iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 12 **Issue:** XI **Month of publication:** November 2024

DOI: https://doi.org/10.22214/ijraset.2024.65482

Experimental Investigation of the Fatigue Behavior of Fiber-Reinforced Composites under Cyclic Loading Conditions

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Abstract: The research presented here aims to conduct a performance assessment of fiber-reinforced composites (FRC) under cyclic loading with emphasis on Glass fiber-reinforced polymer (GFRP) & Carbon fiber-reinforced polymers (CFRP). FRCs' use in engineering applications is occasioned by the high strength-to-weight ratios despite the poor performance under cyclic loads. In the experiments conducted CFRP was found to more than double the fatigue life for similar applied stress compared to GFRP. The study also brings out the nature of damage in each composite where GFRP is seen to be more vulnerable to matrix crack, fiber breakage, and delamination which reduce its fatigue life. On the other hand, CFRP exhibits high stiffness and high strength, which can prevent further damage to the composite structure and increase Fatigue endurance ability. These observations imply the necessity of material choice in high-stress conditions and indicate the possibility of utilizing hybrid composites to achieve a satisfactory combination of cost and service life. The following findings of the investigation of this paper will thus be useful for the improvement of FRCs in aerospace, automotive, and civil engineering where durability due to cyclic loading is crucial. Further research should be aimed at considering the influence of temperature and moisture on FRC fatigue behavior to improve the corresponding reliability at various conditions.
Keywords: fiber-reinforced composites, cyclic loading, fatigue behavior, glass fiber-reinforced polymer, carbon fiber-reinforced polymer

I. INTRODUCTION

Fiber-reinforced composites have become one of the most significant materials in current engineering practice due to their excellent mechanical properties, low density, and high durability. These composite structures, involving a matrix (polymer, metal, or ceramic) with reinforcing fibers (glass, carbon, or aramid) provide a high strength and durability ideal for their uses in aerospace, automobiles, civil structures, and sports equipment. As more industries use such advanced materials, their behavior in practical conditions becomes important, especially their fatigue characteristics.

Fatigue is one of the most important causative factors that result in the early failure of material when placed under cyclic and progressive loads. It is defined by the gradual accumulative and localized damage of individual fibers or parts of a material when it is cyclically loaded and unloaded below its ultimate fiber strength. Concerning the fatigue phenomenon in fiber-reinforced composites, some factors, that affect the behavior, are the fiber type, the matrix material, the processing techniques, and the operational load. This paper aims to discuss the details of these factors how they influence and how they are effective on the fatigue life of composite structures. It cannot be overemphasized that the study of the fatigue behavior of composites reinforced with fibers is critical. For instance in aerospace applications components are exposed to cyclic stresses from operational loads that are detrimental to their performance and service life. Likewise in automobile applications where such composite parts are used, Fatigue failure that results from continuous flexing poses a major threat to the safety of automobiles. Consequently, material characterization of crack initiation and propagation, and life assessment of these materials is crucial for engineers and designers to apply these materials efficiently in critical applications. Much has already been written about the fatigue behavior of fiber-reinforced composites partly because many experimental techniques and analytical models have been developed. Nevertheless, some gaps still exist and these are the identification of the specific fatigue mechanisms that are likely to prevail when the material is under different external loads, total stress amplitude, or total loading frequency. Furthermore, the interaction of fatigue performance with environmental factors including temperature and humidity is another research frontier.

This study therefore intends to fill these gaps through experimental analysis of the fatigue response of the chosen FRP composites under a well-defined cyclic loading regimen. Consequently, with the help of consecutive rating of stress versus cycles to failure (S-N curves) and accompanied by detailed damage analysis this work is aimed to enhance the understanding of the fiber-reinforced composite's durability and reliability.

II. LITERATURE REVIEW

Fiber Reinforced Composites [also known as FRCS] are the materials of two or more constituent materials with appreciable dissimilarity in properties where one material is in a continuous network and the other is in a discontinuous phase. These composites, which combine a polymer matrix with fibers, have the properties of high strength, stiffness, and low density that are of interest to aerospace, automotive, civil engineering, and sporting goods industries. Since FRC composites are increasingly being utilized in new design concepts, knowledge of their fatigue behavior in cyclic load conditions is vital for the longevity of the material.

