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Experimental and Numerical Investigation of Fatigue Behavior of Chopped GFRP Composite Rod under Rotating Bending Load

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ABSTRACT

This work deals with the effect of volume fractions (0, 10, and 20%) on fatigue behavior of unsaturated polyester matrix reinforced with E-glass chopped fiber experimentally and numerically. The composite materials are manufactured by hand layup technique, which is formulated by E-glass fibers immersed in polyester resin. The experimental part includes achieving mechanical tests to estimate the mechanical properties, which represent by tensile, and fatigue tests under completely reversed cyclic loading. The results shows that the tensile strength and elastic modulus of such composite is increased by 44.4% and 60.8% respectively when the volume fraction increased from 0% to 20%, while the fatigue strength of composite reinforced with 20% of volume fraction increased by about 48% compared with that pure polyester. The numerical part includes a finite element method by using ANSYS/16 workbench software to verify experimental data and good agreement has found with maximum overall average error 7%.

KEYWORDS

Chopped glass fiber, composite materials, fatigue, rotating bending load.

INTRODUCTION

Fatigue failure defined as a permanent damage of engineering structures and materials due to dynamic loads. This phenomenon happens when repeated strains act on a material at a stresses that is well below of its static yield stress. Designers of modern military and commercial aerospace vehicles and space launch systems are constantly in use of best materials with lower density, higher strength, stiffness, besides reasonable cost, with high fatigue resistance and more stable at variable temperatures of application [1]. Fiber reinforced composite material are well known by the high properties stiffness/weight and strength/weight ratios than metals; subsequently, they are utilized in various lightweight mechanical applications. The major problem of engineers in many applications, such as power generation and transportation and other application is the prevention of fatigue failure to occur, which is cumulative and unrecoverable in nature. An example, the rotating shaft such as axle cars. The rotation axle leads to create a reversed bending stresses.

These bending stresses are changing from tension to compression. The reverse changing in stress direction can cause fatigue failure which may lead to a suddenly fracture in the material [2, 3]. In the literature, there are few studies regarding the fatigue behavior on the composite structural rod. Such as, Catangiu A. et al [4] investigated bending fatigue behavior of plate made of glass fibers and epoxy resin. It has been found that the fatigue behavior is better when glass fiber in the longitudinal direction of specimens. In addition to that, the fatigue behavior of composite material reinforced with woven glass fiber was investigated by Amelie M. et al to study the effect of fiber orientation under tensile fatigue load. It has concluded that the failure mechanism is depends on the fiber direction such as delamination, cracks in rich-matrix zones and fiber-matrix de-bonding [5]. As well as, D. Pitchaiah et al [6] examined the fatigue life of Chapstan E-glass epoxy and glass fiber epoxy to evaluate the mechanical properties and flexural stiffness. It concluded that the flexural fatigue life of glass fiber polyester epoxy had better result. Rakesh N. et al [7] investigated numerically the fatigue strength of connecting rod made of laminated composite material.

It has found that the laminated composite material has higher safety factor and better fatigue life compared with Aluminum rod. Khashaba U. A. [8] studied rotating bending fatigue of unidirectional glass fiber reinforced polyester composites. The specimens were fabricated in circular form with different volume fraction ratios of fiber. It concluded that the fatigue life at different stress levels is very important, which is need more attention for the application and design of GFRP composite. Mohammed Hussein B. et al [9] investigated the fatigue life of chopped carbon fiber reinforced epoxy resin with variable weight fraction of chopped carbon fibers. It has been found that the increasing the weight fraction of chopped carbon fibers lead to increase the ultimate stress, fatigue strength and fatigue life for all specimen except the specimen with weight fraction 12.5% of carbon chopped fibers due to the de-bonding of reinforced material from the matrix epoxy. Abd Allah M. H. et al [10] investigated the influence of volume fraction of fiber on the fatigue life of GRP rod. The investigation involved three various magnitude of weight fraction which are 0.158, 0.318 and 0.447. It has found that the increasing the magnitude of volume fraction lead to increase the fatigue strength. Selmy A.I. et al [11] conducted flexural fatigue test on unidirectional glass fiber- epoxy with constant volume fraction about 37%.

