JJMIE

Volume 19, Number 3, Sep. 2025
ISSN 1995-6665
Pages 579– 587
https://doi.org/10.59038/jjmie/190310
Editor-in-Chief: Prof. Ali M. Jawarneh

Jordan Journal of Mechanical and Industrial Engineering

Fatigue Analysis of Polyester Composite Plate Reinforced with Carbon Fiber and Nano Silicon Dioxide

Raed Naeem Hwayyin[a,*], Ahmed Salman Hammood[b], Azhar Sabah Ameed[c]

[a]*Electromechanical Engineering College, University of Technology, Baghdad, Iraq.*
[b]*University of Technology/Factory and Training Center, Baghdad-Iraq.*
[c]*Electromechanical Engineering College, University of Technology, Baghdad, Iraq.*

Received 12 May 2025 *Accepted 28 Jul 2025*

Abstract

This research investigates the effect of silicon dioxide nanopowder, with particle sizes ranging from 20 to 30 nm, on the fatigue durability of carbon fiber/polyester composites. A series of fatigue experiments were conducted to assess the lifespan of the samples, which were created using varying amounts of nano silicon dioxide (SiO_2) at weight percentages of 0.16%, 0.20%, and 0.24%, while maintaining a carbon fiber weight fraction of 55%. The study details the properties of the composite material based on these different weight percentages. The experimental results indicated that reinforcing the carbon fiber/polyester composite with silicon dioxide nanoparticles improved its fatigue life across various ratios. The fatigue tests were conducted using a bending alternating method with fully reversed loading (R = -1). The specimens, with a thickness of 7 mm, were tested in a room temperature environment. Fatigue life was evaluated at three distinct stress amplitudes: the first level comprised 78.43, 92.98, and 106.16 MPa; the second level included 87.65, 103.91, and 118.64 MPa; and the third level featured 98.59, 116.89, and 133.45 MPa. The fatigue behavior was described using the Basquin equation. The results showed that, at a weight fraction of 0.16%, an increase in stress rate of 14.03% resulted in a decrease in cycles of 12.43% at the first level and 11.34% at the second level. A similar stress rate reduction at the third level led to a 9.4% decrease in cycles. Higher stress amplitudes significantly shortened life cycles. For the 0.20% additive, an increase in average stress by 14.03% reduced life cycles by approximately 12.43%. Further stress increases at the second level led to an 11.34% decline in cycle count, while the same increase resulted in a 9.35% decrease in cycles. Fatigue evaluations on samples with 0.24% of nanoparticles showed a 14.03% increase in the stress ratio, which consequently resulted in a decrease of fatigue cycles by 7.5% at the first level, 8.3% at the second level, and 9.4% at the third level. This minor change suggests improved durability against failure with the incorporation of 0.24% nano silicon dioxide (SiO_2) as stress levels increased. Scanning electron microscope (SEM) images of the composite samples at a magnification of 2.0 kx demonstrate a homogeneous dispersion of nanoparticles within the microstructure, enhancing the mechanical properties of the composites.

Keywords: Carbon fiber/polyester, Silicon dioxide nanoparticles, Fatigue life, Weight fraction, Microstructure.

Nomenclatures

W_m	Weight of matrix (polyester),(g).
W_c	Weight of composite specimens, (g).
W_f	Weight of fiber (metal mesh),(g).
W_{Nano}	Weight of Nano SiO_2
V_f	The volume fraction of fiber, (cm^3).
V_m	The volume fraction of matrix, (cm^3).
V_{Nano}	The volume fraction, (cm^3).
ρ_f	The density of fiber, (g/cm^3).
ρ_m	The density of matrix, (g/cm^3).
ρ_c	The density of composite, (g/cm^3).
ρ_{Nano}	The density of Nano, (g/cm^3).
σ_a	Amplitude stress (MPa)
a and b	Parameters of the fatigue equation
N_f	Fatigue life in cycles
σ_b	Amplitude bending stress (MPa)
E	Elastic modulus of composite (GPa).
t	Thickness of sample (mm)
δ	The deflection in the bending test (mm)
L	The effective length in (mm)

1. Introduction

Researchers investigated methods for assessing fatigue in composite ship hulls within marine environments, specifically focusing on reductions in stiffness. Fatigue tests were conducted to identify critical hotspots, and a refined mesh was used to accurately capture stress variations. The study integrated spectral fatigue analysis with stiffness degradation to predict fatigue life, revealing that the connection of the bulkhead stiffener exhibited the

* Corresponding author e-mail: 10596@uotechnology.edu.iq.

shortest fatigue life [1]. Despite the advances, composite materials still face significant mechanical challenges, particularly related to fatigue, which involves cyclic loading and can lead to damage that affects performance. This review examined mode I fatigue behaviors, the factors influencing failures, and numerical modeling techniques for life prediction [2]. Additionally, the study explored the tensile fatigue characteristics of glass fiber reinforced polymer (GFRP) plates made from polyester and vinyl ester when exposed to cyclic loading. Researchers investigated how different resin types, stress ratios of 0.1 and 0.5, and environmental factors such as air and water impact failure mechanisms and fatigue life [3]. This research examines how the structure of a layered composite made from polyetherimide (PEI) materials is related to its resistance against cyclic loading. The findings indicate that the PEI composite has a short fatigue life when subjected to cyclic loads at 0.8 of its yield strength. Recent studies suggest that the inclusion of nano-SiO_2 improves interfacial bonding and stress distribution, potentially extending the fatigue lifespan of hybrid composites by up to 35% [4,5]. Carbon fiber-reinforced composites are known for their exceptional performance, as carbon fibers are utilized to strengthen matrices of resins, rubbers, and ceramics [6-8]. Their low density combined with a high modulus of elasticity and versatile design capabilities makes them ideal for various applications, including aerospace, civil engineering, construction, and sports equipment [9-11]. Advancements in technology and the growing range of applications in these sectors have raised the performance standards for composite materials, particularly concerning fatigue life requirements [12-15]. Fatigue cracking can lead to a reduction in stiffness and load-bearing capacity, ultimately diminishing reliability and safety [16]. The extensive use of carbon fiber-reinforced composites in industrial applications, such as in aircraft and aerospace structures, is attributed to their properties, including high stiffness, resistance to creep, and cost-effectiveness [17-19].