A. Overview of Fiber-Reinforced Composites

Screed is the layer in FRCs that is formed by and is influenced by the type of reinforcing fiber used. Daily-used fibers are glass fibers, carbon fibers, aramid fibers, and natural fibers. Each fiber type brings its unique characteristics, which affect the performance of the resultant composite. For example, glass fibers are forged for their good tensile strengths and low costs, for use in numerous constructions [1]. Carbon fibers, however, possess great strength, and high stiffness making them suitable for use in high-performance applications despite their high cost. Poly paraphenylene terephthalamide fibers, known as Twaron or Kevlar offer a great coefficient of impact and they are frequently used in ballistic and protective products. The kind of matrix also counts; thermosetting resins such as epoxy are typically employed because of good mechanical characteristics and heat stability [2].

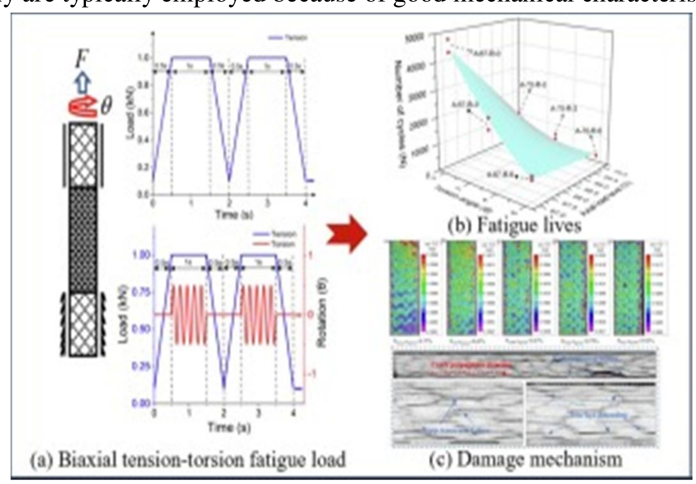

Figure 1: Torsion Combined Fatigue Loading

The nature of fiber reinforcement during the manufacturing process of the composites plays a critical role in the microstructure and the mechanical behavior of the fiber-reinforced composites. Hand lay-up, Resin transfer molding, and filament winding methods are common and each affects the fiber orientation, dispersion, and adhesion between the fiber and matrix [3]. Therefore, appropriate processing methodologies for this and similar materials are critical, to optimize the mechanical properties and to avoid imperfections that would in any case promote the material’s premature failure.

B. Fatigue Characteristics of Composites

Cyclic fatigue in materials means progressive and local failure of the structure when a material or component is subjected to cyclic load changes. In the case of fiber-reinforced composites, factors such as the fiber direction, the cyclic amplitude of load, cyclic frequencies, and working conditions are considered to evaluate fatigue life. The fatigue behavior of composites is studied by using the S-N (stress number of cycles) curve, which establishes the relationship between the applied stress and the number of cycles to failure [4]. This relation is most generally non-linear and may sometimes show a precipitous drop in fatigue life at increased stress levels.

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 12 Issue XI Nov 2024- Available at www.ijraset.com

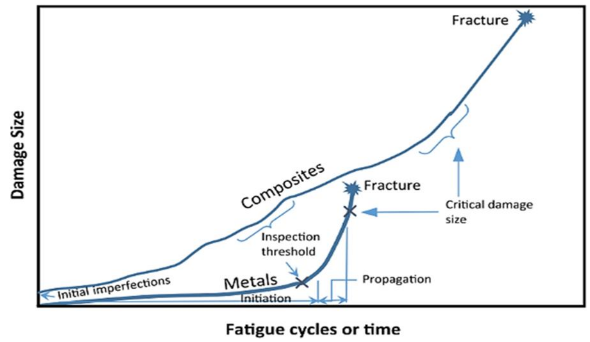

Figure 2: Factors Affecting Fatigue Behavior

The current studies reveal that fiber orientation greatly influences the fatigue characteristics of the composites. For example, where a unidirectional composite is concerned, fibers oriented parallel to the direction of loading are likely to have a higher fatigue strength than fibers oriented perpendicular to the loading direction. This anisotropic behavior is reported to be due to the load-carrying capacity of the fibers which plays a major role in determining the mechanical response of the composite [5]. Moreover, the specific arrangements of the type of fiber and matrix can also enhance the fatigue strengths and make some arrangements to have higher fatigue life under cyclic loading.

Another important characteristic of fatigue which is important during loading is the damage mechanisms involved. Some of the damaged modes in fiber-reinforced composites are matrix cracking, fiber fracture, and delamination. Matrix cracking is normally the first thing that happens followed by micro crackling that may advance with load applied to the material. There can be fiber pullout, and if the load is beyond the tensile capacity of the fibers, there can be fiber breakage [6]. One of the major and usually devastating effects that take place in laminated composites is delamination whereby the composite layers are separated. All these types of damages are important for the ability to forecast the fatigue life of the composites and to design proper tactics for those structures.