It’s found that the fatigue life of using unidirectional glass is higher than using random glass in the composite material. Kar N.K et al [12] investigated the fatigue life behavior of hybrid composite rods under tension-tension fatigue load. The hybrid composite rods made of glass fiber shell and unidirectional carbon fiber core. It’s concluded that the specimens which are tested at high stress ratios have better fatigue strength compared with specimens tested with low stress ratios. Ferreira J.A.M. et al [13] investigated the effect of load conditions and lay-up technique on fatigue life of glass fiber reinforced polypropylene composite materials with constant volume fraction of fiber. It’s found that the damage factor E present almost linear behavior with the increase in temperature. Therefore, it can be noticed form past studies, that the fatigue behavior of laminated composite material of fixed beam under rotating fatigue bending load as well as, the effects of glass fiber volume faction on these kind of loading has a little attention. So, the main aim of this investigation is to study numerically and experimentally the influence of glass fiber volume fraction (v_f =0, 10 and 20 %) on fatigue life behavior of chopped GFRP Composite rod under rotating bending load.

MATERIAL FABRICATION

The composite materials used in this study are made of the glass fiber and resin. The reinforcement are E-glass chopped fibers with random orientations [14], while, the resin are unsaturated polyester [15]. Three groups of samples with volume fraction ratios (v_f=0, 10, and 20%) of fiber reinforced/risen composite rods were tested. The specimens was produced by using hand layup technique [16]. The ‘’TOPAZ-1110 TP type’’ was used as unsaturated polyester resin and mixed up with ‘’ Methyl Ethyl Keton Peroxide, MEKP’’ as hardener with weight ratio of 100:2 [17]. And, the chopped glass fiber (Sinoma Jinjing Fiberglass Co., Ltd) used as a reinforcement material [18]. A steel frame of the mould fabricated in the workshop. The volume fraction of fiber (v_f) can be calculated experimentally regarding to the ASTM D2584 [19]. Due to the experimental investigation of fatigue is destructive test so, analytical procedure is preferred to determine volume fraction of fiber. To calculate the fiber volume fraction analytically, the fiber reinforcement in the sample must be calculated. The fibers volume fraction can be determined from the equation as follows [20]:

$$v_f = \frac{1}{1+\left(\frac{1-\varphi}{\varphi}\right)\frac{\rho_f}{\rho_m}} \tag{1}$$

Where: ρ_f : Fiber density in g/cm^3, ρ_m : matrix density in g/cm^3, and φ: weight fraction of fiber

The specimens has been left in the die to cure for 24 hours at room temperature. Then, the specimens put for 3 hours in oven at 80^{o}C in order to attain an adequate curing [21].

EXPERIMENTAL PROCEDURE

Tensile Test

The tensile test samples shown in figure 1 were designed according to the ASTM D628 standard [22]. This test was performed for all specimens with different volume fraction $_{\text{ratios}}$, in 200KN WDW – 200 E III hydraulic test machine and using a constant strain rate of 2 mm/min. For more accuracy three specimens for each composite material are tested to perform the tensile test, and then the average value for each case of composite materials is recorded.

Figure 1. Tensile test samples

Fatigue Test

Fatigue samples were prepared in a suitable dimension to fulfill the specifications and requirement of the fatigue rotating bending machine test that occupied cylindrical specimen [23]. Figure 2 shows the fatigue-testing machine and the dimensions of the specimen. The fatigue specimen's prepared are shown in figure 3 for volume fraction of (0, 10 and 20 %), respectively.

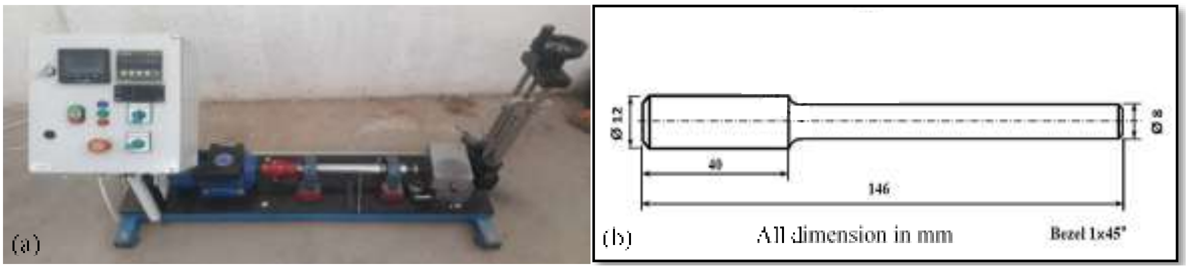

Figure 2. Fatigue testing machine and Schematic diagram of test specimen according to ASTM specifications.

Figure 3. Fatigue specimen’s sample.

