Tikrit Journal of Engineering Sciences (2023) 30 (2): 21-30

DOI: http://doi.org/10.25130/tjes.30.2.3

IRAQI Academic Scientific Journals

ISSN: 1813-162X (Print); 2312-7589 (Online)

Tikrit Journal of Engineering Sciences

available online at: http://www.tj-es.com

TJES Tikrit Journal of Engineering Sciences

College of Engineering

Study the Mechanical Properties and Fatigue Effect of Multilayer Woven E-Glass/Epoxy Composite under Constant and Variable Loading

Saif-Aldeen Ghafel * [a], *Nasri S. M. Namer* [b], *Abduljabar H. Ali* [c]

a Material Engineering Technology Department, Engineering Technical College, Baghdad, Iraq.

b Engineering Mechanics Department, Middle Technical University, Iraq.

c Biomedical Engineering Department, Al-Khwarizmi College of Engineering, University of Baghdad, Iraq.

Keywords:

E-Glass/Epoxy Composite; Fatigue Effect; Multi-Layer; Variable Loading; Woven

ARTICLE INFO

Article history:

Received	01 Mar. 2023
Received in revised form	11 Apr. 2023
Final Proofreading	17 Apr. 2023
Accepted	22 Apr. 2023
Available online	03 May. 2023

Citation: Ghafel S, Namer NSM, Ali AH. Study the Mechanical Properties and Fatigue Effect of Multilayer Woven E-Glass/Epoxy Composite under Constant and Variable Loading. *Tikrit Journal of Engineering Sciences* 2023; 30(2): 21-30.

http://doi.org/10.25130/tjes.30.2.3

Corresponding author:

Saif Aldeen Ghafel

Material Engineering Technology Department, Engineering Technical College, Baghdad, Iraq.

Abstract: The present work studies the effect of adding woven E-glass fibers [0°/90°], 16 layers with 50% weight fraction to pure epoxy (matrix) on fatigue behavior under constant and variable loadings. The CNC water jet cutting machine was used to cut the composite samples with five fiber direction angles, such as (0°, 5°, 15°, 30°, and 45°). The tensile test was used to determine the composite material's mechanical properties. The results showed that the composite material with 5° of fiber direction had the highest ultimate tensile stress, i.e., 353 MPa, and the highest Young's Modulus, i.e., 11940 MPa, compared to other samples with angles of (0°, 15°, 30°, 45°) of fiber direction. The sample with 5° angle was adopted in constant and variable fatigue loading tests. The fatigue test results under constant loading showed a 24.8 times fatigue strength improvement for composite material at 107 cycles compared to pure epoxy. The fatigue test under variable loading was conducted with two types of sequence loading program tests at a constant number of cycles at each stress level: high-low sequence loading with stress of 170-130 MPa with 10,000 and 20,000 cycles for each stress level and low-high sequence loading with stress 130-170 MPa with 10,000 and 20,000 cycle for each stress level loading and so on to failure. The results showed that the fatigue life under high-low sequence loading for both 10,000 and 20,000 cycles was less than that of the low-high sequence loading. Also, the results showed that Miner's rules were safe to calculate the damage of composite material used in this work where the damage was above one (D > 1).

دراسة الخواص الميكانيكية وتأثير الكلال للمادة المركبة المكونة من عدة طبقات من الالياف الزجاجية والايبوكسي تحت تأثير حمل ثابت ومتغير

سيف الدين غافل[1]، نصري نمير[2], عبدالجبار حسين علي[3]
[1] قسم تكنولوجيا هندسة المواد، كلية الهندسة التقنية، بغداد، العراق.
[2] الميكانيكا الهندسية، الجامعة التقنية الوسطى، بغداد، العراق.
[3] قسم الهندسة الطبية الحيوية، كلية الخوارزمي للهندسة، جامعة بغداد، العراق.

الخلاصة

يدرس البحث الحالي تأثير إضافة طبقات من الألياف الزجاجية (0° / 90°)، 16 طبقة إلى إيبوكسي نقي وبنسبة وزنية 50% على سلوك الكلال تحت حمل ثابت وحمل متغير. تم استخدام آلة القطع بنفث الماء CNC لقطع العينات المركبة بخمس زوايا لاتجاه الألياف (0°، 5°، 15°، 30°، 45°). تم اختبار الشد لتحديد الخواص الميكانيكية للمادة المركبة. أظهرت النتائج أن المادة المركبة ذات اتجاه الألياف [5°] لديها أعلى إجهاد شد (353 ميكا باسكال) وأعلى معامل مرونة (1194 ميكا باسكال) مقارنة بالعينات الأخرى ذات الزوايا [0°، 15°، 30°، 45°] لاتجاه الألياف. تم اعتماد العينة بزاوية (5°) في اختبار الكلال عند اجهاد ثابت واجهاد متغير. أظهرت النتائج في اختبار الكلال تحت الحمل الثابت تحسن في مقاومة الكلال للمواد المركبة عند 107 دورة (24.8 مرة) مقارنة مع الايبوكسي النقي. كذلك تم إجراء اختبار الكلال تحت تأثير حمل متغير باستخدام برنامجي اختبار تحميل متسلسل مع عدد ثابت من الدورات عند كل مستوى إجهاد، الأول تحميل متسلسل عالي-واطئ عند اجهاد 170-130 ميكا باسكال مع 10000 دورة عند كل مستوى إجهاد وهكذا الى حصول حالة الفشل، و20000 دورة عند مستوى كل اجهاد الى حصول حالة الفشل والثاني تحميل متسلسل واطئ-عالي عند اجهاد 130-170 ميكا باسكال مع 10000 عند مستوى كل اجهاد وهكذا الى حصول حالة الفشل و20000 دورة لكل مستوى اجهاد وهكذا إلى حصول الفشل. أظهرت النتائج أن عمر الكلال في ظل التحميل المتسلسل عالي-واطئ لكل من 10000 و20000 دورة كان أقل مقارنة بعمر الكلال عند التحميل المتسلسل واطئ-عالي. كما أظهرت النتائج أن استخدام قاعدة ما ينر لحساب تراكم الضرر للمادة المركبة التي استخدمت في البحث امنة حيث كان حساب تراكم الضرر أكبر من واحد ($D < 1$).