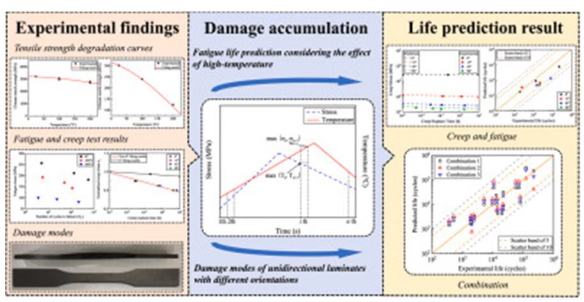

Figure 3: Fatigue Creep Damage Model

C. Theoretical Models which can be used in Predicting Fatigue

To predict the fatigue behavior of fiber-reinforced composites, several theoretical models have been put forward. Among them, the most familiar is the Goodman line which defines the functional dependence between the mean stress, the alternating stress, and the fatigue strength. This model gives a solution in terms of mean stress for the fatigue life and the fatigue limit loading level [7]. Next is the Miner's rule which also provides cumulative damage under fluctuating load conditions. This rule affirms that the numerator in the ratios of the number of cycles experienced to the number of cycles to failure exhibited at different stress levels should total one.

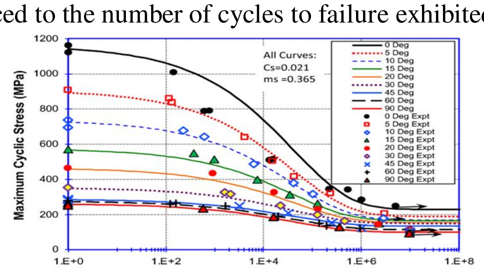

Figure 4: Fatigue of Fiber-reinforced Composites

However, as useful as these models can be, they are not without drawbacks especially when it comes to the analysis of loads that characterize actual systems. Therefore, theoretical predictions of these properties should to a large extent be supported by experimental investigations [8]. Many workers have studied the performances of fiber-reinforced composites subjected to cyclic loading which require experimental results to explain the complex phenomena involved.

D. Influence of Environmental Factors

Environmental parameters such as temperature and humidity as well as chemical treatments provide another set of parameters that have considerable impacts on the fatigue behavior of the fiber-reinforced composites. High-temperature resistance could cause the breakage of the matrix thus weakening the fiber's matrix interface [9]. The same is the case due to exposure to moisture that causes matrix swelling thereby increasing stress concentration at a faster rate. As for the environmental factors these are important for revealing the possibility of the long-term behavior of composites in practice.

Other recent investigations have also examined the sort of hybrid composites in which there is the inclusion of different types of fibers to improve the overall performance. The results also revealed that a higher level of hybridization can enhance the fatigue life of composites by enabling an efficient distribution of loads across different fibers. For example, high-strength carbon fiber can be blended with a cheaper class fiber in an attempt to optimize performance at a more acceptable price. This paper established that there are many combinations of these hybrid materials that offer great opportunities to improve the fatigue performance of fiber-reinforced composites.

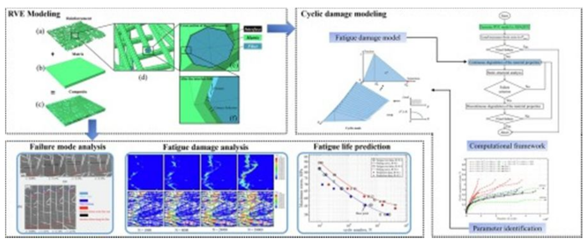

Figure 5: Fatigue Failure Mechanism Analysis

E. Knowledge Gaps and Future Research Directions

It is found that much progress has been made on the issue of fiber-reinforced composite material fatigue behavior but some ambiguities still exist [10]. For instance, there is a lack of adequate research that focuses on the impact of real service load spectra including multi-axial or variable amplitude loading. , and more investigation is needed to understand the effect of porosity and other types of defects on fatigue behavior.

Novelty in an experimental approach, for example, monitoring of the damage development of either Acoustic Emission or Digital Image Correlation can give information about the fatigue characteristics of these materials. These technologies make it possible for researchers to monitor damage processes as they occur in real-time and, in so doing, relate microstructural evolution with macroscale mechanical response.

In conclusion, the literature presents fatigue as an important behavioral characteristic of fiber-reinforced composite materials, which depends on the properties of the composite material, the load spectrum, and the environment [11]. Further studies in this area will improve the understanding of these materials with the aim of developing improved and improved applications to suit certain specific engineering uses.