In the present work, the fatigue testing machine is a single cantilever rotating bending machine with fully reversed bending (constant amplitude), with 3000 r.p.m., 220 V, 50 Hz and 0.5 HP power capacity. The specimen is subjected to a reverse pure bending load in the machine. The reversed stress amplitude is infinitely adjustable. The cycle’s number of load is displayed by a digital counter. The rotating specimen is fixed on one side and loaded with a concentrated load with a maximum capacity of (500 N), on the other side. A sine wave cyclic load with a stress ratio of R=-1 is applied during the experiment test. When the cylindrical specimen is subjected to alternating bending stresses, the specimen will fail due to material fatigue. The applied load F on the other side of the specimen is perpendicular to the specimen axis in order to generate rotating bending fatigue conditions, hence; bending moment is developed. Therefore, the surface of the specimen is under succession of tension and compression stress as it rotates. When the specimen is broken, the machine will stop automatically due to the shutdown sensor. Then, the cycle’s number is displayed and recorded on control board screen. A number of experiments were conducted on each set of samples (seven samples) via changing the magnitude of applied load every time and counting the cycles number to failure and draw the S-N curve for recorded data.

The magnitude of bending moment is used to calculate the alternating bending stress, which can be calculated from the equation (6).

The bending moment was calculated with the load and the lever arm as follows [24]:

$$M= F.a \tag{2}$$

By using the section modulus of the specimen, the alternating stress amplitude can be calculated as:

$$\sigma = \frac{M}{W} \tag{3}$$

$$W = \frac{\pi\, d^3}{32} \tag{4}$$

$$\sigma = \frac{32\, F.a}{\pi\, d^3} \tag{5}$$

$$\sigma \backsimeq 2F \ \text{(MPa)} \tag{6}$$

Where, σ: maximum applied stress (MPa), F: applied load (N), a: bending arm=106mm, d: specimen diameter=8mm, M: bending moment (N.mm), and W: section modulus of the specimen.

The S-N curve is a plot representation of the fatigue information. It represents the relationship between applied stress and number of cycles to failure for a specific material. Basquin's equation is a model most commonly used for providing an analytical form of S-N curve. The fatigue life of the material can be estimated with a few information on the material [25]. The simple Basquin's equation is:

$$\boldsymbol{\sigma}_a=a\,(N_f)^b \tag{7}$$

Where, σ_a: stress amplitude in (MPa), and N_f: number of cycles to failure. The a and b parameters are constants, their values depends on the geometry and material. The power law equation is expressing the fatigue behavior of the materials.

NUMERICAL ANALYSIS

The FEM method is a numerical technique used to analysis complex engineering structure. In the present work, the ANSYS/16 workbench software program was used in modeling fatigue test to predict the fatigue behavior for each of the three types of the composite materials under constant amplitude loading. The fatigue life analysis was conducting by adopting the stress-life approach with aim of ANSYS software as a numerical method. The analysis involve the effect of Von-Mises, max shear and max principal stresses based on stress ratio (R=-1). The element type used in this investigation is a default element which is SOLID186 a brick solid element. The element is a 20-node solid element and higher order 3-D that shows quadratic displacement behavior [26].

In fatigue simulation the data that explain the failure cycle's number with applied stress on the specimen cannot be predicted mathematically, therefor the experimental data of the mechanical properties and fatigue test will be used. After meshing process, the boundary conditions were applied. According to configuration of the geometry for the model used. Finally, the fatigue tool used to utilize the life at different loads, safety factor, total deformation, equivalent stress, and maximum shear stress. A fully reversed bending (R=-1) was used in the current work of fatigue investigation. Figure 4 presents the model that built which was simulating the same model used in the experimental work. The simulation mesh was done by choosing the number and the volume of elements in each structure. The automatic size control (automatic mish) was used to mesh the model as shown in figure 5. Where in this work, the model was a cantilever beam where it was fixed from one end and the load apply at the other end, as can be seen in figure 6.

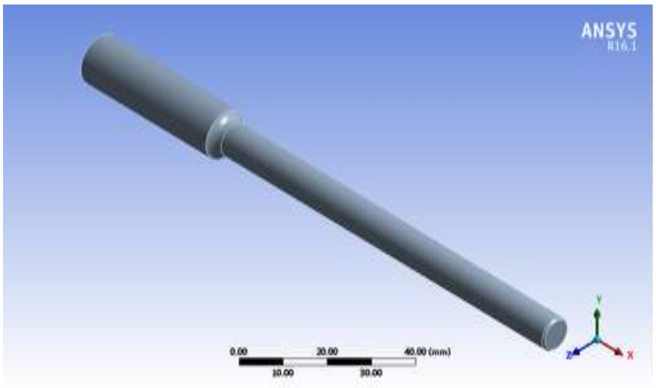

Figure 4. Geometry of the model used for fatigue analysis.