الكلمات الدالة: تأثير الكلال، مركب الالياف الزجاجية/الايبوكسي، متعدد الطبقات، منسوج، تحميل ثابت، تحميل متغير.

1.INTRODUCTION

Fatigue is the deterioration of a material's qualities due to applying various loads over time. While fatigue failure refers to the subsequent failure [1, 2]. As a crucial component of mechanical design, fatigue has been widely encountered by engineers. Most of the machine's components are subject to fluctuating loads, whereas just tiny portions are subject to constant loads. Fatigue failure was caused by cyclic stress much below the yield strength of the material. The fatigue failure occurs under loads with constant amplitude, defined as the stress during periodic loading with constant amplitude [3, 4]. The fatigue test measures a material's resistance to cyclic loading conditions. The material is selected to meet or exceed the anticipated service loads in fatigue testing applications. The fatigue test repeatedly applies tension and compression loads. The objective of a fatigue test is to estimate the lifespan of a material subjected to cyclic loads. The fatigue test measures the maximum load a sample can tolerate for a predetermined number of cycles [1, 5]. The composite materials' fatigue failure process is more complex than metallic materials [6]. Composite materials are anisotropic and inhomogeneous, whereas metals are isotropic and homogeneous. The material's structure affects its fatigue failure behavior under cyclic load [7]. These loadings are repeated forever on the structure throughout operation hours, and the fatigue behavior of these structures is crucial for design endurance [8]. Aerospace, aircraft, and wind turbine blades are continually subjected to cyclic stress resulting in structural degradation. The occurrence of fatigue failure is caused by cyclic loading. Fatigue can be developed when a structure is subjected to a repeated or cyclic load with stress levels below its ultimate tensile strength and ultimate compressive strength. Fatigue is a degradation mechanism that produces irreversible material deterioration as the number of load cycles rises, resulting in load-bearing capacities decreasing. Failure due to fatigue can occur under constant amplitude loads, defined as cyclic loading with constant amplitude and constant primary stress or load, or under various cyclic loading [1, 9]. Cyclic loading types can be identified based on the minimum and maximum stress. It is tension-tension loading (T-T), Tension-compression loading (T-C), Compression-compression loading (C-C), and Torsional twisting loading. The composites' fatigue performance is determined by fiber type, matrix type, stacking sequence, reinforcement structure, loading circumstances, and environmental variables [10, 11]. When composites are susceptible to distinct forms of fatigue failure, then metals, such as a fiber fracture, eliminate the adhesion between the fibers and matrix, preventing the propagation of fractures between layers. Intense cyclical stresses destroy the matrix fracture that originates and spreads within the matrix [8, 12]. Lamon et al. [13] evaluated how the reinforcing design affects woven composites' tensile strength and fatigue behavior. The E-glass/epoxy laminates with a woven layer at [0°/90°] and [∓45] were created using the stacking sequence unidirectional UD - woven - unidirectional UD. The same matrix and fibers were utilized for both plain and twill textiles. The results of the tensile and fatigue tests results showed that the best composite material strength was with woven E-glass fiber/epoxy [0°/90°], two unidirectional layers according to model calculations. Mahboob et al. [14] tested flex fiber and glass fiber reinforcement for fatigue under constant strain amplitude. Four commonly studied flax/epoxy layups ([0°] 16s, [0°/90°] 4s, and [45°] 4s) were evaluated alongside two glass epoxy cross ply configurations ([0°/90°] 3s, [45°] 3s). ([0°/45°/90°/-45°] 2s) Quasi-isotropic. Mechanical characteristics, including stiffness, elasticity, peak stress, and strength, were assessed as possible markers of ongoing damage linked to (SEM) detected microstructure cracking. It was found that the flax samples outperformed glass samples in terms of fatigue endurance due to the strong flexibility of flax fibers. Liu et al. [15] presented experimental results comparing the tensile test and tensile fatigue characteristics of biaxial warp in woven glass fiber composites ($0^{\circ}, 30^{\circ}, 45^{\circ}, and\ 90^{\circ}$) with those of 3D orthogonal woven composite. The stress-strain, S-N, and stiffness degradation curves were acquired using tensile and tension-tension fatigue tests. According to their findings, stress was the highest in the woven glass fiber with [0°]. Khalifah [16] investigated the effects of weariness on behavior, including fatigue strengths, fatigue life, and fatigue limit composites for epoxy resin and E-glass Fiber (2, 4, 6) laminates, and nano clay reinforced with (2%, 4%, and 6%) weight fractions. The (S-N) curve of the samples was examined according to the kind of E-glass, the number of fibers, the number of laminates, and the inclusion of nano clay with a small granular volume. Following water immersion, all specimens exhibited good fatigue resistance, and the brittleness of the epoxy resin was considerably decreased by adding clay**.** Venkatesha [17] investigated the effect of a multilayer stacking sequence of woven bamboo and E-glass fiber with epoxy resin composite under tensile and fatigue tests. (6 layers) of bamboo fiber and (7 layers) of "E-glass fibers." Two sample types were produced by hand lay-up technique with [0°, 90°] and [∓45°], and the maximum tensile strength was applied to the composite samples. The results were used to draw the S/N curve, and [0°, 90°] showed better fatigue strength than [∓45°]. Broer [18] described a technique for predicting the fatigue life of carbon fiber-reinforced epoxy laminates loaded with constant amplitude tension-tension or tension-compression forces. Only state strength and fatigue life data according to traditional stress radio (R = 0.1 or R = -1) were used to establish predictions. Using layups $[45/90/\text{-}45]_{2s}$, $[0/60/\text{-}60]_{2s}$, and $[0/90]_{3s}$, three laminates from the literature were examined. For forecasts of fatigue life with a comparable level of accuracy, the input data was necessary. Therefore, using the provided model to estimate fatigue life at scales comparable to the experimental validation data resulted in a decrease in the experimental effort. The outcome showed fiber orientation $[0/90]_{3s}$ has the best fatigue strength. Round et al. [19] established the fatigue behavior of E-glass/epoxy composite materials subjected to varying stress ratios and plies orientation angles. The specimens were subjected to cyclic tensile testing to determine the stress ratios and stacking sequence ($[0_2/90_2]$ s, $[90_2/0_2]$ s, $[0_3/90]$ s, and $[90_3/0]$s) effects on the fatigue characteristics of E-glass/epoxy. Experimentally performed static analysis was used to determine the stress-strain diagrams, Young's modulus, and the tensile strength for each stacking sequence. This study's outcomes can help select the ideal stacking sequence for providing boundary conditions to attain the highest fatigue life. Mostafa et al. [20] produced woven E-glass/polyester composites with fiber orientations of (0°,15°,30°, and 45°) with different equi-biaxial fabric pretension amounts. Fatigue experiments were conducted to determine the influence of fabric pretension on the fatigue life of the prestressed composite under cyclic loading. To determine the optimal amount of fabric prestressing tension-tension, monotonic quasi-static tensile tests were initially performed on specimens with a fabric pretensioning level of up to 100Mpa. The samples were then subjected to three distinct fatigue tests: prestressed (pristine), prestressed at 50Mpa, and prestressed at 100Mpa (over prestressed). The (S-N) curve relationship indicated that the fabric prestressing approach might be employed to increase the fatigue life of composites in the intermediate and low-stress zones. The study showed that [0°] had the highest fatigue stress resistance. The present research aims to study the fatigue strength improvement for composite material made up of a matrix of polymer (epoxy) reinforced by 16 layers of woven E-glass [0°/90°] with 50% weight fraction under constant amplitude fatigue stress and variable amplitude fatigue stress at room temperature. Also, the study aims to sketch the (S-N) curve and compare the fatigue strength result between the pure epoxy and the composite substances.

