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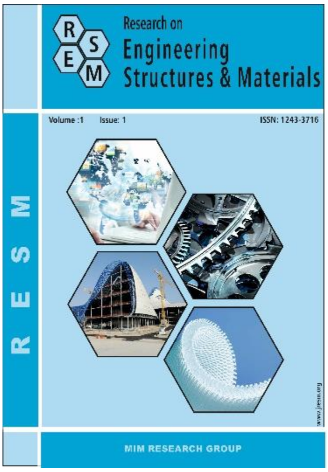

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Research Article

The design of multi-sample flexural fatigue device and fatigue behavior of glass/epoxy laminated composites

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Abstract

Due to fiber reinforced polymer composite materials have a brittle structure, it is important to know their behavior under dynamic loads. Therefore, it is necessary to know the S-N curve that characterizes the fatigue life of the composite material, when selecting and sizing the material. In this study, fatigue behavior of glass/epoxy laminated composites was investigated under flexural loading. For this aim, computer controlled fixed end type flexural fatigue test machine was developed and glass/epoxy test samples were tested under flexural stress corresponding to 80%, 70%, %60, %50, and %40 of the static 3-point bending strength. In addition, the static strengths of the epoxy-laminated composites under tensile, compressive and flexural loads were also determined. It has been observed that the damage such as matrix and fiber cracks and delamination in the glass/epoxy laminated composites, which were exposed to flexural deformation. Also, it has been seen that, the developed fixed end type flexural fatigue test machine can be used to determine fatigue behavior of thin-walled composite materials.

1. Introduction

Composite materials are formed by combining two different components called fibers and matrices at the macro level. The occurred new material has superior mechanical and physical properties than both fiber and matrix material. Composite materials have come to the forefront by result of studies, which were did in order to meet the economical, high strength and very light material needs that required by the development of technology. So that, they have become an alternative to traditional building materials and their usage has become increasingly widespread, due to their superior mechanical and physical properties.

Many building elements are subjected to repetitive loads or repetitive elastic deformations during their usage. As a result of repetitive loads, the materials lose their rigidity over time and damage at the stress values under yield strength. This phenomenon is called fatigue. Fatigue behavior of composite materials detection is more difficult unlike isotropic materials. The reason for this, the number of parameters handled during the design of composite materials is high. Composite materials tend to accumulate damages in structures and damage does not always occur in a macroscopic dimension. Some damage mechanism such as fiber damage, separation, reverse layer cracks and matrix cracks can occur in laminated composites, during fatigue. Several studies have been carried out to

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understand this complex damage mechanism under fatigue loading of layered composite materials.

Shenoi et al. [1] have presented an investigation on the fatigue behavior of sandwich beams with fiber reinforced polymer (FRP) skins and PVC foam core. Their study revealed core shear as dominant failure mode via gradual loss in foam core stiffness and concluded that beam fatigue life of sandwich is dictated by the core fatigue life. Nikforooz et al. [2] have investigated the fatigue performance of laminated glass fiber polyamide having eight layers under tension-tension loading. The test results showed that the fiber orientation and layer thickness were effective on fatigue behavior of glass/polyamide and glass/epoxy composites. Bureau and Denault [3] produced woven glass/polypropylene laminates using different process parameters. Flexural fatigue tests showed a general decrease of the life to final failure and increase in the stiffness drop in the presence of porosity. Dickson et al. [4] studied the fatigue behavior of cross ply 0/90 and ±45 carbon/PEEK and carbon/epoxy. They found that 0/90 lay-up for both materials had comparable fatigue resistance while ±45 carbon/PEEK laminates had better fatigue resistance than carbon/epoxy laminates. The other result obtained from fatigue test that the fatigue response of a cross-plied carbon/PEEK laminate in the ±45^{o} orientation is much better than that of equivalent carbon/epoxy composites, again because the superior properties of the thermoplastic matrix.