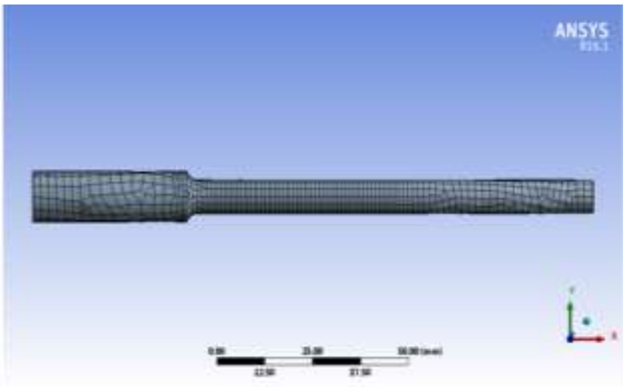

Figure 5. The model with mesh.

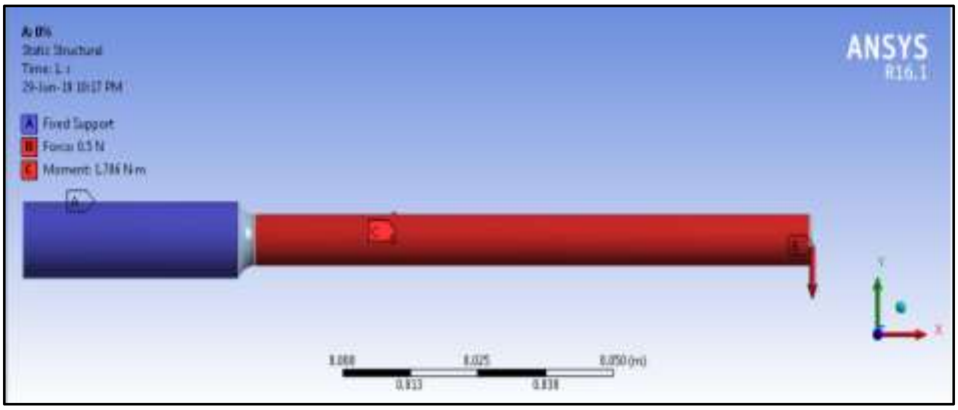

Figure 6. The model with boundary condition

RESULTS AND DISCUSSION

The tensile test specimens have been installed in universal tensile test machine and the test has been done. The test was repeated three times for all the tensile experimental test results of the composite specimens to take the average value of the data. Tables 1 summarize the average values of the three measurement data results of the elastic modulus and tensile strength of the tested specimens respectively with its increment of volume fraction. Figure 7 shows the stress strain diagram, it can be noticed that the increase of the volume fraction of the composite will increase the tensile strength and modulus of elasticity. The addition of the fibers contributes to strengthening of the composite which cause failure retarding through the composite material and leads to decrease strain failure. The elastic modulus and tensile strength of the composite is increased by 60.8% and 44.4% respectively when the weight fraction increased from 0 to 20%.

Table 1. Tensile test results

Modulus of elasticity (GPa)			Tensile strength (MPa)		
$v_f=0\%$	$v_f=10\%$	$v_f=20\%$	$v_f=0\%$	$v_f=10\%$	$v_f=20\%$
3.6	6.9	9.2	55	79	99

Many factors affect the fatigue performance such as volume fraction of fiber and resin**.** The fatigue test was carried out for the prepared composite materials, and for each volume fraction (i.e. 0. 10 and 20%), there are seven specimens were tested with different applied moments. Therefore, twenty-one specimens were tested during the fatigue test and the results presented by of S-N curves. These curves are acquired by curve fitting the experimental as well as numerical data of fatigue test. The power law equations constants, which show the fatigue life behavior of the composite materials, as can be seen in table 2.

Table 2. Basquin's equations comparison for present study for experimental and numerical fatigue data

Volume fraction	**Experimental**	**Numerical**
$v_f=0\%$	$\boldsymbol{\sigma_f = 201.46(N_f)^{-0.201}}$	$\boldsymbol{\sigma_f = 475.36(N_f)^{-0.258}}$
$v_f=10\%$	$\boldsymbol{\sigma_f = 1902.8(N_f)^{-0.347}}$	$\boldsymbol{\sigma_f = 1439.6(N_f)^{-0.317}}$
$v_f=20\%$	$\boldsymbol{\sigma_f = 8164.5(N_f)^{-0.434}}$	$\boldsymbol{\sigma_f = 8274.1(N_f)^{-0.427}}$

In the first set of the experimental results which shown in figure 8. It can be observed that fatigue life strength of the materials was decreased in various rates with the cycles number increasing. The decreasing happened rapidly in first hundred thousand cycles due the damage initiation and crack initiation in this region by fatigue. When the number of fatigue cycles increases, the decreasing in fatigue stress rate are changed and taken a new pattern which is become less sharp than the first region. The new pattern of stress behavior is approximately linear behavior, which can be seen in between two readings of final failure. The linear behavior of stress can be interpreted due to growing the crack and causing fiber matrix de-bonding, following by area delamination, which is noticeable, and then, the final failure or breakage of fiber occurred. Figure 8 shows that the increase of volume fraction will increase the fatigue limit, its increasing by about 45% when volume fraction increase from 0 to 20%.