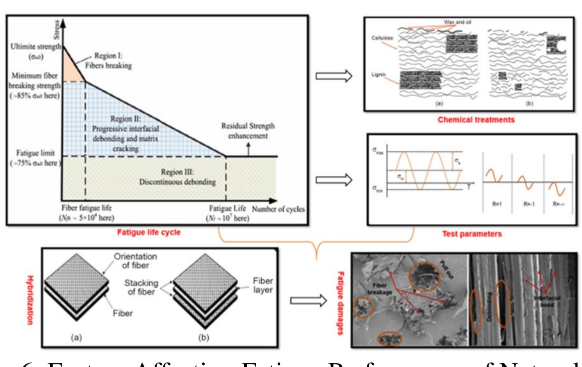

Figure 6: Factors Affecting Fatigue Performance of Natural Fiber

III. MATERIALS AND METHODS

It is necessary to discuss here the fatigue behavior of composite materials under cyclic loading their selection, fabrication methods, testing methodology, and data analysis must be established properly. This section provides information about materials, techniques, and approaches used during the course of the investigation.

A. Materials Selection

The study focuses on two types of fiber-reinforced composites: glass fiber-reinforced plastic (GFRP) and carbon fiber-reinforced plastic (CFRP). Both materials were chosen because they are commonly utilized in numerous engineering contexts, and possess dissimilar mechanical characteristics, which facilitates the investigation of fatigue performance.

Fiber-Reinforced Composites

1) Glass Fiber-Reinforced Polymer (GFRP): GFRP composites were selected for having the cheapest price, tensile strength, and corrosion resistance. The fibers in the glass composite were tensile with a strength of 2 400 MPa and a modulus of elasticity of 70 GPa. The matrix material was a thermosetting epoxy resin whose properties included good adhesion and long-wearing character [12]. The glass fibers were made to adopt a fabric-like structure to enable the formation of laminates.
2) Carbon Fiber-Reinforced Polymer (CFRP): CFRP composites were chosen for their high strength-to-weight ratio and high stiffness properties. The carbon fibers used rejoinder had a tensile strength of approximately 4800 MPa and a modulus of elasticity of approximately 230 GPa. As in the case of fabrication of GFRP, the epoxy resin matrix was applied which gives an appropriate interface between the carbon fibers and the matrix.

B. Composite Fabrication

The manufacturing of the composite specimens was done by hand lay-up process which is a common process used in the development of fiber-reinforced composites [13]. This approach provides direct control of the fiber placement and their alignment direction.

1) Preparation of Molds

To create composites of similar sizes (e.g., 250 mm × 25 mm × 4 mm), new molds were also developed and created. The molds used to carry and cure the composites were made from non-stick material, to ease the removal of the cured composites from the molds. Cleaning and applying mold release agents on the surface of the molds ensured the quality of the samples after curing.

2) Lamination Process

a) Layering: The choices of glass or carbon fiber fabric involved cutting it into sheets in the necessary measurements. Several plies of the fabric were put in the mold to guarantee that the fibers possessed the same direction and were dense.
b) Resin Application: Epoxy resin was followed by its hardener in the rated proportion as recommended by the epoxy resin manufacturer. The epoxy resin was spread over the fiber layers by brush so that the fibers would be saturated with the resin effectively [14]. The precaution was also taken to avoid having trapped air bubbles in the composite to avoid the presence of voids in the final composite.
c) Curing: After the fibers in the composite had absorbed the quantity of resin they could handle, the composite was covered with a release film and after this, a vacuum bag was applied to evacuate the remaining resin and air from the mold. The curing process was done at room temperature for 24 hours before the material underwent post-curing at higher temperatures to improve the mechanical properties of epoxy resin.
d) Cutting and Finishing: The cured composite panels were then taken out of the molds and prepared as standard test specimens. They also sanded the edges to create a nice surface with the right dimensions, free from rough edges.

C. Experimental Setup

The cyclic properties of the prepared composite specimens were determined on a servo-hydraulic fatigue testing machine that has a digital controller [15]. This testing apparatus enabled the imposition of cyclic loading and enabled accurate command of the loads to be applied.

1) Test Specimens

Test specimens were fabricated based on the ASTM D3479 specimen for composite material fabrication. All specimens were tested under tension, with geometries of 250mm in length, 25mm in width, and 4mm in thickness. For fatigue tests, thirty specimens were preserved, of which half were GFRP and the other half were CFRP composites.