Belingardi et al. [5] conducted a detailed material characterization and study of bending fatigue property of relatively complex un-notched intra-ply hybrid composite that consists of distinct layers of biaxial glass-fiber-reinforced composite and biaxial carbon fiber-reinforced composites as well as biaxial layers of bundles of carbon and glass fibers mixed within a single layer. Beyene et al. [6] have investigated the effect of notch on flexural fatigue performance of twill glass/epoxy composite. Displacement-controlled flexural fatigue tests have been conducted on the specimens and damage in the composite has been continuously monitored during cycling. Test results showed that it is observed that different notched geometry behave differently for quasi-static and fatigue loading. Koricho et al. [7] have investigated the fatigue behavior of glass/epoxy laminated composites by using displacement controlled flexural fatigue test machine. Test results showed that when the fatigue load level increases, the fatigue life decreases is short and the extent of damaged zone prior to catastrophic failure becomes smaller. Also, at low fatigue load level, the fatigue life is long and the extent of damaged zone becomes wider. Sakin et al. [8] investigated flexural fatigue behavior of glass fiber reinforced polyester composite materials, glass-fiber woven and randomly distributed glass-fiber mat samples with polyester resin. According to the test results, the highest fatigue life has been obtained from 800 g/m^2 fiber glass woven specimens with 0/90 lay-up. Liang et al. [9] conduced an experimental investigations of tension–tension fatigue tests on flax/epoxy and glass/epoxy composites specimens with $[0/90]_{3S}$ and $[\pm 45]_{3S}$ stacking sequences. The stiffness degradation of both composites exhibits similar trend despite the loading level. Ellyin and Kujawski [10] investigated the frequency effect on the tensile fatigue performance of angle-ply glass fiber reinforced laminate and concluded that there was a considerable influence of test loading frequency. Especially for matrix dominated laminates and loading condition, frequency becomes important due to the general sensitivity of the matrix to the loading rate and because of the internal heating generation and associated temperature raise.

Fatigue tests are performed in loading conditions such as tensile, compressive, flexural and torsion, which is at the stress values below the static strengths of the material. Fatigue test machine, which can test under different load conditions with load control or displacement control, have been developed for fatigue tests. Kulkarni et al. [11] have developed plane flexural fatigue testing machine for composite material. Gheilmetti et al. [12] have developed flexural fatigue test machine for high frequency applications of flat aluminum specimens. Mokhtarnia et al. [13] have developed an original flexural fatigue test machine, which have capable of applying stress control load in different loading waveforms, frequencies, and stress ratios, for fatigue characterization of composite materials. Balcioglu et al. [14] have developed a multi-sample fatigue test machine, which characterizes the flexural fatigue behavior of fiber-reinforced composite sheets, wooden sheets, plastic-based sheets and light metal sheets.

In this study, a displacement controlled fatigue device capable of testing 10 samples at the same time was developed to characterize flexural fatigue behavior of composite materials. The flexural fatigue behaviors of glass/epoxy laminated composites were investigated by the developed device. The three-point bending strength and three-point bending modulus were statically calculated to determine the displacement values to be applied to the glass/epoxy samples during the fatigue test. After that, the fatigue test specimens were subjected to fatigue tests at loading values corresponding to 80%, 70%, 60%, 50% and 40% of the static three-point bending strengths in order to obtain the S-N curve characterizing the glass/epoxy composite fatigue behavior. In addition, tensile and compressive behavior of glass/epoxy laminated composites were determined within static tests.

2. Fatigue Test Machine

In fatigue tests, the two most important parameters that determining fatigue life of the material are amplitude and frequency. In addition, the test frequency of the fatigue device and the resonance frequency of the material under the actual loading conditions must be the same. It is not right to choose a material, which work under low frequency, according to the high frequency fatigue test results and It is not right to interpret the fatigue life of that material. Since heterogeneous materials such as composites are anisotropic, it is difficult to characterize fatigue behavior parameters with conventional fatigue devices and methods. The standard test frequency range for polymer matrix composites is frequency as low as 1-10 Hz. The temperature increases during the test due to hysteretic heating at higher frequencies and in this case the isothermal behavior of the composite changes [8,13].