2.EXPERIMENTAL WORK

2.1.Materials and Methods

Two types of materials were used, i.e., pure epoxy and composite material. The pure epoxy matrix was prepared by mixing epoxy resin with a hardener in a ratio (2:1) weight fraction in a bowl by using electric stirring for (5 min) at (300 rpm), pouring the contents into a mold (50cm, 50cm, and 3mm) coated with wax, and left the material to dry for (20 days) in room temperature before starting the tests. Sheet pure epoxy is shown in Fig. 1. The composite material was manufactured in a special composite material manufacturing company in China, with special specifications in the form of panels with dimensions of (3mm, 60cm, and 50cm), as shown in Fig. 2. The specifications determined by the researchers were the composite material consisting of woven E-glass fiber/epoxy [0°/90 °], 16 layers with 50% weight fraction, and thickness of 3mm. The composite materials were technically manufactured in a vacuum and free from defects. The material was chemically examined by (DSC, XRD, FTIR, SEM, and microlight microscopy) before cutting the composite material to fiber's angles $[0^{\circ}, 5^{\circ}, 15^{\circ}, 30^{\circ}, and\ 45^{\circ}]$ and starting the mechanical tests.

Fig. 1 Pure Epoxy Sample.

Fig. 2 Composite Material Sample

Table 1 lists the mechanical and physical properties of epoxy resin, Table 2 lists the physical and mechanical properties of E-glass fiber, and Table 3 lists the chemical composition of E-glass fiber. Epoxy resin is a thermosetting polymer class made from monomers containing at least two epoxide groups. The most common epoxy resin is produced from a reaction between epichlorohydrin (ECH) and bisphenol – A (BPA) [22, 23].