The addition of the fibers contributes to strengthening of the composite that leads to impede the progress of the failure through the composite material. This is attributed to high modulus of elasticity, tensile strength, shear stress, and fracture toughness when increasing the volume fraction of the composite. The ANSYS/16 Workbench software package used to study fatigue life strength of composite material numerically with various volume fraction, which are used in experimental work based on simple beam theory. A fully reversed load (R=-1) with constant amplitude was used to determine fatigue life. The numerical results are compared with experimental results, as shown in figures 9, 10, and 11. Numerical model using ANSYS package; where a specific moment is applied as cyclic load to find the amount of equivalent alternating stress resulting in the specimen. Equivalent alternating stress is the stress used to predict the fatigue S-N curve with respect to many factors such as R-ratio and loading type. The moment of the experimental part was applied in numerical model by determining it using the simple theory of a cantilever beam (equation 2).

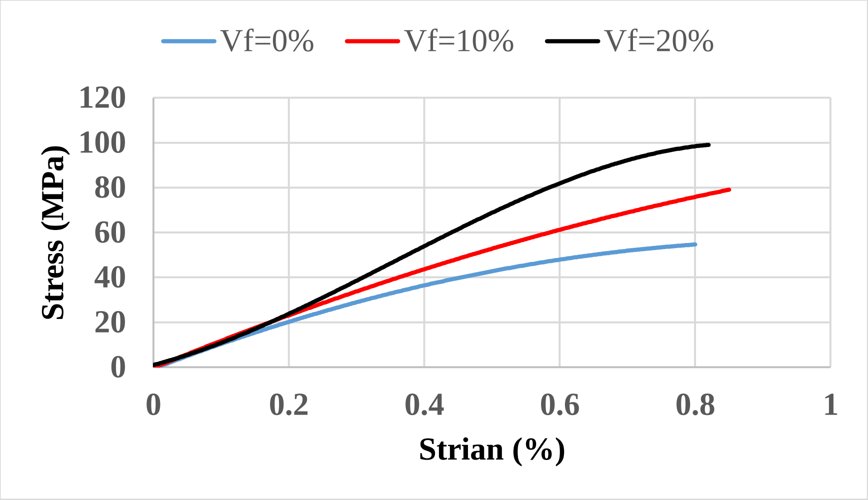

Figure 7. Experimental stress strain diagram of E-glass/UP composites with Different volume fraction.

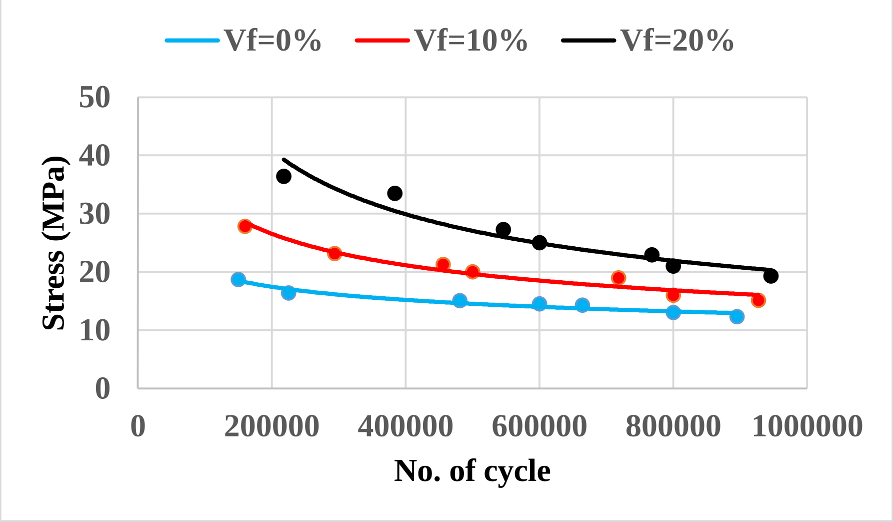

Figure 8. Experimental S-N Curve of E-glass / UP composites with Different volume fraction.