Almost all of the fatigue testing machines are tested at the same time as the single sample. However, in order to obtain the S-N curves characterizing the fatigue strength limit of the material, it is necessary to test at least 5 samples in response to each deformation or stress value. Generally; fatigue tests are performed to accurately form the S-N curve at 7-8 different stress values that below the static strength of the material. In this case, an average of 35-40 samples must be subjected to the fatigue test to obtain the S-N curve for a single material parameter. In a fatigue test performed on a classical fatigue testing machine, it is necessary to use a total of 80 samples if considered 2 different material parameters and 5 repetitions for each stress value. Assuming the fatigue test frequency is 10Hz, the total test duration for our high cycle fatigue test, which we plan to continue to 10 million load cycles, is approximately 146 days. In this study, it was aimed to develop a new multi-samples fatigue testing machine to investigate the fatigue behavior of fiber reinforced composite plates when considering limitations and disadvantages of previous fatigue test machines, such as total test time, mechanical efficiency, low production cost.

There are very few multi-sample fatigue testing machines available for lightweight plate materials [15–17]. In this study, differential from literature, a flexural fatigue test machine was developed, which has a remotely controllable, user-friendly interface, take instantaneous fatigue data for each sample without loss even at high frequencies. Computer-controlled fixed-end type flexural fatigue testing machine is fully computer controlled thanks to the developed software. Fatigue testing of viscoelastic materials is carried out in two different modes, either as a displacement-controlled or stress-controlled test [13,18]. The main feature of the fatigue testing device in this study is the ability to perform a constant displacement-controlled test (Figure 1).

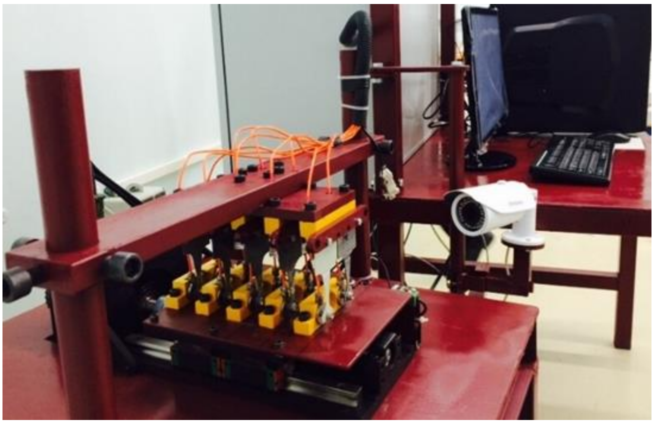
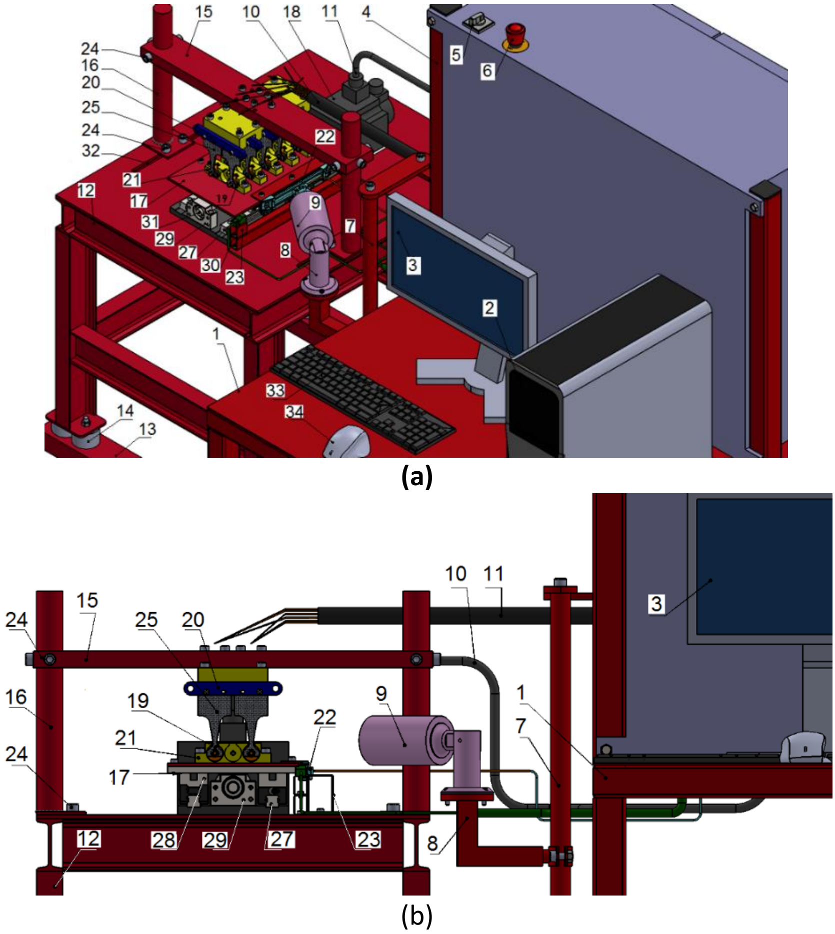