The inclusion of nanoparticles in fiber-reinforced polymer (FRP) composites significantly enhances their functionality and mechanical properties. This study investigates the use of nanoparticles, nanofibers, and various nanocoatings to improve these properties and their roles in industrial applications [20]. One aspect of the research focused on the effect of silicon dioxide nanopowder on the mechanical properties of polyester/carbon fiber composites. The results showed that incorporating nanomaterials into these composites is cost-effective, particularly in applications such as boat hulls [21]. Additionally, the researchers examined how environmental factors influence the mechanical properties, including impact and tensile strength, of glass fiber-reinforced polyester composites with varying weight fractions [22]. They also studied the tensile properties and microstructure using SEM images of carbon fiber/polyester composites reinforced with multi-walled carbon nanotubes. Their findings indicate that the addition of nanoparticles enhances both tensile strength and elongation [23]. Further investigation centered on the effect of salt concentration on the impact strength andfracture toughness of a glass fiber-reinforced polyester composite material. This material was immersed in salt solutions with concentrations of 15%, 35%, and 55% for 40 days. The results revealed that impact strength and fracture toughness increased with higher salt concentrations, demonstrating improved material performance under saline conditions [24]. Finally, the study explored fatigue damage and its effect on the lifespan of fiber-reinforced composites, specifically carbon fiber-reinforced epoxy resin matrix laminates. The main damage patterns were identified by evaluating the fatigue failure process and its microscopic morphology, as well as using finite element analysis to enhance the reliability of material life predictions [25].The significance of this study lies in its aim to predict the flexural fatigue life of carbon fiber composites reinforced with nanoparticles, which are utilized in various industrial applications, including aircraft structures and ship hulls. This research focuses on exploring the fatigue characteristics of polyester composite plates reinforced with 55 wt.% carbon fibers, in combination with varying concentrations of nano-SiO_2, ranging from 0.16 to 0.24 wt.%. Fully reversed bending tests, with a ratio of R = -1, were performed at three different stress amplitudes: Level 1 (78–106 MPa), Level 2 (88–119 MPa), and Level 3 (99–133 MPa). By analyzing the S-N curves, fatigue life, and microstructure using scanning electron microscopy (SEM), this study aims to clarify the relationship between nanoparticle concentration, stress levels, and fatigue lifespan. The findings will contribute to the development of composite designs that improve resistance to high-cycle fatigue under various stress conditions, in alignment with current industrial trends favoring lightweight and durable materials. Furthermore, the research seeks to predict the fatigue behavior at each stress level using the Basquin equation.

2. Methodology

Any composite substance composed of two or more materials is assessed through experimental and laboratory evaluations, considering the weight ratio of each material in the composite, known as the weight fraction. Furthermore, the volume fraction, which is based on the volume of each material relative to the final volume of the overall composite, helps determine its mechanical properties. Experimental tests and their descriptions in mathematical equations provide accurate information for determining mechanical properties. The weight of the polyester is calculated by subtracting the fiber's weight from the total weight of the composite sample. Equation (1) illustrates the calculation of the weight of the matrix material (polyester).

$$w_m = w_c - w_f \tag{1}$$

Additionally, the equation consists of three materials will be:

$$w_m = w_c - w_f - w_{Nano} \tag{2}$$

Where (W_m, W_c, W_f, and W_{Nano}) is the weight of matrix, composite,fiber and NanoSiO_2 (grams) respectively. The volume fraction of the carbon fiber in the composite [26]:

$$V_f = \frac{w_f}{\rho_f} \tag{3}$$

The volume fraction ratio of carbon fibers (fibers) to polyester (matrix) in the samples was as in Equation (4):

$$\frac{V_f}{V_m} = \left(\frac{W_f}{W_m}\right) * \left(\frac{\rho_f}{\rho_m}\right) \quad (4)$$

The composite material's density:

$$\rho_c = \rho_f.V_f + \rho_m.\ V_m + \rho_{Nano}.V_{Nano} \quad (5)$$

Where (V_f, V_m,and V_{Nano}) is the volume fraction of fiber, matrix, and Nano (cm^3) respectively ;while, (ρ_f, ρ_m, and ρ_{Nano}) is density of Fiber, matrix, and Nano (g/cm^3) respectively.

2.1. The Fatigue S-N Curve

The S-N diagram is a visual tool that demonstrates the behavior of materials under repeated stress. It depicts that the maximum stress a material can endure diminishes with every loading cycle. The strength value observed after a large number of cycles, typically around 106, is referred to as the fatigue limit. Some materials have a specific "true" fatigue limit, which indicates the stress level below which fatigue failure does not initiate. However, in many cases, failure occurs only after a significant number of cycles. In composite materials, which are made up of fibers embedded in a matrix, using the S-N diagram can be complex. It can be difficult to illustrate how each component affects the overall fatigue life. Talreja [27] introduced a conceptual model aimed at comprehending the fatigue behavior of composites, starting with on-axis tension-tension fatigue in

$$\sigma_a = a.N_f^b \quad (6)$$

In this context, (a) and (b) are constants that vary based on the material properties and the shape of the object, while (N) denotes the number of cycles until failure occurs. By applying the fatigue life estimation formula at (10^6) cycles, we can determine the fatigue limit using the fatigue life information obtained from the created S-N curve.

$$\sigma_b = \frac{1.5*E*t*\delta}{L^2} \quad (7)$$

In this context, (E) represents the elastic modulus (GPa), (t) indicates the thickness of the specimen, (δ) refers to the displacement measured by the dial gauge (mm), and (L) signifies the effective length. The stress calculation was based on analyzing a square-section plate subjected to reverse bending fatigue. The deflection at the end of the plate is a key factor in determining the stress applied to the specimen over a fixed length, which represents the effective bending length.unidirectional composites. This testing can yield S-N curves for the samples, and common fatigue life characteristics are assessed using Basquin's law. When analyzing finite life situations, encompassing both low and high cycle fatigue, Basquin's equation offers a quantitative depiction of the S-N curve. This method allows for the estimation of a material's durability with relatively minimal data, as shown in the Duan QQ et al. [28]. The stress amplitude (expressed in MPa) can be determined by adjusting the data to align with Basquin's curve.