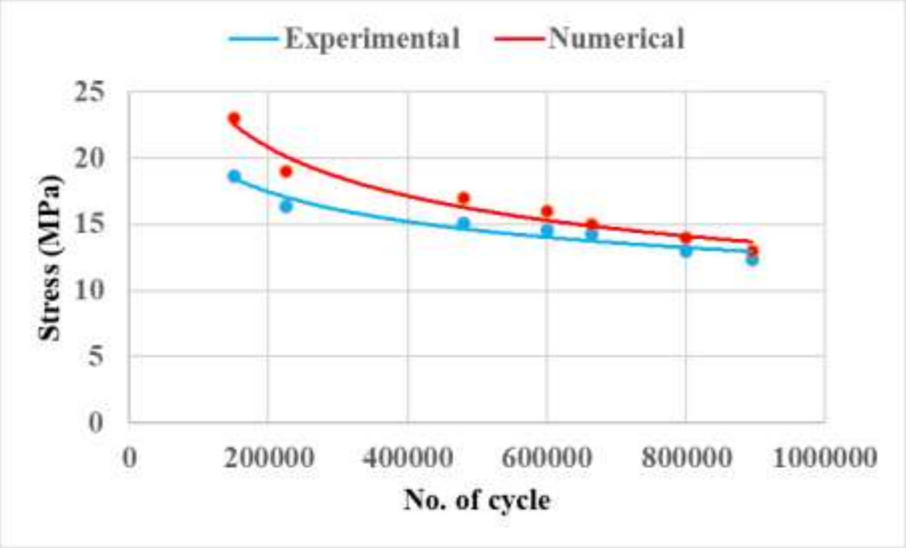

Figure 9. Comparison between numerical and experimental results for volume fraction of 0%**.**

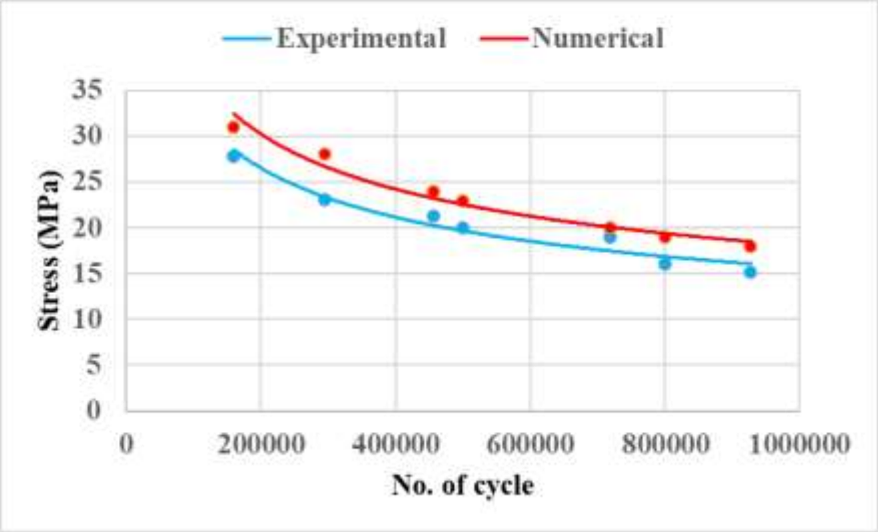

Figure 10. Comparison between numerical and experimental results for volume fraction of 10%.

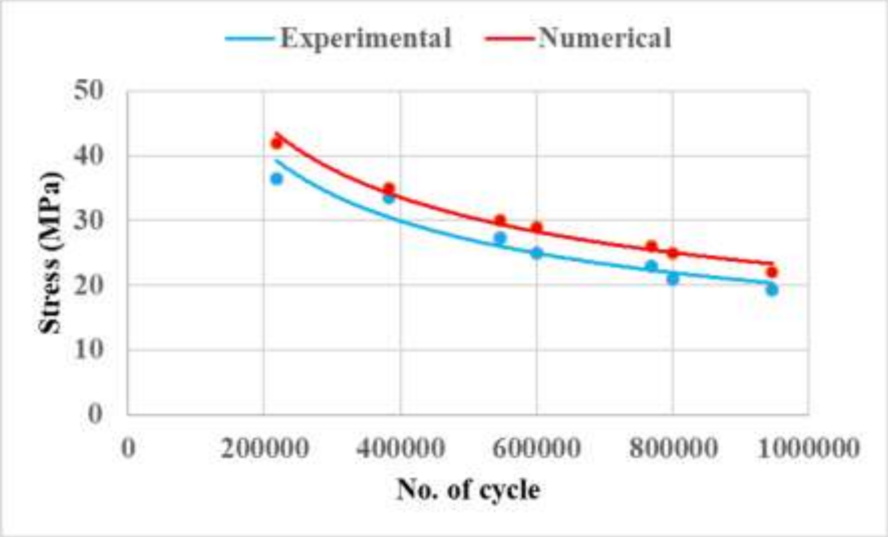

Figure 11. Comparison between experimental and numerical results for volume fraction of 20%**.**

Figure 12 shows contour plot of the available life for the given fatigue analysis for pure polyester. This figure represents the cycle's number until the component fail due to the fatigue at a constant amplitude loading. So it can be noted that the best life in the composite material with (20%) of glass fiber, as shown in table 3.