Fig. 1 Displacement controlled multi-sample fixed-end type flexural fatigue tester

In most of the classical flexural fatigue test machines, the displacement value is obtained by the crank-pinch mechanism. The maximum and minimum displacement values are usually adjusted manually by means of mechanical construction. In this case, it is difficult to obtain a precise value. In addition, the effect of centrifugal force come in view due to high frequency in the fatigue tests that performed on these types of test machine. The displacement value is provided with 5μm accuracy by means of the linear screw moving table which is moved forward/backward by helping of servo-motor controlled by software in the developed fatigue test machine. In classical fatigue testing machines, defining and setting the initial zero position is another important challenge. If the initial zero position cannot be precisely determined in the fixed-end type fatigue devices, it will occur pre-tensioning at sample due to the momentum which occurs by axis misalignment. In this case, the true S-N curve that express the fatigue behavior of the material cannot be determined. In the developed fatigue testing machine, the initial zero position was defined once to the device precisely. The device comes to the initial zero position with a single button fall in to the software interface and each test starts from the same zero position. In order to better understand the working principle of the fatigue device, the parts of the machine are numbered and given definitions in Figure 2.



1. Chassis-1
2. PC
3. Software interface
4. Main control panel
5. System start / stop button
6. Emergency stop-switch
7. Rotating camera holder
8. Camera adjustment mechanism
9. IP camera
10. Load cell cabling
11. Power cable
12. Chassis-2
13. Lower fixing U profile
14. Rubber shock absorbers
15. Height adjustment block
16. Holding arms
17. Linear sliding table
18. Servo-motor
19. Load cell
20. Holder -1 (sample fixture)
21. Holder -2 (sample movement area)
22. Magnetic readers and linear encoder
23. Sensor holder
24. Distance adjustment screws
25. Test samples
26. Couplings
27. Linear cradles
28. Linear rails
29. Bearings
30. Limit safety sensors
31. Screw shaft (step = 20mm)
32. Sliding base plate
33. Keyboard
34. Mouse

Fig. 2 The components of multi-sample fixed-end type flexural fatigue test machine [14]

3. Experimental Studies

The tests carried out in the scope of the study were carried out in two stages; as static and dynamic. In the first stage, the tensile strength, tensile modulus, compressive strength, three-point bending strength and bending modulus of the glass/epoxy composite were determined under static loads. Then the fatigue behavior of glass/epoxy composite were determined by using the stress and strain values obtained from the three-point bending test data.