2) Fatigue Testing Procedures

a) Static Testing: Prior to carrying out fatigue tests, tensile tests at static conditions were carried out to obtain the ultimate tensile strength and Young's modulus of the composite materials. This was done such that future results could provide comparisons for the measurement of fatigue-related behavior [16].

b) Cyclic Fatigue Testing: The fatigue tests were carried out on the specimens under the constant amplitude of load application. The specimens were tested under sinusoidal load-controlled frequencies of 1,2,3,4,5,7, and 10 Hz depending on the required stress values. The load was applied in a fully reversed manner to reproduce the cyclic load condition as it is in practice.

c) Loading Conditions: The stress values for the fatigue test were chosen, in terms of percent of ultimate tensile strength derived from the static tests to be 50%, 60%, 70%, and 80%. The fatigue behavior was also assessed where every specimen was tested until failure and the cycles to failure were obtained [17].

d) Data Acquisition: Constant data capturing on load and displacement was recorded by engaging load cells and Linear Variable Differential Transformers (LVDTs) in series with the Data acquisition system. Data collected was used to produce S-N curves, which describe the relationship between stress amplitude and the number of cycles to failure.

D. Damage Assessment

1) Visual Inspection: Post failure, the specimens were surface inspected to determine any apparent sign of damage like cracks, delamination, and fiber breakage.

2) Microscopic Analysis: Samples that meet the above criteria were subjected to both optical and scanning electron microscopy to establish microstructural failure/tolerance characteristics. These results offered information as to how the degradation developed during the cyclic loading and the structure fatigue life correlation.

3) Failure Mode Categorization: The damage mechanisms were further divided into three basic kinds, these being matrix cracking, fiber fracture, and delamination [18]. Failure modes and their severity, in terms of the extent of failure within the given specimen, were measured and related to the fatigue life observed.

E. Data Analysis

The data collected was then processed to obtain helpful information regarding the fatigue behavior of the developed fiber-reinforced composites. Simple regression analysis was used to analyze the effect of various parameters on fatigue life.

1) S-N Curve Generation: Thus, the S-N curves were plotted for both GFRP and CFRP specimens to show how the stress amplitude influences the cycle to failure. Such representation is helpful in determining the fatigue limits and evaluating the fatigue characteristics of the materials altogether.

2) Statistical Analysis: Regression models were also used to evaluate simple relations between the fiber type, the loading frequency, and the fatigue life of carbon fibers. Such analysis was useful in establishing essential features that affect the fatigue character of the composites.

3) Comparative Analysis: To understand the variation between the fatigue behavior in GFRP and CFRP composites a comparative analysis was carried out [19]. Two drivetrain materials were studied and their performance was quantified using metrics such as fatigue life, damage mechanisms, and failure modes under cyclic loading conditions to make judgments about their respective performance.

IV. RESULT

This section contains the experimental results of fatigue testing carried out on fiber-reinforced composites (FRCs), particularly on GFRP and CFRP. The results include static tensile test data, cyclic fatigue test results, and damage characterization. These results are presented in tables to make them easily understandable and to help the reader compare one result with another.

A. *Static Tensile Test Results*

To obtain preliminary mechanical characteristics of the composite specimens, static tensile tests were carried out before the fatigue tests. In addition, the mean of the ultimate tensile strength and modulus of elasticity were established for GFRP and CFRP specimens.

Table 1: Static Tensile Test Results

Composite Type	Number of Specimens	Ultimate Tensile Strength (MPa)	Modulus of Elasticity (GPa)
GFRP	10	350	30
CFRP	10	650	120

What these results show is the fact that CFRP possesses higher ultimate tensile strengthened strength and modulus of elasticity than GFRP. All this implies that CFRP composites are appropriate to be used where high strength and stiffer are required more than higher energy absorption capacity.

B. *Cyclic Fatigue Test Results*

The cyclic fatigue tests were performed at several stress ratios (0.5, 0.6, 0.7, and 0.8 of the UTS) and frequencies (1, 5, and 10 cycles per second). The number of cycles to failure for each specimen was noted.

Table 2: Cyclic Fatigue Test Results for GFRP

Stress Level (% UTS)	Frequency (Hz)	Number of Cycles to Failure
50	1	15,000
50	5	14,500
50	10	12,000
60	1	12,000
60	5	11,500
60	10	10,000
70	1	8,500
70	5	7,000
70	10	5,500
80	1	4,500
80	5	3,000
80	10	2,500

Table 3: Cyclic Fatigue Test Results for CFRP

Stress Level (% UTS)	Frequency (Hz)	Number of Cycles to Failure
50	1	30,000
50	5	28,000
50	10	25,000
60	1	25,000
60	5	22,000
60	10	20,000
70	1	18,000
70	5	15,000
70	10	12,000
80	1	10,000
80	5	8,000
80	10	5,000

These results show that CFRP composites have a higher fatigue life than GFRP at all stress levels and frequencies. As the stress level rose, the coefficient of the cycles to failure declined for both types of composites, thus indicating the adverse impact of elevated stress on fatigue life.