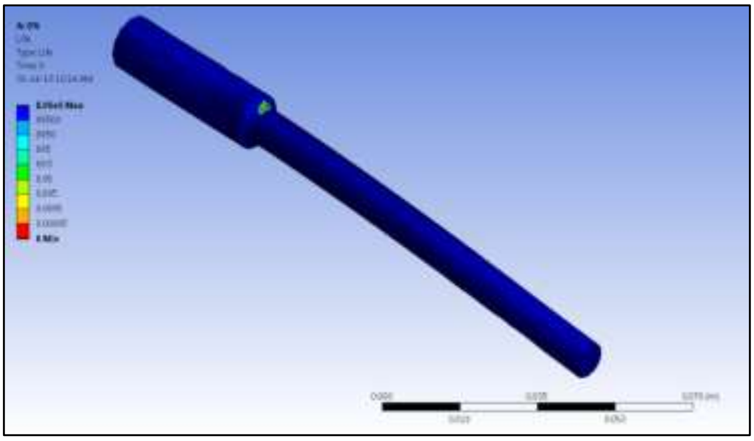

Figure 12. Fatigue life analysis pure polyester

Regarding to fatigue failure for the given design life, the maximum safety factor appeared is 15 as shown in figure 13, like life and damage, this result may be watched. For safety factor of fatigue, the magnitude less than 1 means failure before the design life was reached. It can be noticed from table 3 that the material, which consists 20 % glass fiber has minimum safety factor 3.4, which is the best the best. Also, it can be noticed that the investigated materials with value of volume fraction are safe due to the magnitude of safety values are more than 1 which show that the failure will not occur during design life except the material with volume fraction 0% which is a pure polyester where the minimum safety factor is (0.606).

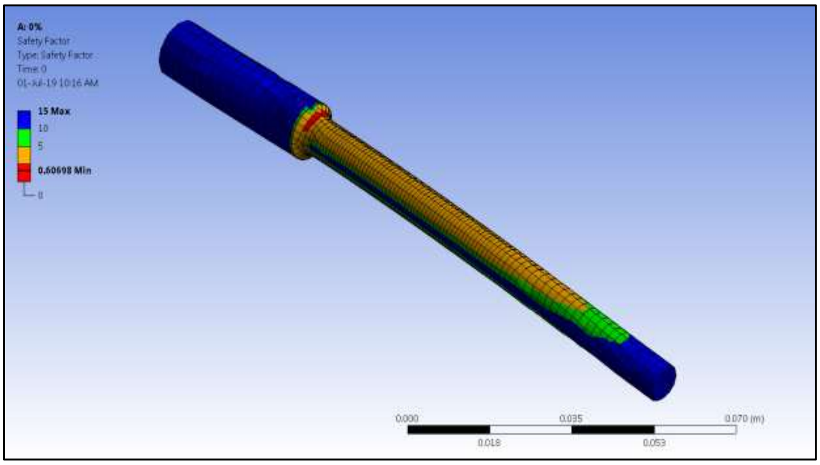

Figure 13. Safety factor for pure polyester

Figure 14 shows an example for the von-Mises stress produced in the model of pure polyester. It can be noticed that the connection region between the specimen and the device has highest magnitude of equivalent Von-Mises stress because the reaction forces are high in the contact part and its normal behavior. It can be shown that the in the experimental side, applying the same value of moment was applied in numerical simulation by applying the deflection at the end of sample gradually from the extreme value down to the smallest value in excess then the number of cycle 10^6 cycles before fail. Sample may not fail when exceeded that number, where it is considered the value of stress at this point is the fatigue limit.

According to the Von-Mises theory, it can be noted that equivalent stress is less than tensile stress of the composite as shown in table 3, which will be safe in design because the minimum magnitude of equivalent Von Mises stresses which is obtaining a maximum structural strength. Also; it can be noted that the increase in the volume fraction in composite material will increases the value of the elastic properties of composite material and have effect on the final result of equivalent Von Mises stress which can be seen, while the material with volume fraction (20%) of glass fiber has minimum value of stress around (17.2 MPa).