3. Material and Methods

3.1. Material and Methods

The current study used polyester resin as a matrix for composite materials to decrease production cost compared to epoxy or vinyl ester. The polyester characteristic used in the composite sample is shown in Table 1. The properties of the carbon fiber mat used in the composite samples have a weight fraction of about 55%, as presented in Table 2. Nanoparticles of silicon dioxide (20-30) nm. Nanoparticles were incorporated into the composite sample at varying weight percentages of 0.16%, 0.2%, and 0.24%. These percentages were determined by weighing the nanoparticles in relation to the total weight of the composite using a high-precision balance. Many studies, including one conducted by Azhar Sabah Ameed et al., have explored similar methods and utilized these weight percentages to analyze mechanical properties. Table 3 presents the specifications according to Hongwu International Group Ltd. in China. The study used a 7 mm thick sample of composite material to simulate the effects of fatigue stress in applications such as ship hulls, airplanes, and various industrial products, consistent with Jijun Liu et al. [29], who adopted the same thickness. His study also adopted a thickness of 7 mm for the cap cone of aircraft ENG as shown in Figure 1, which was found to maintain its integrity without pits, cracks, or defects in the bolt joints.

Figure 1. The cap cone of aircraft engine

Table 1. The Mechanical characteristics of polyester

Characteristics	Value
The specific density of the polyester	1.22 g/cm³ at 20°C
Tensile stress	65 N/mm²
Elongation at break (50 mm gauge length)	3.0 %
Modulus of elasticity	3600 N/mm²
Density (ρ)	1268 kg/m³
Rockwell Hardness	70

Table 2. The properties of the carbon fiber mat

Properties	Nominal
The mass, for each unit area (g/m²)	200
The weave	Plain
The width in (mm)	1000/2000
The thickness in (mm)	0.16

Table 3. The specifications of the SiO_2

Items	Value
Purity	99.8 %
coloring	White
Melting	1610-1728 C°
Boiling's Point	2230
Density	At 20 C° 2.77-2.66 g/cm^3

Developing composite fatigue specimens with precision is crucial for obtaining reliable and uniform fatigue testing results. Composite materials, such as fiber-reinforced polymers (FRPs), exhibit complex failure behaviors, including matrix cracking, delamination, and fiber fracture, which are especially responsive to the integrity of the samples. Insufficient preparation may lead to defects, cause premature failures, and produce inaccurate data. A CNC machine was used to create a two-part acrylic mold for the fabrication of fatigue samples, illustrated in Figure 2. The mixture was poured into the mold, which was layered with carbon fiber. To prevent air bubbles and ensure uniform thickness between the layers, the carbon fiber was added gradually. This process was carried out at room temperature (25°C ± 2°C) for a curing cycle of 24 hours. To accurately measure the weights of nanoparticle additives and the composite material components, a precision scale, displayed in Figure 3, was utilized. Achieving a homogeneous mixture of polyester and nanoparticles using the Ultrasonic Processor UP200Ht, shown in Figure 4, is crucial before placing the mixture into the die. The mixing process was conducted in pulse mode, alternating between 10 seconds of operation and a 5-second pause. This cycle continued for a total of 15 minutes, resulting in a mixture volume of 100 grams at a room temperature of 25°C. A longitudinal probe with a diameter of 7 mm was submerged to a depth of 15 mm below the surface of the mixture. Afterward, the fatigue samples are cut according to the standard dimensions, as shown in Figures 5-a and b.

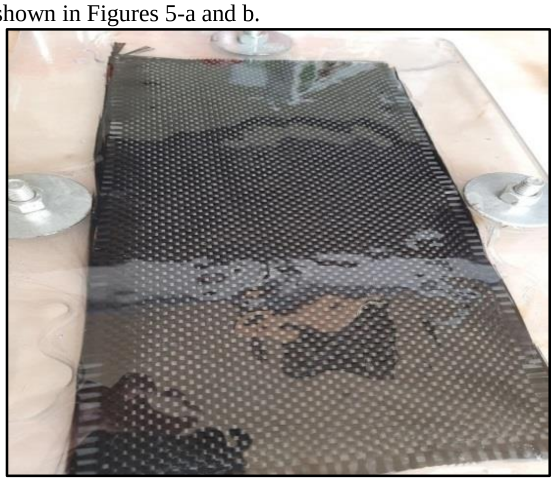

Figure 2. The die-casting of the samples

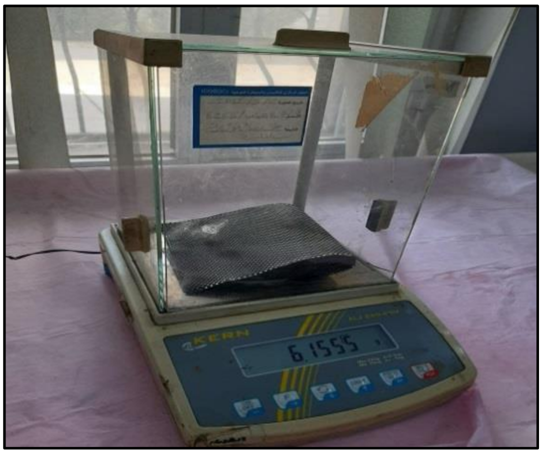

Figure 3. High precision weighing scale

Figure 4. The device of the ultrasonic processor type UP200Ht

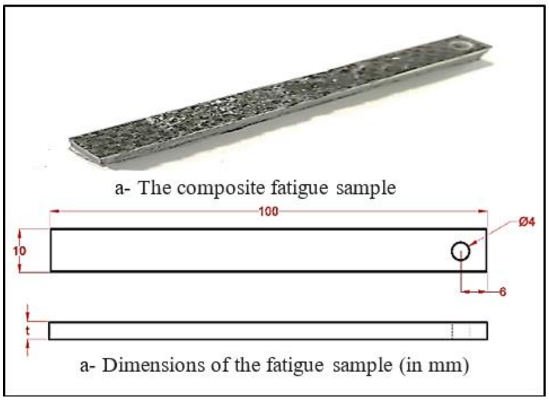

Figure 5-a and b. Fatigue sample according to device HSM20

3.2. Fatigue test

Fatigue evaluations were conducted at room temperature using a cyclic stress ratio (R = -1) with alternating bending stress applied to a plate-shaped specimen secured at one end. The ratio R = -1 represents the most intense type of cyclic loading, where stress levels equally alternate between tension and compression. This understanding is essential for comprehending how materials respond to severe fatigue conditions in real-world applications and for creating components capable of withstanding repeated stress changes. Generally, each loading cycle is characterized by documenting the peak stress level in conjunction with an R-value [30].

$$R = \frac{\sigma_{min}}{\sigma_{max}} \quad (8)$$

Where, (σ_{min}) denote the lowest cyclic stress value, while (σ_{max}) represents the highest cyclic stress value as shown in Figure 6.