Table 1 Mechanical and Physical Properties of Epoxy Resin [21].

Property	Unit	Value	Standard of Test
viscosity 25c	cps	200	ASTM 445
density kg/litre	Kg/litter	1.1	ASTM D4052
flexural strength	MPa	61	DIN 53452
E-modulus	GPa	1.8	DIN 53452
Tensile Strength	MPa	37	ISO 527

Table 2 Mechanical and Physical Properties of E-glass Fiber [22, 23].

Density (g/cm³)	Tensile Strength GPa	Young's Modulus GPa	Elongation %	Coefficient of Thermal Expansion 10^{-7}/°C	Pioson's Ratio
2.58	3.445	72.3	4.8	54	0.2

Table 3 Chemical Composition of E-glass Fiber [21].

SiO_2	MgO	Al_2O_3	CaO	B_2O_3	TiO_2	Na_2O	Fe_2O_3	K_2O	F_2	ZrO_2
52-56	0.4-4	12-15	21-23	4-6	0.2-0.5	0-1	0.2-0.4	Trace	0.2-0.7	0.2-0.5

2.2. Tensile Test

The tensile Specimen test was performed by (ASTM D-638) standardization, as shown in Fig.3.

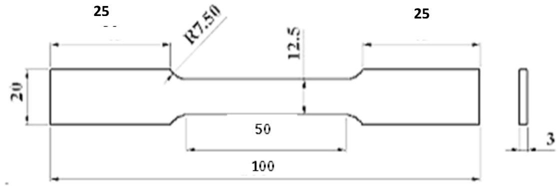


Fig. 3 Schematic of Tensile Specimen According to ASTM D-638 (All Dimensions in mm).

The Specimens were cut to [0°, 5°, 15°, 30°, and 45°] according to fiber orientation with a gauge length of 50mm by a CNC water jet cutting machine. The tensile Specimens are shown in Fig. 4.

Fig. 4 Tensile Test Specimens.

The test was conducted at the University of Technology, the material engineering department, by using Laryee UE XX Series tensile test machine, Fig. 5.

Fig. 5 Tensile Test Machine.

2.3. SNC Water Jet Cutting Machine

The cutting experiments were conducted utilizing a power jet model (flow 45 CNC water jet cutting equipment) available in the local industrial markets, Baghdad, as shown in Fig.6. The cutting with a CNC water jet is an engineering method for cutting samples by using the energy from high speed, high density, and ultra-high-pressure water containing an abrasive slurry is delivered. The target material was removed through erosion. The water was pressurized to (293 MPa) (approximately 4000 atmospheres) and projected from a small-bore nozzle (Ø 0.1mm). The jet velocity was (5-15 $m.sec^{-1}$), and the flow rate was up to (75$L.min^{-1}$), which produced a force of (5-135N) on the workpiece.

Fig. 6 CNC Water Jet Cutting Machine

2.4.Fatigue Specimens Preparation and Machine Test

This test was conducted using HSM-20 alternating bending fatigue apparatus from high-tech education, Hampshire, UK. The specimens with dimensions of (100, 10, and 3mm) were as designated by the device manufacturer; the test was for comparison between the fiber's reinforcement position and interface or desponding influence on the failure of the specimens and fatigue life prediction of the composite specimens and pure epoxy specimens. The fatigue device depicted in Figs. (7, 8) shows a repeating fatigue device with a composite specimens' dimension.

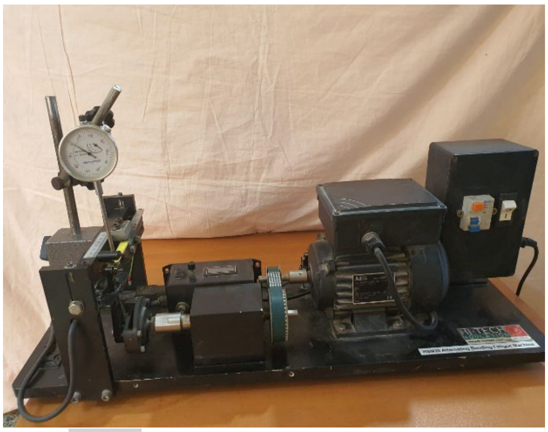


Fig. 7 Alternating Fatigue Machine.

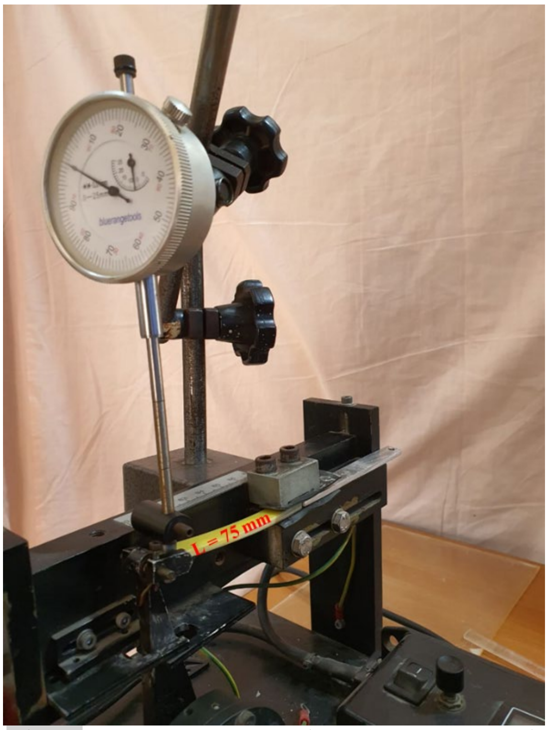


Fig. 8 Fatigue Device with Composite Sample, Cantleaver Length 75 mm.