3.1. Static Tests

In the study, glass/epoxy laminated composite materials were produced by hand lay-up methods. The stacking sequence of $[0/90]_4$ laminate consists of 8 layers of biaxial fabrics having 300g/m^2 weight. The matrix material was procured from Duratek Epoxy and Polyurethane System in Turkey. It has two components as DTE 1100 epoxy and DST 1105 hardener. They were prepared by mixing 74/26 in weight, respectively. Glass/epoxy laminated composites, which manufactured by hand lay-up method, were cured at 100^{o}C under pressure of 6MPa for 100min, by using temperature–time–pressure controlled hydraulic press.

The test specimens were sized according to ASTM D 3039M-93 standard to determine the tensile strength of the produced sandwich composites [19]. Longitudinal Young modulus (E_1) and longitudinal tensile strength (X_t) were obtained by using longitudinal direction of glass/epoxy composite specimens (Figure 3(a)). Transverse Young modulus (E_2) and transverse tensile strength (Y_t) were also obtained by using transverse direction of glass/epoxy laminated composite specimens (Figure 3(b)). The tensile strengths in the longitudinal and transverse directions (Xt and Yt) were determined by dividing the failure load by the cross-sectional area of the longitudinal and transverse specimens, respectively.

Shear properties were determined according to the ASTM D3518M-13 standard test method [20]. This test method determines the in-plane shear response of polymer matrix composite materials reinforced by high modulus fibers (Figure 3(c)). The composite material form is limited to a continuous-fiber-reinforced composite ±45° laminate capable of being tension tested in the laminate x direction. The in-plane shear modulus (G_{12}), was defined by using Eq. 1, where E_{45} is elasticity modulus in 45^o fiber direction and ϑ_{12} is major Poisson's ratio [21]. Poisson's ratio ϑ_{12} was accepted as 0.32 according to studies in the literature [22].

Compressive properties were determined according to the ASTM D3410-87 standard test method [20]. Longitudinal and transverse compressive strength of glass/epoxy composite specimens (X_c and Y_c) were calculated by dividing the failure load to the cross-sectional area of the specimens in longitudinal and transverse direction, respectively (Figure 3(d)).

$$G_{12} = \frac{1}{\frac{4}{E_{45}} - \frac{1}{E_1} - \frac{1}{E_2} + \frac{2\vartheta_{12}}{E_1}} \tag{1}$$

The flexural strength and flexural modulus of the glass/epoxy composites were determined according to ASTM D7264 test standard [24] . According to this standard span-to-thickness ratio is 32:1, the standard specimen thickness is 4 mm, and the standard specimen width is 13 mm with the specimen length being about 20% longer than the support span (Figure 3(e)).