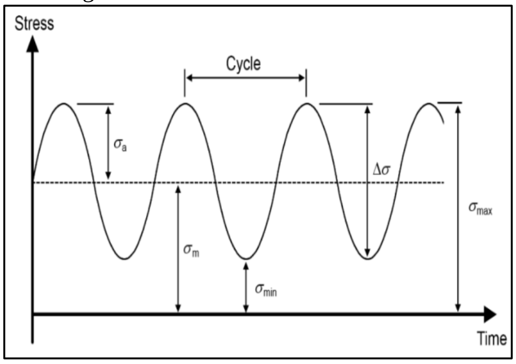

Figure 6. illustrates the stress in a fully reversed manner (R=-1)

The testing was performed with a HI-TECH HSM20 device [31]. The experiments measured the number of failure cycles for the composite specimen and the maximum displacements observed during the tests as shown in Figure 7. During fatigue testing under fully reversed sine wave cyclic bending conditions (with a stress ratio of R = -1), the sample remained within its elastic limits. A total of five fatigue bending samples were adopted for each case. However, due to the cyclic nature of this stress, it led to material fatigue, the initiation of cracks, and eventual failure after a specific number of cycles. Grasping the number of operational cycles for the samples is essential. This knowledge aids in setting suitable application limits for the composite material and predicting its expected longevity in its designated use.

Figure 7. Bending-alternating fatigue device HSM20

4. Results and Discussion

The research examined the outcomes of experimental fatigue assessments on composite materials, specifically highlighting how varying the weight percentages of silicon dioxide nanoparticles (0.16%, 0.20%, and 0.24%) influenced fatigue life across three different stress levels. The Basquin equation was employed to characterize the fatigue response of the composite material under these stresses. Additionally, the investigation explored the microstructure of the composite and the arrangement of nanoparticles within it, utilizing a Vega Tescan scanning electron microscope (SEM) for analysis.

4.1. The Impact of Silicon Dioxide Nanopowder Weight on Fatigue Life

The figure provided illustrates the investigation of fatigue behavior in a composite material containing a 55% weight fraction, enhanced with 0.16% by weight of Nano Silicon Dioxide (SiO_2). In Figure 8, the relationship between the number of fatigue cycles and the stress amplitude is depicted, showing an inverse relationship between stress levels and the lifespan of fatigue.

As the applied stress rises, the number of cycles that the material can endure prior to failure diminishes. This pattern aligns with the conventional S-N curve (Stress vs. Cycles) seen in fatigue research. The maximum stress level evaluated in this study resulted in heightened concentration of the stress within the microstructure of the composite material, which is composed of carbon fibers and polyester reinforced with nano-silicon dioxide particles. This elevation in stress leads to localized concentrations of stress, generating specific areas where stress is heightened. As a result, this intensification causes increased movement of dislocations within the material. Ultimately, the heightened movement of dislocations may result in the failure of the composite. Figure 8 demonstrates the relationship between stress amplitude and the number of cycles, known as the S-N curve, for a composite material containing a reinforcing component at a weight fraction of 55% along with 0.16% Nano Silicon Dioxide (SiO_2). This material was tested at a thickness of 7 mm. The experimental results at an additive concentration of 0.16% show that increasing the stress rate by 14.03% at the first level leads to a 12.43% decrease in the number of cycles. At the second level, a similar increase in the stress rate results in an 11.34% reduction in the average number of cycles. At the third Level, reducing the stress rate by the same percentage also decreases the number of cycles by 9.4%. The accompanying figure illustrates a downward slope, which is a characteristic feature of S-N curves; this indicates that lower strain amplitudes are associated with a longer fatigue life. The addition of nano-SiO_2 is expected to improve fatigue resistance by hindering crack growth through particle reinforcement. This enhancement is due to more effective interfacial bonding between the matrix and the filler, which delays the onset of cracks. Additionally, a more even distribution of stress reduces localized damage. The significant weight proportion of 55% carbon fiber (which may originate from fibers or another reinforcing material) boosts stiffness and strength, thereby enhancing the composite's ability to bear loads. The sample's thickness of 7 mm could influence stress distribution and heat dissipation during cyclic loading, as thicker specimens generally have a lower surface-to-volume ratio, potentially postponing crack formation from surface flaws. Three distinct stress levels were utilized on the sample throughout various fatigue tests by modifying the fatigue duration while keeping a consistent weight ratio of the nano-additive. In summary, the composite demonstrates improved fatigue performance attributed to the synergistic interactions of nano-SiO_2 and a considerable amount of the reinforcing phase. The S-N curve aligns with the expected behavior for engineered composites, indicating that nano-additives enhance durability during cyclic loading.

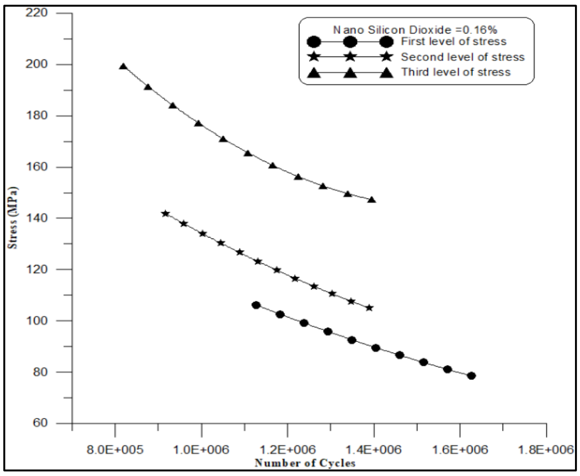

Figure 8. Amplitude stress vs. Number of cycles for a composite with 55% weight fraction and 0.16% Nano SiO_2 at 7 mm thickness

Table 1 presents the basic equation for the fatigue behavior of a composite material reinforced with 0.16% Nano Silicon Dioxide particles. This composite sample consists of a polyester matrix and carbon fiber, with a fiber weight percentage of 55%. The experimental results from fatigue tests conducted at three different stress levels are also shown in the table. It outlines the equation that describes how the material behaves when subjected to fatigue stress under three levels of cyclic load applied to the test sample

Table 1. Fundamental equation for carbon fiber fatigue behavior at 55% weight fraction with 0.16 Nano SiO_2 under varying stress levels.