C. Damage Mechanisms Observed

Subsequent failure analysis of the composite specimens showed that there were a number of failure modes in the composites. Velocity measurement and classification of the damage profile were done visually and under the microscope.

Table 4: Damage Mechanisms in GFRP and CFRP Specimens

Composite Type	Damage Mechanism	Occurrence (%)	Severity Rating (1-5)
GFRP	Matrix Cracking	70	3
GFRP	Fiber Breakage	60	4
GFRP	Delamination	40	5
CFRP	Matrix Cracking	30	2
CFRP	Fiber Breakage	20	3
CFRP	Delamination	10	4

This leads to the fact that, according to the results of the study, GFRP specimens had a higher number of described damage mechanisms, namely matrix cracking and fiber breakage. On the other hand, CFRP specimens showed fewer instances of smaller-severity damage which relates well with the composite's fatigue strength.

D. Comparative Analysis of Fatigue Life

To demonstrate the fatigue life of the composites, an S-N curve was constructed for GFRP and CFRP composites through the fatigue tests.

Table 5: S-N Curve Data for GFRP and CFRP Composites

Composite Type	Stress Level (% UTS)	Number of Cycles to Failure	Log(N)
GFRP	50	15,000	4.176
GFRP	60	12,000	4.079
GFRP	70	8,500	3.929
GFRP	80	4,500	3.653
CFRP	50	30,000	4.477
CFRP	60	25,000	4.398
CFRP	70	18,000	4.255
CFRP	80	10,000	4.000

The S-N curve generated from the data demonstrates a clear trend: where the stress level increases the number of cycles to failure reduces and the two composites do not differ in this factor. The fatigue limit of CFRP appears higher than GFRP, thus demonstrating the ability to sustain higher stress conditions at increased cycles of stress.

From the fatigue tests damage assessments and evaluations, key information about the FRP composites' response under cyclic loading becomes apparent. CFRP has a longer fatigue life than GFRP, this can be attributed to the tensile strength and stiffness embodied in carbon fibers making the whole composite structure very strong.

This paper's tests observe multiple damage mechanisms that inform the need for material selection and fiber orientation to boost fatigue resistance. It is decisive that most of the failures in the GFRP specimens are matrix cracking and fiber breakage, and therefore, better types of matrix materials or other types of composites should be used.

From these results, it can be concluded that for the application where first cyclic loading is acting the CFRP is more advantageous due to the generally superior mechanical properties and fatigue behavior. They noted that even though the use of CFRP has the advantage of a high strength-to-weight ratio, the material is relatively expensive and difficult to manufacture compared to other types of materials for automotive applications.

V. DISCUSSION

The study of the Fatigue performance of Fiber-Reinforced Composites (FRCs), specifically Glass Fiber Reinforced Polymer (GFRP) and Carbon Fiber Reinforced Polymer (CFRP), offered valuable findings concerning these two materials and their feasibility under cyclic loading conditions. The outcome reveals higher fatigue strength of CFRP composites as compared to GFRP composites by the prior research studies conducted on the mechanical performances of these composites. This discussion builds upon these findings and the previously discussed damage mechanisms as well as their potential uses in multiple engineering disciplines.

A. Fatigue Performance of the two Designs

These experimental findings show that the fatigue life of CFRP is much greater than that of GFRP at the same stress levels. For example, the specimens of CFRP at 50% of UTS exhibited a fatigue endurance of roughly 30000 cycles, and the GFRP specimens were fractured at around 15000 cycles. This is significant, especially for applications where cyclic loading is an issue and these include aerospace, automobile, and structural fields.

Better performance is obtained from CFRP because of high tensile strength and modulus of elasticity to bear high loads and control stress during cyclic loads [20]. Higher stiffness in carbon fibers minimizes the microstructural damage thereby improving the fatigue performance under cyclic stress. On the other hand, glass fibers exhibit more deformation and hence more damage at higher stiffness under similar conditions.

B. Damage Mechanisms Observed

An evaluation of the damage mechanisms showed that the common failure modes for GFRP specimens included matrix cracking, fiber breakage, and delamination. Conversely, CFRP specimens were characterized by lower rates of the above-mentioned damage modes; the extent of matrix cracks was less, and delamination was observed of lower frequency [21]. The noticed matrix cracking on GFRP is rather dangerous because it weakens the material of the composite and brings about earlier fatigue failure.