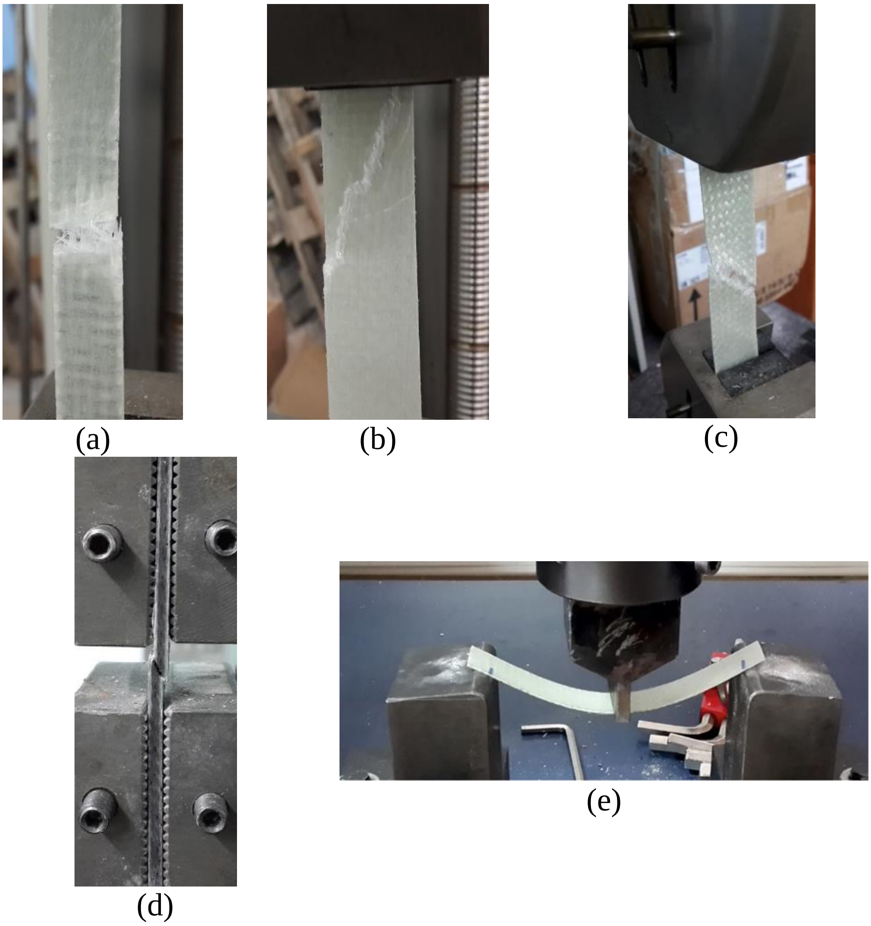


Fig. 3 Static test set up (a-c) tensile test, (d) compression test and (e) flexural tests

The load-displacement graph of each test sample was drawn thanks to the computer-controlled software of the test device. Then, three-point bending strength and flexural modulus was calculated by using data, which was obtained from the graphs, in Equations 2-3.

$$\sigma_f = \frac{3PL}{2bh^2} \tag{2}$$

$$E_f = \frac{L^3 m}{4bh^3} \tag{3}$$

where, P maximum load, L support span, b width of specimen, h thickness of beam, m slope of the load-displacement curve. Three specimens were tested for each material parameters and average of the obtained three test results was accepted as main value.

3.2. Fatigue Tests

Fatigue tests are repeated for lower stress levels starting from stress values at least 20% below the static strength of the material. The device manufactured within the scope of the study is displacement controlled. For this reason, it is necessary to calculate the value of the strain (displacement) which will occur the desired level of stress. In this context, the Hooke law, which expresses the relationship between the stress and stress of the material, has been utilized. The displacement values which will give the desired stress value were calculated by using the equation (4-5) given below [24];

$$\sigma_f = \varepsilon . E_f \tag{4}$$

$$\varepsilon = \frac{6\delta h}{L^2} \tag{5}$$

In these equations, "ε", "E_f", and "δ" denotes the unit flexural deformation, flexural modulus, and the maximum flexural deformation value, respectively. The maximum flexural strength value obtained from each composite sample was used as one cyclic flexural strength in the fatigue test. The displacement value (δ) required for the desired stress value was calculated separately for each test parameter. This value was transferred to the developed multi-sample flexural fatigue device by its servo motor software.

Test sample that were prepared according to the ASTM D671-93 test standard shown in Figure 4 was used for the fatigue tests. This test method covers the determination of the effect of repetitions of the same magnitude of flexural stress on plastics by fixed-end type testing machines, designed to produce a constant-amplitude-of-force on the test specimen each cycle [25]. To prevent hysteretic heating, fatigue tests were carried out at a test frequency of 5Hz and under a R = ±1 strain rate.