Type of Stress	Stresses (MPa)	Basquin Equation, $\boldsymbol{\sigma_a = a.N_f^b}$	R^2
First stress level	78.43, 92.98, and 106.16	$\sigma_a = 138.54 * N_f^{-0.1024}$	0.992
Second stress level	87.65, 103.91, and 118.64	$\sigma_a = 132{,}52 * N_f^{-0.0959}$	0.994
Third stress level	98.59, 116.89, and 133.45	$\sigma_a = 129.15 * N_f^{-0.0922}$	0.992

Figure 9 illustrates the relationship between stress amplitude and the number of cycles, known as the S-N curve, for a composite material containing a reinforcing component at a weight fraction of 55% and an additive of 0.2% Nano Silicon Dioxide (SiO_2). The relationship between stress amplitude and the number of cycles is displayed, as three levels of stress were applied to the composite sample during the fatigue tests. The experimental findings show that an increase in stress amplitude leads to a reduction in the number of life cycles. For example, when the average stress is elevated by 14.03% from the first to the second level, the life cycles for the sample with a 0.2% additive decrease by approximately 12.43%. Likewise, increasing the average stress at the second level results in an 11.34% drop in the cycle count. Furthermore, with the same ratio of stress increase, the cycle count diminishes by 9.35%.

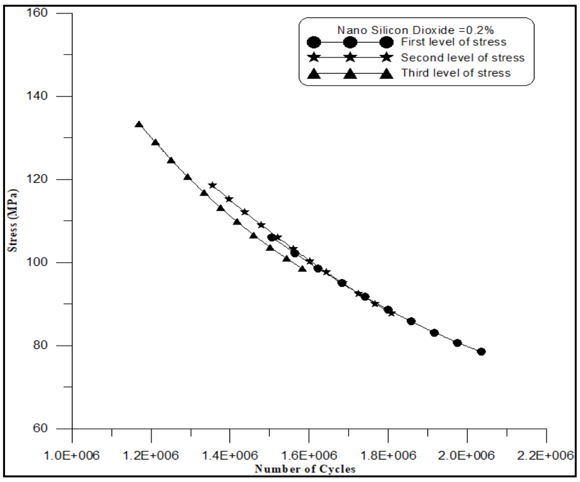

Figure 9. Amplitude stress vs. Number of cycles for a composite with 55% weight fraction and 0.2% Nano SiO_2 at 7 mm thickness

Table 2 displays the primary equation describing the fatigue properties of a composite material that includes 0.2% nano-silicon dioxide particles. This composite is composed of a polyester matrix reinforced with carbon fiber, where the fiber accounts for 55% of the overall weight. Additionally, the table provides the results from fatigue testing conducted at three varying stress levels. It illustrates Basquin's equation, which defines the material's behavior under fatigue stress when exposed to three different levels of cyclic loading applied to the specimen enhanced with 0.2% nano-silicon dioxide.

Table 2. Fundamental equation for carbon fiber fatigue behavior at 55% weight fraction with 0.2 Nano SiO_2 under varying stress levels.

Type of Stress	Stresses (MPa)	Basquin Equation, $\boldsymbol{\sigma_a = a.N_f^b}$	R^2
First Stress level	78.43, 92.98, and 106.16	$\sigma_a = 171.56 * N_f^{-0.1057}$	0.993
Second stress level	87.65, 103.91, and 118.64	$\sigma_a = 159.31 * N_f^{-0.095}$	0.992
Third stress level	98.59, 116.89, and 133.45	$\sigma_a = 148.69 * N_f^{-0.085}$	0.99

The relationship between amplitude stress and the number of cycles, illustrated in Figure 10, represents the S-N curve for a composite material comprising 55% weight-percent of a reinforcing component when adding 0.24% nano-silicon dioxide (SiO_2). This material was tested using a sample that is 7 mm thick. The experimental results from fatigue tests on the sample reinforced with 0.24% nanoparticles indicated that increasing the stress ratio by 14.03% at the first level led to a reduction in the number of fatigue cycles by 7.5%. Additionally, at the second level of fatigue, the cycles decreased by 8.3%. Furthermore, at the third stress level, the number of fatigue cycles decreased by 9.4%. The minimal variation in the number of fatigue cycles highlights the improved resistance to failure properties associated with the addition of 0.24% nano-silicon dioxide (SiO_2) as the stress levels increase. The S-N curve depicts a relationship where higher stress corresponds to fewer cycles, meaning that as stress rises, the number of fatigue cycles diminishes. Experimental findings for a composite sample reinforced with 0.24% CFRP, which showed a fracture weight of 55% CFRP, revealed that the S-N curves began to converge as the stress levels increased. This convergence is linked to enhanced failure resistance due to the incorporation of nanoparticles. Nonetheless, the S-N curve also showed a pattern indicating a reduction in the number of fatigue cycles as the applied stress levels increased. Table 3 presents the Basquin equations for each stress level, illustrating the behavior of the specimen under fatigue loading at three different applied stress amplitudes.