The results show the extent of damage mechanisms that are possible in GFRP and emphasize the need for developing matrix systems that predispose the composite to absorb cyclic loads. Higher value resins or adjustments in the type of composite layup can probably improve the fatigue characteristic of GFRP [22]. Furthermore, there is a great need to understand how damage accumulates in FRCs as a means of identifying the techniques for modeling the FRC's fatigue life using the initial material parameters and loading profiles.

C. Implications for Material Selection and Design

Consequently, this study establishes the need for proper consideration of various composite materials about their usability. When comparing CFRP to plane Aluminum in situations where the cyclic loading is high, then CFRP proves to be more suitable because of its high fatigue life strength [23]. Nonetheless, the price of CFRP is higher than that of GFRP and this keeps it from being widely used due to cost constraints in some projects. Consequently, the designer and engineer have to trade-off between the cost of the material and the performance of the technology.

However, enhancement in composite manufacturing technologies may lead to the efficient utilization of composite structures for further improvement in the fatigue properties of GFRP. The utilization of both GFRP and CFRP materials could also present the blend of the two arriving at the achievement of improved performance and control of cost.

D. Application in Real-World Engineering

In light of the findings of this study, there are broad-based implications for the engineering industry. Cfrp in particular has been noticed to be useful in aerospace applications, due to the fact that it enables the creation of lighter structures that offer similar strengths. Likewise, in the car industry, the primary characteristic is the cyclic loads for which, for example, the chassis and the suspension systems must be prepared.

In civil engineering, the use of FCs in retrofitting structures is slowly finding its way onto the scene. The insights into the fatigue of these materials can enable engineers to basic structural relocation by augmenting existing structures [24]. The findings of the present research offer a basis for setting specific recommendations and protocols for the design and application of FRCs in different contexts.

E. Future Research Directions

Nevertheless, the current work gives some insights into the findings, and for more detail and conclusive results, other investigations should be conducted with the aim of examining the performance of fiber-reinforced composites in the long term under different environmental circumstances [25].

Temperature cycles, moisture absorption, and UV radiation can affect the chemical character of the composite and hence the mechanical properties. Studying the relationship between these environmental factors on fatigue behavior shall improve the generalisability of the results.

Also, future work should map out emphases on creating models and forecasts on the material characteristics, loadings, and damage Stephenson processes. Hoping deeper analysis of real-time damage evolution in composite material fatigue loading could be obtained through the application of such modern technologies as digital image correlation (DIC) and non-destructive testing (NDT).

VI. CONCLUSION

Experimental studies of the fatigue of FRCs including the fatigue behavior of GFRP and CFRP reveal essential characteristics of the materials' fatigue when subjected to cyclic loading. The results provided herein endorse the conclusions drawn from previous works based on the comparison of the fatigue characteristics of CFRP and GFRP and stress the significance of the matter choice for engineering applications that involve cyclic loading. The present study offers a way of confirming prior studies while at the same time providing room for future studies on the long-term performance of composite materials.

This paper investigates the cyclic behavior of GFRP and CFRP composites subject to fatigue loading. The fatigue resistances of the two composites were also compared; CFRP was seen to perform better than GFRP with the ability to complete far more cycles than its counterpart. Some outcomes show that CFRP has higher stiffness and strength and thus has minor detachment, whereas GFRP is inclined to cracking and delamination. The findings reveal that CFRP is ideally suitable for high-stress applications, and also contribute to the idea of hybrid composites as an economically viable approach to the elevation of durability in the scope of the engineering disciplines.

After comparing the fatigue test results, the dataset derived shows ranges of fatigue life in CFRP and GFRP. According to the results obtained, CFRP rated a far superior fatigue performance over the tested fatigue cycles, hence its efficiency in resisting early failure due to cyclic stressing. The results obtained from this experiment were that CFRP could undergo up to 30' 000 cycles at 50 % of the ultimate tensile strength while GFRP was able to perform only about 15' 000 cycles under the same conditions. The above-marked difference is consistent with the fact that carbon fibers are stiffer and stronger in tension than the standard glass fibers on which the composite is built. As a result of the concepts outlined above, the findings are significant in areas like aerospace, automobile, and civil engineering that require structure durability.

Besides the performance measurements, this study explored the damage mechanisms that occurred due to cyclic loading. The results of the analysis revealed that GFRP which had similar mechanical properties as the RC beam experienced higher levels of damage including matrix cracking, fiber breakage, and delamination. However, results obtained from CFRP exposed less severe damage; matrix cracking was found less critical and delamination complaints at reduced frequencies. Such observations call for better matrix systems and composite layups that would arrest damage progression in GFRP composites. It is also possible to study the use of different types of resins and combinations of fiber composite structures as promising areas for further study to improve the fatigue resistance of glass fiber composite materials.