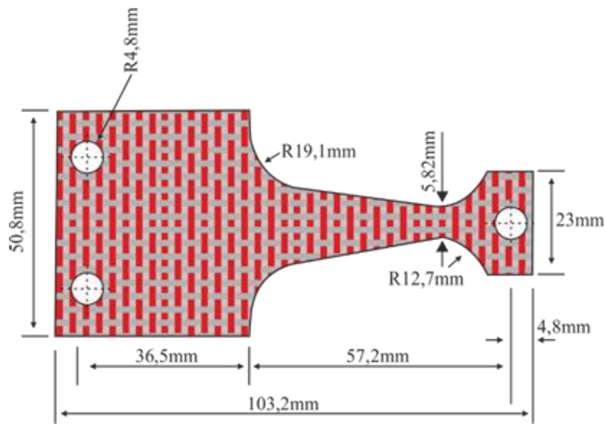


Fig. 4 Fatigue test specimen and dimensions

Fatigue behavior of a material is usually characterized by S-N diagram, showing the relationship between the stress amplitude or maximum stress and number of cycles to failure on a semi logarithmic scale. This diagram is obtained by testing a number of specimens at various stress levels. S-N diagram is of considerable value to the designer especially when the structure contains a critical component where any failure is catastrophic. In order to obtain S-N curves characterizing the fatigue strength-fatigue life behavior of the glass/epoxy composite material, the test specimens were exposed to fatigue at stress level of 80%, 70%, 60%, 50% and 40%, which correspond to the static three-point flexural strength of the material. Fatigue stress (σ_F), which causes fatigue fracture or fatigue damage during flexural load, was determined according to equation 6 given below;

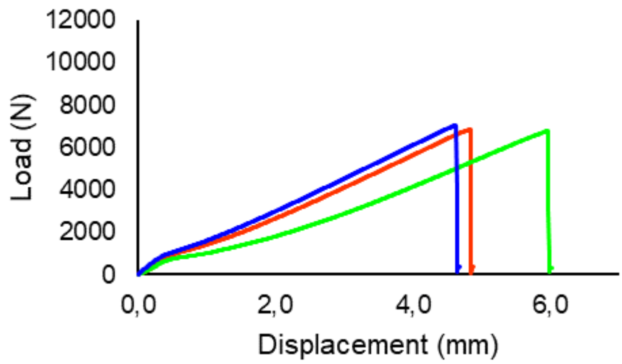
$$\sigma_F = \frac{6PL}{bh^2} \tag{6}$$

where, P is the force read from the load cell, L is the distance from the load applied site to the fatigue damage region, b is the width of the sample damage region, and h is the sample thickness. In order to draw the S-N curve of the material, the force value on the sample was read and recorded once per 1000 cycles via the load cell. Then, the fatigue strength corresponding to the relevant cycle value is calculated using Equation 6. The stress when the test sample was subjected to fatigue damage was considered as fatigue damage strength (σ_{FD}). Five samples were tested for each stress level and the average of the obtained values was taken as the main fatigue life.

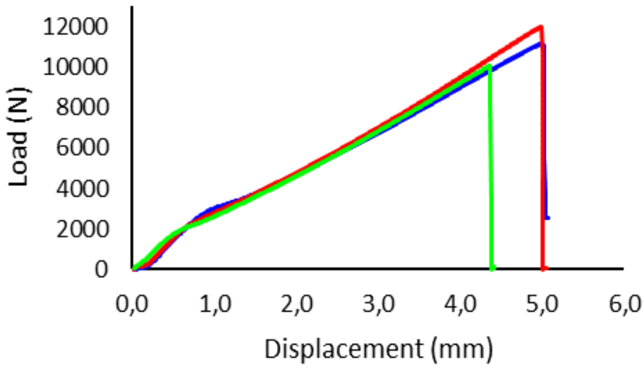
4. Results and Discussions

4.1. Static Test Results

Static tests were achieved at U-Test brand 50kN capacity universal tensile test machine at room temperature. Totally three samples were tested from each type of test. The average of the results obtained from the three samples was accepted as a main mechanical property value. The load-displacement curves of glass/epoxy laminated composites in tensile tests are shown in Figure 5. Accordingly, the glass/epoxy composites showed similar behavior by damage as brittle in the longitudinal fiber direction and transverse fiber direction. Matrix cracking and fiber breaking under tensile loading are successive damage mechanisms (Figure 3(a)). In addition, the fracture progressed angularly rather than linearly, depending on the orientation of the fiber in the sample (Figure 3(b-c)).