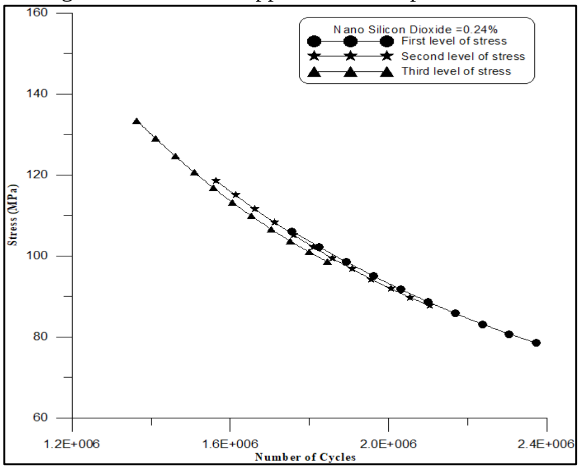

Figure 10. Amplitude stress vs. Number of cycles for a composite with 55% weight fraction and 0.24% Nano SiO_2 at 7 mm thickness.

Table 3. Fundamental equation for carbon fiber fatigue behavior at 55% weight fraction with 0.24 Nano SiO_2 under varying stress levels.

Type of Stress	Stresses (MPa)	Basquin Equation, $\boldsymbol{\sigma_a = a.N_f^b}$	R^2
First stress level	78.43, 92.98, and 106.16	$\sigma_a = 188.45 * N_f^{-0.1072}$	0.99
Second stress level	87.65, 103.91, and 118.64	$\sigma_a = 170.21 * N_f^{-0.0924}$	0.98
Third stress level	98.59, 116.89, and 133.45	$\sigma_a = 164.89 * N_f^{-0.0878}$	0.96

Experimental results show that increasing the level of applied stress leads to a reduction in the number of fatigue cycles. This is due to the fact that increased stress rates accelerate crack propagation in the specimen and lead to the development of dislocations within the composite material. These results align with the observations made by Borrego et al. [32], who stated that lowering stress levels can prolong fatigue life. This effect can be linked to varying levels of stiffness degradation. The Basquin Model demonstrated a strong correlation with the experimental results, as indicated by the R-squared values (R^2) at three stress levels.

4.2. SEM Images of Composite Fatigue Specimens

Composite materials are renowned for their remarkable strength-to-weight ratio and versatility, making them vital in sectors like aerospace, automotive, and renewable energy. However, their susceptibility to fatigue from repetitive loading poses significant challenges, necessitating advanced analysis to predict and mitigate failure risks. Scanning Electron Microscopy (SEM) has emerged as a key technique for uncovering microstructural damage processes in fatigued composites, offering outstanding resolution and depth of field.

Figure 11 shows a comparison of SEM images using a Vega Tescan at 2 kV, which enables the analysis of properties between 1 and 5 microns. A voltage of 20 kV was used, suitable for imaging carbon fibers for three samples with different silicon dioxide particle concentrations, at working distances of 13.27 mm, 14.51 mm, and 14.28 mm, respectively. The images showed good homogeneity in the distribution of nanoparticles, with a regular finish of carbon fibers and polyester. Furthermore, the images indicated that the nanoparticles adhered to the carbon fibers, with no gaps in the composite structure. Scanning Electron Microscopy (SEM) images revealed that the average grain size of the composite sample with 0.16% Nano SiO_2 was 28.2 ± 3.5 nm. For the sample containing 0.20% SiO_2, the average grain size was equal to 26.7 ± 4.1 nm, while the sample with 0.24% SiO_2 had an average grain size of 27.9 ± 3.8 nm. All images displayed a consistent gray surface at a magnification of 20 microns, indicating homogeneous dispersion. This is caused by the effective mixing process of the composite components, which prevents the formation of clumps in the microstructure. Images 11-a, 11-b, and 11-c show that the nanoparticles are evenly distributed around the carbon fibers (appearing as smooth, rectangular structures), indicating strong interfacial bonding and uniform reinforcement. The incorporation of nanoparticles enhances microstructural bonding, leading to improved stress distribution and load transfer efficiency in the durable carbon fibers. Thus, the images demonstrate a high uniformity in nanoparticle distribution and strong integration between the fibers and the matrix, a significant factor in improving the mechanical and thermal performance of advanced composite materials.

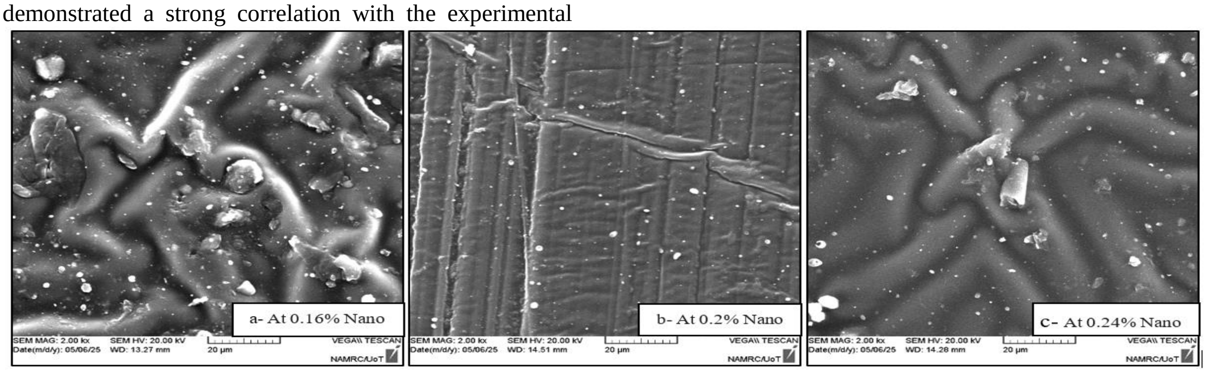

Figure 11. a- At 0.16% Nano, b- At 0.2% Nano, and c- At 0.24% Nano: The SEM images of the composite fatigue samples at 2.0 kV, HV: 20.0 kV, and wavelengths of 13.27 mm, 14.51 mm, and 14.28 mm, respectively.