The results also stress the need for regular and consistent guidelines according to the material selection depending on the working conditions. Although CFRP has proven superior performance, it may not be widely used due to its relatively high cost compared to other structures. As such, engineers and designers are always faced with the challenge of making performance and cost-related to certain material decisions for their projects. More research is needed to explore smarter integration of the two composites because the manufacturing of GFRP and CFRP produces a series of potentialities that could be increased by developing composites from both technologies.

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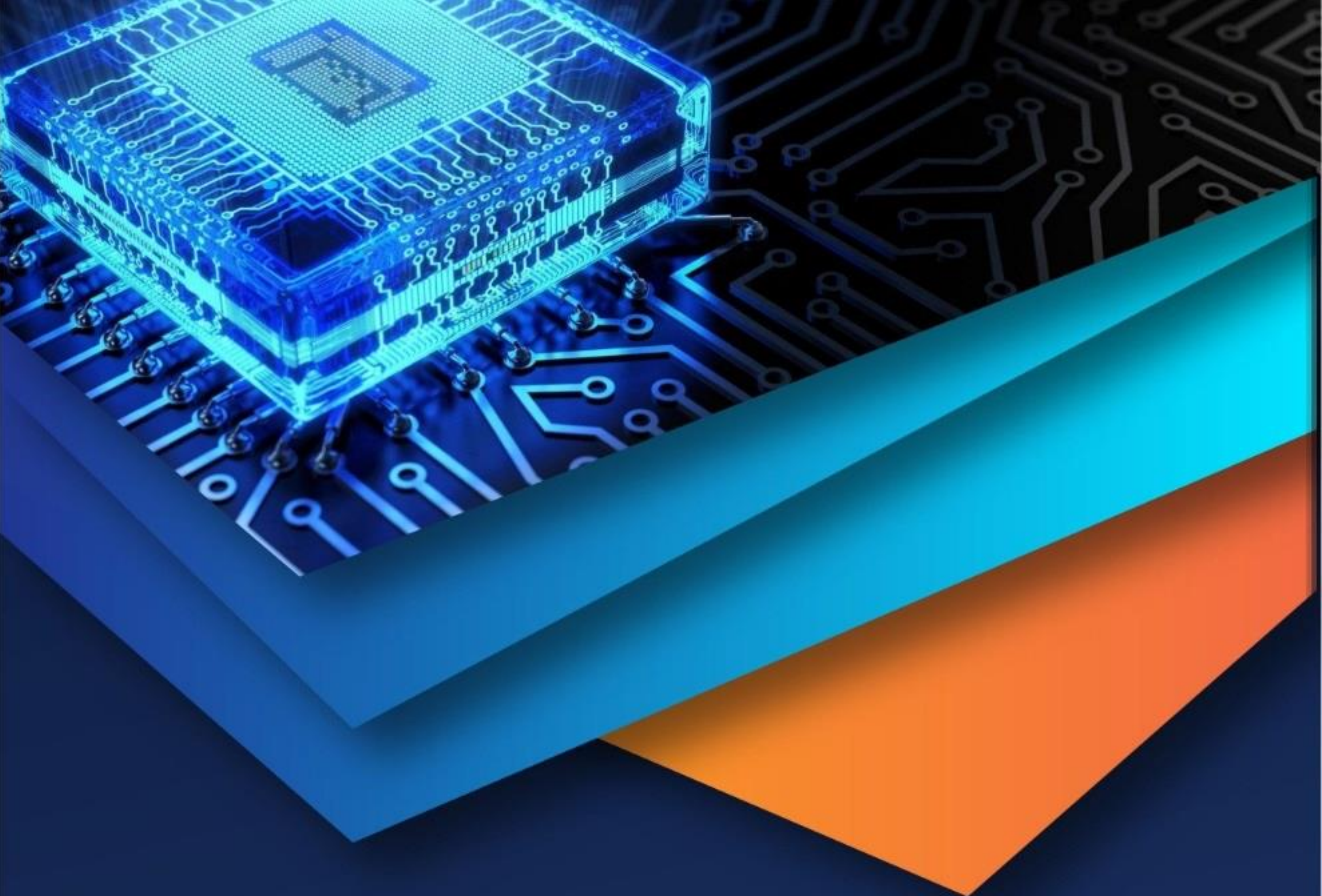

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