The goal of using this device was to apply a precise oscillator (alternating) on the specimens installed on one side by applying the load amount (P) caused by the deflection amount (δ) (mm) and then to calculate each stress applied to the sample (σ), sample length (L), and Young's modulus (E). Calculating the deflection (δ) (mm) by using Eq.1. Fig. 9 shows the fatigue sample dimension, and Fig. 10 shows the fatigue sample deflection amount (δ) (mm).

$$\delta = \frac{L^2\sigma}{1.5tE} \quad \textbf{(1)}$$

where:

L = cantilever length (mm)

δ = deflection (mm)

σ = stress (MPa)

t = thickness (mm)

E = Young's modulus (MPa)

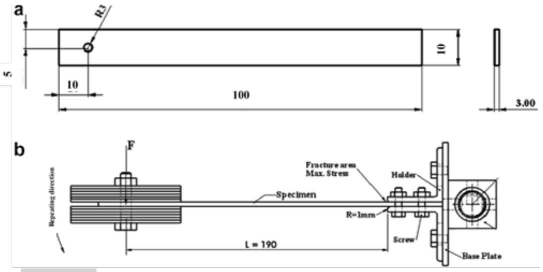


Fig. 9 Fatigue Sample Dimensions (mm).

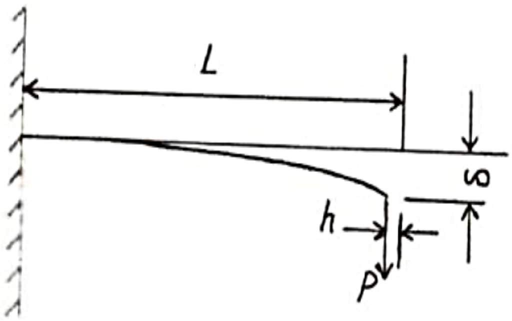
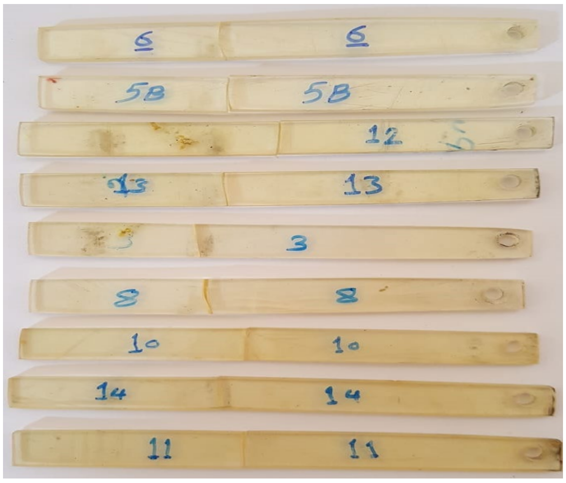


Fig. 10 Illustration of the Fatigue Sample Bending.

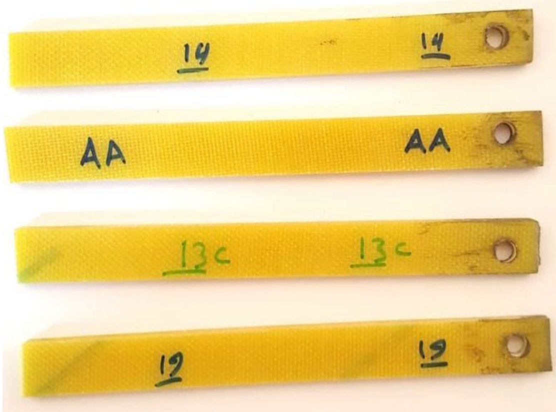
Fig. 11 shows the pure epoxy fatigue specimens, and Fig. 12 shows the composite material fatigue Specimens.

A



B

Fig. 11 Fatigue Specimens of Pure Epoxy; (A) Before Testing, (B) After Testing.



A

B

Fig. 12 Fatigue Specimens of Composite Material; (A) Before Testing, (B) After Testing.

2.5.Scanning Electron Microscopy (SEM)

The test was performed using SEM inspector S-50 produced by FEI/USA Company, available in the College of Applied Sciences/University of Technology. The SEM equipment is shown in Fig. 13.

Fig. 13 Scanning Electron Microscope.

3.RESULTS AND DISCUSSION

3.1.Tensile Test

The tensile test, which is destructive, reveals details on the material's tensile strength and plasticity modulus. To obtain the optimal angle as the direction of the fiber and high strength, the composite material was cut to [0°, 5°, 15°, 30°, and 45°], and the tensile test data was recorded on a computer as load against elongation. Tensile stress was applied to these samples. Table 4 displays the tensile test results.