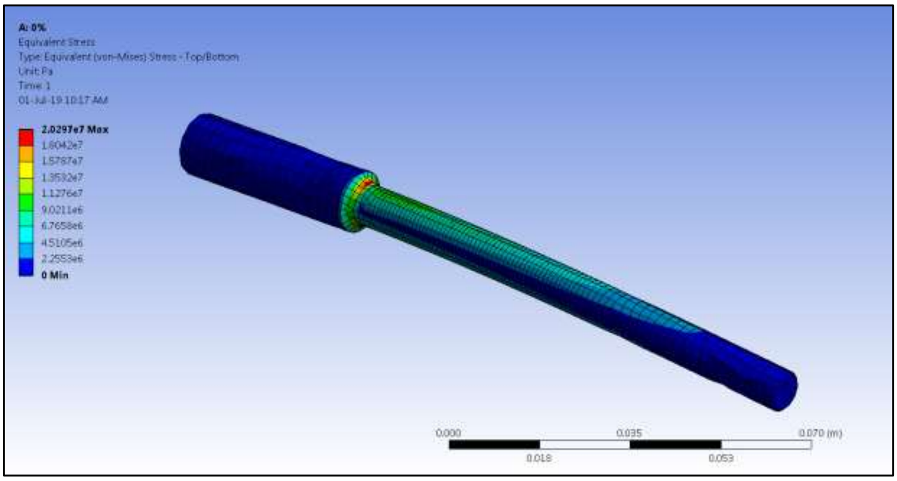

Figure 14. Equivalent Von-Mises stresses for pure polyester.

Figure 15 shows the maximum shear stress distribution throughout the specimen also, the value and location of Maximum Shear stress. It can be noticed from the figure that the maximum value of maximum shear stress allocated in the contact area between the thin and wide part of the sample.

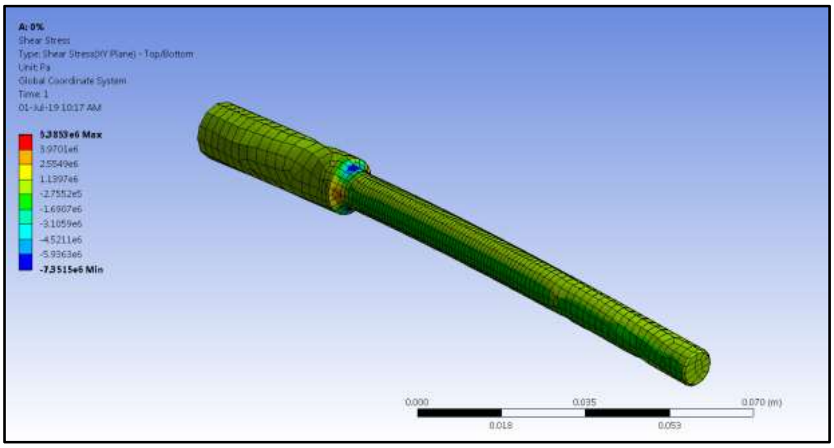

Figure 15. Shear stress for pure polyester

Table 3 shows a summary of the results of the simulation part for fatigue testing for the composite materials used and for different volume fractions.

Table 3. Summary of the numerical results

Volume fraction	**Life (No.)**	**Min. Safety Factor**	**Von-Mises (MPa)**	**Shear Stress (MPa)**
0 %	8.95×10^5	0.606	20.29	5.38
10 %	4.75×10^6	2.75	18.45	4.98
20 %	9.54×10^6	3.4	17.2	4.23

CONCLUSIONS

The analysis of glass fiber reinforced polymer composite material behavior has been done experimentally and numerically, under different volume fraction (0, 10, and 20%) in the current work. In view of the results obtained, the following main conclusions can be summarized:

1- The mechanical properties of such composite improved with the volume fraction increases from zero to 20%. The tensile strength and modulus of elasticity increased by 44.4% and 60.8% respectively, while the fatigue strength increased by about 48% compared with that of pure polyester.
2- The models are active in the prediction of fatigue behavior of the composite materials.
3- The fatigue life result showed the success of all composite materials and the best magnitude of safety factor is around 3.4 for the material contain 20% of class fiber.
4- The equivalent Von-Mises stress is less than tensile stress of the composite, which will be safe in design for all composites.
5- The highest magnitudes of max shear stresses and equivalent Von-Mises are allocated in the connecting region of sample with device.
6- The experimental results are compared with numerical results and good agreement has been found with maximum overall average error of 7%.

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