2. Conclusions

The current research examined the fatigue characteristics of polyester composite plates reinforced with 55% carbon fiber and varying amounts of nano silicon dioxide (SiO_2) additives (0.16%, 0.2%, and 0.24%). The main results are as follows:

- Enhancement of fatigue resilience through Nano SiO_2 where an increase in the concentration of nano SiO_2 resulted in a longer fatigue lifespan of the composite material. At the 0.24% additive level, a stress ratio increase of 14.03% resulted in minor reductions in fatigue cycles (7.5%, 8.3%, and 9.4% across three stress levels), demonstrating better crack prevention and stress distribution compared to lower concentrations.
- Effect of Stress Amplitude: Elevated stress levels consistently resulted in fewer cycles until failure, consistent with the expected S-N curve behavior. Where the stress increase of 14.03% with a 0.2% additive resulted in a reduction of cycles by 12.43%, 11.34%, and 9.35% at different stress levels.
- Combined Reinforcement Effects: The incorporation of 55% carbon fiber along with nano SiO_2 enhanced interfacial bonding, rigidity, and capacity to bear loads.
- The 7 mm thickness of the sample helped to minimize the surface-initiated cracks by improving the distribution of stress effectively, so it is optimal for marine applications due to reduced surface-initiated cracks.
- Validation of Basquin's Equation: Predictions of fatigue life using Basquin's law showed a significant alignment depending on experimental findings.
- The equations related to varying stress levels and additive concentrations are used to describe fatigue behavior. Significantly, the inclusion of nano SiO_2 led to a reduction in the exponent (b), suggesting a slower rate of degradation.
- The scanning electron microscope (SEM) analysis indicates that the SiO_2 nanoparticles are homogeneously distributed throughout the material, contributing to preventing crack progression by enhancing stress redistribution and strengthening the bond between the matrix and fibers.

The distinctive properties of nano-SiO_2-reinforced composites have become common in many industrial applications, especially in the aerospace and marine sectors, and have therefore become the focus of numerous studies to improve their properties.

Acknowledgement

We extend our gratitude to the University of Technology, especially the Electromechanical Collage, for assistance in finalizing this study.

References

[1] Kaiyan Li, Guanyi Gao, Guoqing Feng, Yaozhong Fan, and Yiyang Han, "Investigation of Fatigue Assessment Method for Glass Fiber Reinforced Composite Hull Structures Based on Stiffness Degradation", J. Mar.Sci. Eng., Vol.12, No.12, 2324, 2024, pp. 1-18; https://doi.org/10.3390/jmse12122324.

[2] Gao X, Umair M, Nawab Y, Latif Z, Ahmad S, Siddique A, Yang H., "Mode I Fatigue of Fibre Reinforced Polymeric Composites: A Review", Polymers (Basel), Vol.14, No. 4558, 2022, pp.1-29:4558, doi:10.3390/polym14214558.

[3] Ferdous, W., Manalo, A., Yu, P.; Salih, C., Abousnina, R., Heyer, T., Schubel, P., "Tensile Fatigue Behavior of Polyester and Vinyl Ester Based GFRP Laminates—A Comparative Evaluation", Polymers, Vol.13, No. 386, 2021, pp. 1-10, https://doi.org/10.3390/polym13030386.

[4] Mohammed Fuseini, Moustafa Mahmoud Yousry Zaghloul, Djibrine Abakar, Mai Mahmoud Yousry Zaghloul, "Review of Epoxy Nano-Filled Hybrid Nanocomposite Coatings for Tribological Applications", FlatChem, Vol. 49, No.100768, 2024, pp. 1-40, https://doi.org/10.1016/j.flatc.2024.100768.

[5] Feng JG, Safaei B, Qin ZY, Chu FL., "Nature-Inspired Energy Dissipation Sandwich Composites Reinforced with High-Friction Grapheme", Compos Sci Technol.,Vol. 233, No. 109925, 2023, https://doi.org/10.1016/j.compscitech.2023.109925.

[6] Feng JG, Safaei B, Qin ZY, Chu FL, Scarpa F., "Bio-Inspired Metallic Cellular Material with Extraordinary Energy Dissipation Capability", Chem Eng J., Vol.475, No.146382, 2023, https://doi.org/10.1016/j.cej.2023.146382.

[7] Hui Li, Yang Liu, Haiyang Zhang, Zhaoye Qin, Zhaoyang Wang, Yichen Deng, Jian Xiong, Xiangping Wang, Sung Kyu Ha, "Amplitude-dependent Damping Characteristics of All-Composite Sandwich Plates with A Foam-Filled Hexagon Honeycomb Core", Mech Syst Signal Process. Vol. 186, No.109845, 2023,https://doi.org/10.1016/j.ymssp.2022.109845.

[8] Zhou S, Wu X., "Fatigue life prediction of composite laminates by fatigue master curves", J Mater Res Technol.;Vol. 8, No.6, 2019, pp. 6094-6105, https://doi.org/10.1016/j.jmrt.2019.10.003.

[9] Das AD, Mannoni G, Früh AE, Orsi D, Pinalli R, Dalcanale E., "Damage-Reporting Carbon Fiber Epoxy Composites", Appl Polym Mater., Vol.1, No.11, 2019, pp. 2990–2997, https://doi.org/10.1021/acsapm.9b00694.

[10] Vassilopoulos AP., "The history of fiber-reinforced polymer composite laminate fatigue", Int J Fatigue., Vol.134, No.105512, 2020, https://doi.org/10.1016/j.ijfatigue.2020.105512.

[11] Safaei B, Onyibo EC, Hurdoganoglu D., "Thermal Buckling and Bending Analyses of Carbon Foam Beams Sandwiched by Composite Faces under Axial Compression", Facta Univ Ser: Mech Eng., Vol. 20, No. 3, 2022, pp.589–615, https://doi.org/10.22190/FUME220404027S.

[12] Safaei B, Onyibo EC, Goren M, Kotrasova K, Yang ZC, Arman S, Asmael, M., "Free Vibration Investigation on Rve of Proposed Honeycomb Sandwich Beam and Material Selection Optimization", Facta Univ Ser: Mech Eng., Vol. 21, No.1, 2023, pp. 31–50, https://doi.org/10.22190/FUME220806042S

[13] Safaei B, Onyibo EC, Hurdoganoglu D., "Effect of Static and Harmonic Loading on the Honeycomb Sandwich Beam by Using Finite Element Method", Facta Univ Ser: Mech Eng., Vol.20, No.2: 20222, pp.79–306, https://doi.org/10.22190/FUME220201009S.

[14] Chawla N, Tur YK, Holmes JW, Barber JR, Szweda A., "High-Frequency Fatigue Behavior of Woven-Fiber-Fabric-Reinforced Polymerderived Ceramic-Matrix Composites", J Am Ceram Soc., Vol.81, No.5, pp.1221–1230, 1998, https://doi.org/10.1111/j.1151-2916.1998.tb02472.x.