Table 4 Tensile Test Parameters

Description	Tensile Strength MPa	Young's Modulus MPa
Composite with 0°of fiber direction	324	11126
Composite with 5°of fiber direction	353	11940
Composite with 15°of fiber direction	295	10506
Composite with 30°of fiber direction	256	8463
Composite with 45°of fiber direction	249	7838
Pure Epoxy	30	1178

In comparison to other specimens of composite with fiber direction [0°, 15°, 30°, and 45°], the composite with fiber direction 5 had the best tensile strength. From the tensile test, the composite material sample with the angle of fiber (5°) was adopted in the fatigue test because it had more tensile strength than other samples [0°, 15°, 30°, and 45°].

3.2.Fatigue Test Results under Constant Amplitude Loading

To conduct a fatigue stress investigation, fatigue samples were subjected to continuous amplitude loading with a stress ratio R = -1 at room temperature. In this study, pure specimens with dimensions of (100, 10, and 3 mm) and a composite material comprised of 16 layers of woven E-glass [0°/90°]/epoxy with a weight percentage of 50% were utilized. The pure epoxy fatigue test findings at eight different stress levels are shown in Table 5. Three specimens were tested at each degree of stress, and the average number of cycles until failure was recorded. It can be seen that the number of cycles until failure decreased when the stress rate on the face material increased. The S-N curve was made for pure epoxy specimens. The empirical power law equation with a good coefficient (R^2) showed that the experimental data were well described by the power law shown in Eq. 2. The S-N curve is shown in Fig.14. The fatigue parameter and fatigue strength at 10^7 cycles of pure epoxy are shown in Table 6.

$$\sigma_a = aN_F^b \quad \textbf{(2)}$$

where (σ_a) is the applied stress, (N_F) is the number of cycles to failure, and (a, b) are material constants (fitting parameters).

Table 5 Exiremental Fatigue Testing under Constant Amplitude Loading of Pure Epoxy.

Samples	Stress (MPa)	No. of cycles to failure Specimen -1	No. of cycles to failure Specimen -2	No. of cycles to failure Specimen -3	Average number of cycles to Failure
1	25	1862	1730	1990	1860
2	22.5	3283	3272	3290	3281
3	20	5014	4981	5043	5012
4	17.5	7569	8103	7031	7567
5	15	21160	21131	21192	21161
6	12.5	33363	33512	33210	33361
7	10	60463	60212	60714	60463
8	7.5	109666	110221	109107	109664

Table 6 Fatigue Parameter and Fatigue Strength of Pure Epoxy.

Description	a	B	Equation $\sigma_a = aN_F^b$	Correlation Coefficient R^2	Fatigue strength at 10^7 cycles MPa
Pure	218.3	-0.281	$\sigma_a = 218.3 (N_F)^{-0.281}$	0.9714	2.35

The fatigue test results for a composite material with fibers at a (5°) angle are shown in Table 7 for ten different stress levels. The composite material had the highest ultimate tensile strength (353 MPa) and Young's modulus (11940 MPa). The average number of times it took three samples to break was recorded at each stress level.

Table 7 Experimental Fatigue Testing under Constant Amplitude Loading of Composite Material (5°).

Samples	Stress (MPa)	No. of cycles to failure sample (1)	No. of cycles to failure sample (2)	No. of cycles to failure sample (3)	The average number of cycles to failure
1	230.30	5303	5827	4780	5303
2	210.33	9710	9618	9805	9711
3	190.23	17700	17290	18106	17698
4	170.28	51572	52823	50317	51570
5	150.43	159973	160952	158993	159972
6	130.50	362520	374420	350625	362522
7	110.44	555685	511253	600113	555683
8	100.36	1082927	1127631	1038226	1082928
9	80.32	1570112	1527117	1613110	1570113
10	60.22	3218015	3237415	3198620	3218017

As observed, raising the stress rate on the composite material [5°] reduced the cycle number before breakdown. The S-N curve was created for composite specimens. The empirical power law with a strong correlation coefficient (R^2) demonstrated that the S-N curve and power law remark described the experimental data. The fatigue parameter and fatigue strength for composite material at (10^7) cycles are displayed in Table 8.

Table 8 Fatigue Parameter and Fatigue Strength of Composite Material.

Description	a	B	Equation $\sigma_a = aN_F^b$	Correlation Coefficient (R^2)	Fatigue strength (MPa) at (10^7) cycles	Improvement of fatigue strength %
Composite	1235.5	- 0.187	$\sigma_a = 1235.5 (N_F)^{-0.187}$	0.9321	60.65	96.12

According to the findings of a fatigue test conducted under a constant load, a composite material's fatigue strength improved by 24.8 times over pure epoxy after 10^7 cycles.

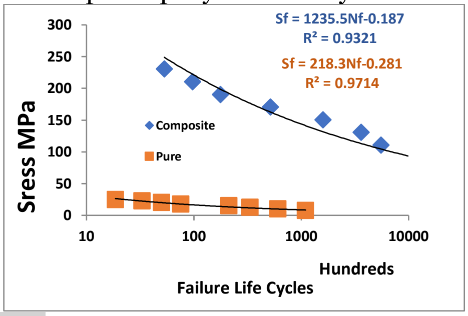


Fig. 14 S-N Curve of Pure Epoxy and Composite Material.

