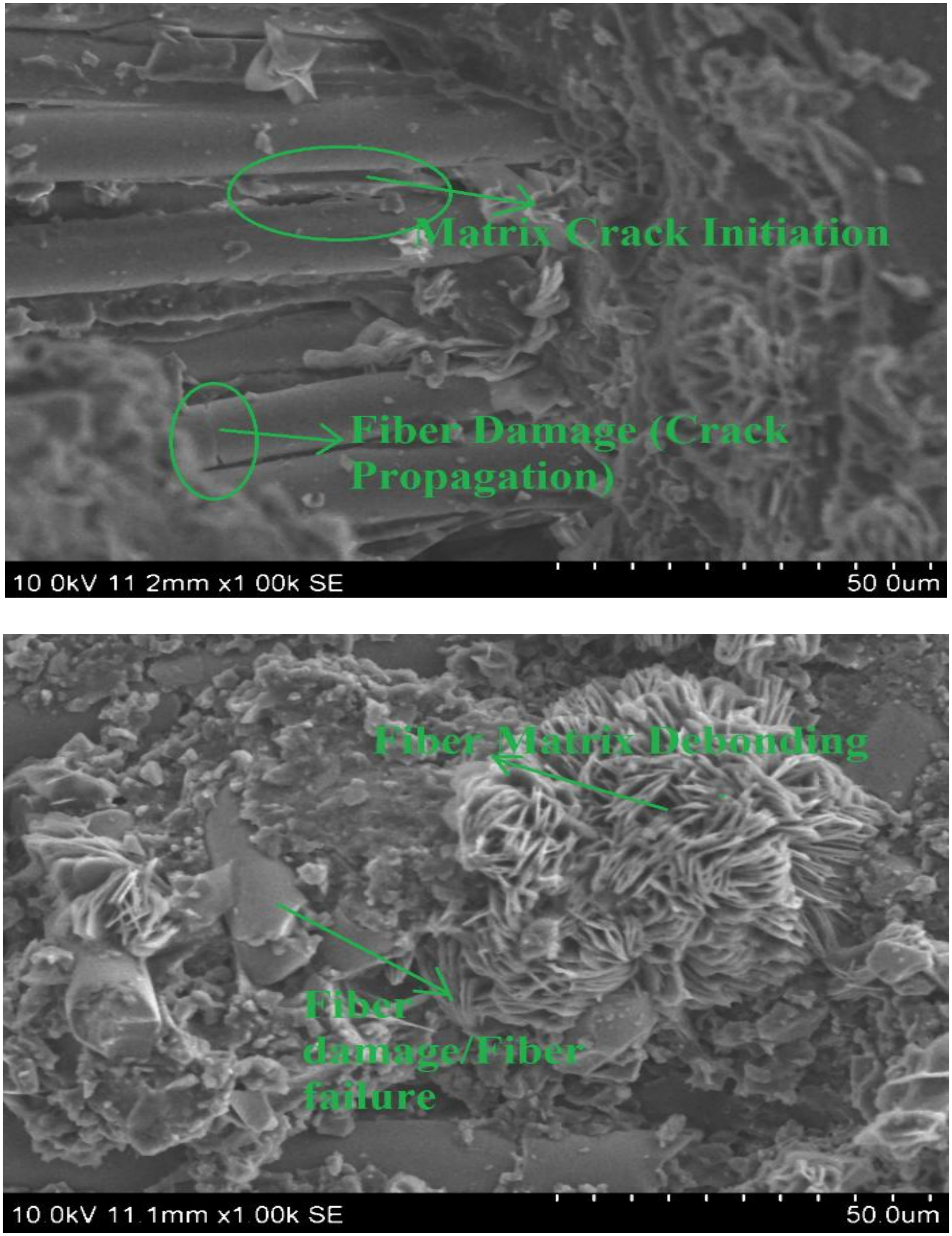

Figure 5: Post- test inspection approach using SEM for finding the different failure modes

The Scanning Electron Microscope (SEM) is employed as a post- test inspection approach to obtain microscopic evidence for the presumed failure modes such as matrix cracking, fiber matrix debonding, fiber damage (crack propagation) as shown in the figure 5.

V. CONCLUSION

1. After fabricating the fatigue testing machine and fixing the composite specimen, strain values are measured using a strain indicator. The stress values in the X, Y, and Z directions are calculated using the formula $\sigma 1 = E1\varepsilon 1$, where $\sigma 1$ is the stress, E1 is the Young's modulus, and $\varepsilon 1$ is the strain in the corresponding direction.
2. The strain characterization of the composite material is determined using the strain indicator. The measured strain values are compared with adjacent values to identify and analyze any errors or discrepancies.
3. Strain gauges are positioned along the boundary of the workpiece specimen to capture strain data. This data is subsequently utilized to compute and interpret stress distributions along the composite specimens, leveraging an S-N (stress-life) graph. The S-N graph establishes the relationship between stress levels and the corresponding number of cycles to failure for the specific material under examination.
4. The outcomes from the fatigue testing machine across the X, Y, and Z axes illustrate the profound influence of stress on a material's fatigue life. Higher stress levels correspond to reduced cycles-to-failure capacity. This study underscores the critical need to grasp stress's impact on material fatigue, emphasizing the significance of understanding fatigue behavior and devising strategies to enhance material fatigue resistance in engineering design and product development.
5. SEM (Magnified views) used to identify the failure mechanisms of the composite specimen, including matrix failure, crack initiation, and fiber failure (crack propagation) in the directions of the X, Y, and Z axes, respectively.
6. The coupon-level investigations conducted in the lab may be expanded to real-size structures based on this research finding.

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