[15] Kocsis J.K., Mahmood H., Pegoretti A., "Recent Advances in Fiber/Matrix Interphase Engineering For Polymer Composites", Prog. Mater. Sci., Vol. 73, 2015, pp.1- 43, https://doi.org/10.1016/j.pmatsci.2015.02.003.

[16] Samuel, J.J.J., Ramadoss, R., Gunasekaran, K.N., Logesh, K., Gnanaraj, S.J.P., Munaf, A.A., "Studies on mechanical

properties and characterization of carbon fiber reinforced hybrid composite for aerospace application”, Mater. Today, Vol. 47, 2021, pp.1-6, https://doi.org/10.1016/j.matpr.2021.05.304.

[17] Muhammad, A., Rahman, M.R., Baini, R., Bakri, M.K.B., “Applications of sustainable polymer composites in automobile and aerospace industry”, Advances in Sustainable Polymer Composites, 2021, pp. 185-207. https://doi.org/10.1016/B978-0-12-820338-5.00008-4

[18] Mansor, M.R., Nurfaizey, A.H.,Tamaldin, N.; Nordin, M.N.A., “Natural Fiber Polymer Composites: Utilization in Aerospace Engineering”, Biomass, Biopolymer Based Materials, and Bioenergy, 2019, pp. 230-234.https://doi.org/10.1016/B978-0-08-102426-3.00011-4.

[19] Adib Bin Rashid, Mahima Haque, S M Mohaimenul Islam, K.M. Rafi Uddin Labib, “Nanotechnology-Enhanced Fiber-Reinforced Polymer Composites: Recent Advancements on Processing Techniques and Applications, Heliyon, Vol. 10, Issue 2, 2024, https://doi.org/10.1016/j.heliyon.2024.e24692.

[20] Zhang Y., Wang H., & Liu J., “Enhancing Fatigue Resistance in Carbon Fiber Composites through Nano-Filler Incorporation: An Experimental Study”, Composite Structures, Vol. 248, No.3, 2020, 112556, http://dx.doi.org/10.1016/j.compscitech.2017.06.018.

[21] Raed Hwayyin, S.K. Hussien, and A.S. Ameed, “The Effect of Nano-Silica on the Mechanical Properties of Composite Polyester/Carbon Fibers”, J. Mech. Eng. Sci., Vol. 16, No. 4, pp. 9175–9186, 2022, doi: 10.15282/jmes.16.4.2022.03.0727.

[22] R N. Hwyyin, AS Ameed, ZK Hantoosh, “A Study on the Effects of Salt Concentration Environment on the Mechanical Properties of Polyester and Composite Materials”, Eng. & Tech. Journal, Vol. 31, Part (A), No.8, 2013, pp. 1459-1473, http://dx.doi.org/10.6084/m9.figshare.19291892.

[23] Azhar Sabah Ameed, Raed Naeem Hwayyin, Abbas Khammas Hussien, “The Effect of Multi-Walled Carbon Nanotubes on the Mechanical Properties of Composite Material Carbon Fibers/Polyester Used in Ships Hulls”, Jordan Journal of Mechanical and Industrial Engineering, Vol. 17, No. 3, 2023, pp. 357– 366 https://doi.org/10.59038/jjmie/170304.

[24] Raed N. Hwayyin, Azhar S. Ameed, Ahmed S. Hamood, “The Effects of Salt Concentration on the Impact Strength of Composite Material”, Proceedings of the 2nd International Conference on Petroleum Technology and Petrochemicals - 2021: ICPTP2021 Conference Proceedings, Baghdad, Iraq, 2021.

[25] Lai, Jiamei, Xia, Yousheng, Huang, Zhichao, Liu, Bangxiong, Mo, Mingzhi and Yu, Jiren, "Fatigue Life Prediction Method of Carbon Fiber-Reinforced Composites", e-Polymers, Vol. 24, No. 1, 2024, pp. 1-18. https://doi.org/10.1515/epoly-2023-0150

[26] Abdalla F. H., Megat M. H., Sapuan M. S. and B. B. Sahari, “Determination of Volume Fraction Values of Filament Wound Glass and Carbon Fiber Reinforced Composites”, ARPN Journal of Engineering and AppliedSciences, ISSN 1819-6608, Vol.3, No. 4, 2008, pp.7-11, http://psasir.upm.edu. my/ id/eprint/13969/.

[27] Ramesh Talreja, R. Fatigue of Composite Materials. 2nd ed. Elsevier. Texas A&M University, Texas 77843-3141; 1981, DOI:10.1007/978-3-7091-2544-1_6.

[28] Duan QQ, Pang JC, Zhang Pl, Li SX and Zhang ZF, “Quantitative Relations between S-N Curve Parameters and Tensile Strength for Two Steels: AISI 4340 and SCM 435”, Research & Reviews: Journal of Material Science, Volume 6, Issue 1, January, 2018, pp.1-16, DOI: 10.4172/2321-6212.1000207.

[29] Liu, J., Jiang, Y., Li, K.; Wang, Y., “Optimum Selection Analysis of Composite Cap Cone”, Eng. Proc. , Vol. 80, No. 10, 2024, pp.1-11, https://doi.org/10.3390/engproc2024080010.

[30] N. Wahl, D. Samborsky, J. Mandell, and D. Cairns, “Effects of Modeling Assumptions on the Accuracy of Spectrum Fatigue Lifetime,” Aiaa, Vol. 23, , 2002, pp. 1–9, https://doi.org/10.2514/6.2002-23.

[31] N. P. Roberts, and Nigel R. Hart. Alternating Bending Fatigue Machine (HSM20). Instruction Manual. Hi-Tech Ltd. UK., 2001.

[32]L.P. Borrego, J.D.M. Costa, J.A.M. Ferreira, H. Silva, “Fatigue Behaviour of Glass Fibre Reinforced Epoxy Composites Enhanced with Nanoparticles”, Composites Part B: Engineering, Vol. 62, 2014, pp. 65-72, https://doi.org/10.1016/j.compositesb.2014.02.016.