3.3.Fatigue Test Results under Variable Amplitude Loading

The fatigue test was performed under variable loading under the same conditions at room temperature and a stress ratio of R = -1. The fatigue test was performed with two types of sequence loading program tests with a constant number of cycles at each stress level, high-low sequence loading with stress 170-130 MPa with 10,000 and 20,000 cycles for each stress level, and low-high sequence loading with stress 130-170 MPa with 10,000 and 20,000 cycles for each stress level loading and so on to failure. The results revealed that the fatigue life under high-low sequence loading was poorer than that under low-high sequence loading for 10,000 and 20,000 cycles. Table 9 displays the varied fatigue test results.

Table 9 Fatigue Test of Composite Material for Variable Stresses.

	Stress (MPa)	No. of cycles to failure	No. of cycles Stress for each step	Sequence loading
H – L	170 – 130	183117	10000	170 10000 / 130 10000
L – H	130 – 170	210203	10000	130 10000 / 170 10000
H – L	170 – 130	171305	20000	170 20000 / 130 20000
L – H	130 – 170	205423	20000	130 20000 / 170 20000

3.4. Accumulative Fatigue Damage

According to Eq.2 for variable loading, Miner's rule may be used to calculate the potential accumulative fatigue damage [24]. Table 10 displays the experimental findings of the cumulative damage for [5°] composite material using Miner's Rule, as stated in Eq 3.

$$D = \sum_{i=1}^{k} \frac{ni}{Ni} = 1 \text{ OR } \frac{ni}{Ni} + \frac{n2}{N2} + \frac{n3}{N3} + \frac{n4}{N4} + \cdots \frac{ni}{Ni} \quad \textbf{(3)}$$

where:

D = total damage.

k = the number of stress levels.

ni = the number of cycles at stress level i.

Ni = the fatigue life cycles at stress level i.

Demonstrating the experimental findings of the accumulative damage by Miner's Rule is widely used to forecast the fatigue performance of composite materials and metals with some success of High-Low (H-L) loading sequence and Low-High (L-H) loading. The findings demonstrated that the Miners' guidelines could safely calculate the composite damage greater than one (D > 1).

Table 10 Total Damage of Composite Material.

Loading Sequence (MPa)	Damage of Composite Material with[5°] with (10.000) Cycles for each stress level	Damage of Composite Material with[5°] with (20.000) Cycles for each stress level	Miners Damage
H-L (170-130)	1.14	1.61	1
L-H (130-170)	1.22	1.76	1

3.5. Scanning Electron Microscopy (SEM):

The fiber-reinforced composite material samples were analyzed using the scanning electron microscope application (20 to 30,000 X) (SEM). Three composite samples were evaluated without fractures, and three were evaluated with fatigue fractures at high fatigue stress (= 230.3 MPa) and low fatigue stress (= 60.22 MPa). The (SEM) test findings demonstrated that at the fatigue fracture zone of composite material, the fibers were fractured, however, not detached from their location in the matrix, nor they withdrew from the resin region, which implies that the fiber and matrix were compatible. The composite material layers were unseparated from one another. As illustrated in Fig.15, the matrix had no holes or faults. The examination results showed that the fiber diameter was 10.22 µm, and the beam diameter was 78.56 µm, as shown in Fig.16.

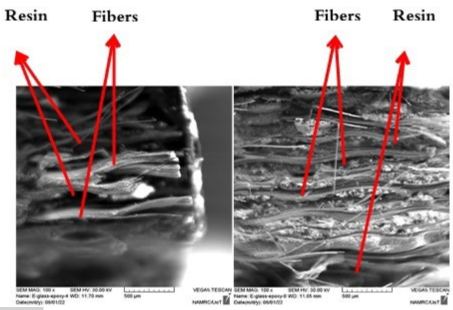


Fig. 15 (SEM) Image for Composite Material at High Fatigue Stress.

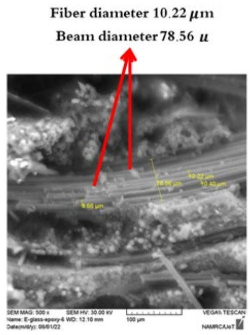


Fig. 16 (SEM) Image for Composite Material with Diameter of Fibers.

4.CONCLUSION

1. The composite material with a fiber orientation of [5°] had the highest ultimate tensile stress compared to samples with fiber orientations of [0°, 15°, 30°, and 45°] due to the tiny variation in fiber orientation in the direction of the applied tension, which absorbed stress and enhanced the material's resistance to applied stress.
2. Compared to pure epoxy (matrix) under constant amplitude stress, the fatigue strength of composite material with E-glass fiber woven at (107 cycles) increased 24.8 times with E-glass fiber.
3. The Miner's rules were safe to be employed for calculating the accumulative damage of composite that was greater than one (D > 1) for both the test High-Low (H-L) and Low-High (L-H) loading sequences.
4. Three composite specimens were examined using (SEM). The examination results revealed that while the fibers were broken, they remained attached to their positions in the matrix and undeparted from the resin region because of the fiber and matrix's excellent compatibility.
5. During the fatigue test, it was discovered that the fiber-matrix bonding prevented matrix fractures from spreading further until full cracks appeared, which finally led to a failure that could virtually be fixed, however, at least the sample would continue to be in one piece.

REFERENCES

[1] Vassilopoulos A. Introduction to the fatigue life prediction of composite materials and structures: past, present and future prospects, in Fatigue life prediction of composites and composite structures. 2010, Elsevier.

[2] Halford G, R. Fatigue and durability of structural materials. 2006, Asm International.

[3] Alalkawi H, Khenyab A, Y, K, and Ali A, H. **Improvement of Mechanical and Fatigue Properties for Aluminum Alloy 7049 by using Nano Composites Technique**. *Al-Khwarizmi Engineering Journal* 2019; **15**(1): 1-9.

[4] Frost N, Marsh K, and Pook L. Metal fatigue. 1974, Oxford ED; Clarendon.

[5] Harris B. Fatigue in composites: science and technology of the fatigue response of fibre-reinforced plastics. 2003, Woodhead Publishing.

[6] Talreja R. **Fatigue of Composite Materials: Damage Mechanisms and Fatigue-Life Diagrams**. *Proceedings of the Royal Society of London. A. Mathematical and Physical Sciences* 1981; **378**(1775): 461-475.

[7] Mousavi Khorasani M, A, Sahebian S, and Zabett A. **Effects of Toughened Polyester on Fatigue Behavior of Glass Fiber Reinforced Polyester Composite for Wind Turbine Blade**. *Polymer Composites* 2021; **42**(1): 70-82.

[8] Curtis P. **The Fatigue Behaviour of Fibrous Composite Materials**. *The Journal of Strain Analysis for Engineering Design* 1989; **24**(4): 235-244.

[9] Laseure N, Schepens I, Micone N, and De Waele W. **Effects of Variable Amplitude Loading on Fatigue Life**. *International Journal of Sustainable Construction and Design* 2015; **6**(3):1-10.

[10] Degrieck J,and Van Paepegem W. **Fatigue Damage Modeling of Fibre-Reinforced Composite Materials**. *Applied Mechanics Reviews* 2001; **54**(4): 279-300.

[11] Rice RC. Fatigue design handbook (Vol. 10). Society of Automotive Engineers 1988.

[12] Taşdemir B. Fatigue and static behavior of curved composite laminates. Master's thesis; 2018, Middle East Technical University.

[13] Lamon F, Maragoni L, Carraro P, and Quaresimin M. **Fatigue Damage Evolution in Woven Composites with Different Architectures**. *International Journal of Fatigue* 2023; **167**: 107365.

[14] Mahboob Z, Fawaz Z, and Bougherara H. **Fatigue Behaviour and Damage Mechanisms under Strain Controlled Cycling: Comparison of Flax-Epoxy and Glass-Epoxy Composites**. *Composites Part A: Applied Science and Manufacturing* 2022, 107008.

[15] Liu C, Wu X, and Gao X. **Comparisons of Tension–Tension Fatigue Behavior between the 3D Orthogonal Woven and Biaxial Warp-Knitted Composites**. *The Journal of The Textile Institute* 2021; **112** (8): 1249-1257.

[16] Khalifah K, M. **Effect of Nano Clay on the Fatigue of Epoxy and Glass Fiber Composites**. *Journal of Physics: Conference Series* 2021; **1829** (1): 012011.

[17] Venkatesha B, Kumar S, P, Saravanan R, and Ishak A. **Tension Fatigue Behaviour of Woven Bamboo and Glass Fiber Reinforced Epoxy Hybrid Composites**. in *IOP Conference Series: Materials Science and Engineering* 2020; **1003** (1): 012087. IOP Publishing.

[18] Broer A. Fatigue life prediction of carbon fibre-reinforced epoxy laminates using a

single SN curve. M.Sc. Thesis; 2018, Delft University of Technology.

[19] Roundi W, El Mahi A, El Gharad A, and Rebière J, L. **Experimental and Numerical Investigation of the Effects of Stacking Sequence and Stress Ratio on Fatigue Damage of Glass/Epoxy Composites**. *Composites Part B: Engineering* 2017; **109**: 64-71.

[20] Mostafa N, H, Ismarrubie Z, Sapuan S, and Sultan M. **Effect of Fabric Biaxial Prestress on the Fatigue of Woven E-Glass/Polyester Composites**. *Materials & Design* 2016; **92**: 579-589.

[21] Mahltig B, and Kyosev Y. Inorganic and composite fibers: production, properties, and applications. 2018.

[22] Sathishkumar T, Satheeshkumar S, and Naveen J. **Glass Fiber-Reinforced Polymer Composites–A Review**. *Journal of Reinforced Plastics and Composites* 2014; **33** (13): 1258-1275.

[23] Al-alkawi J, H, Al-Fattal S, D, and Ali H, A, J. **Fatigue Behavior of Woven Glass Fiber Reinforced Polyester under Variable Temperature**. *Elixir Mechanical Engineering* 2012; **53**: 12045-12050.

[24] Miner, M. A. (March 9, 2021). **Cumulative Damage in Fatigue**. ASME. *Journal of Applied Mechanics* 1945; **12**(3): A159–A164. https://doi.org/10.1115/1.4009458.