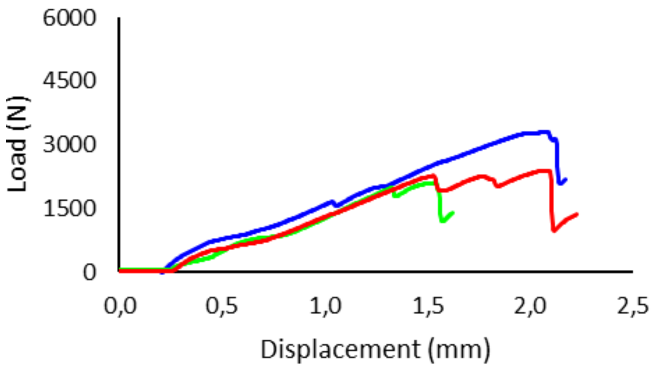
(a)



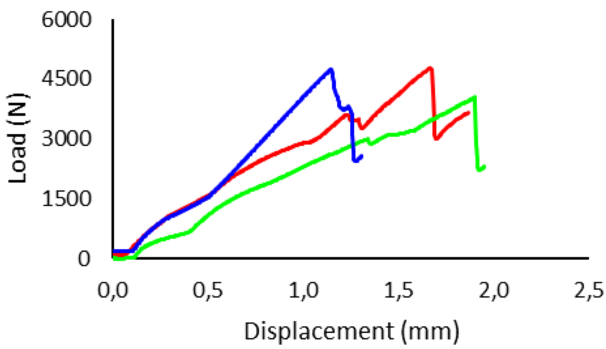
(a)

Fig. 5 Load-displacement curve obtained from tensile test (a) longitudinal fiber direction and (b) transverse fiber direction

Compression tests were carried out longitudinal fiber direction and transverse fiber direction as being in tensile test. The load-displacement curve obtained from the compression tests is given in Figure 6. As a result of the compression loading, fiber breakage and shear failure occurred fractionally. The ultimate damage ensured by breaking of fiber brittle (Figure 3 (d)).



(a)



(b)

Fig. 6 Load-displacement curve obtained from compression test (a) longitudinal fiber direction and (b) transverse fiber direction

Flexural strength (σ_f) and flexural modulus (E_f) of glass/epoxy laminated composites were investigated under three-point bending load. The load-displacement curve obtained from the three-point bending test of glass/epoxy laminated composites was given in Figure 7. All results were plotted in terms of applied load versus center displacement of the sample under the crosshead of the electronic universal tester machine.

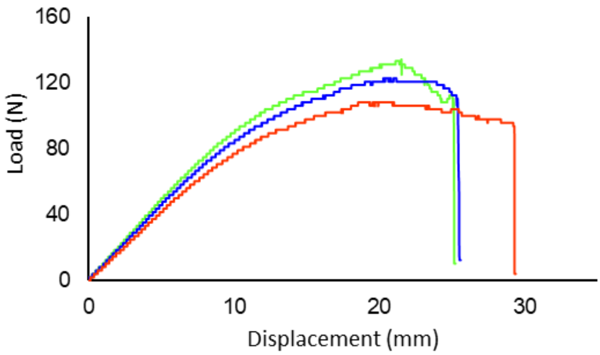


Fig. 7 Load-displacement curve of glass/epoxy laminated composite obtained from three-point bending test

The obtained curves were divided into three stages. The first stage, which is appearance in linear, can explain the elastic deformation of the glass/epoxy composite laminate. There is no linear relationship between displacement and load in the second stage. The load increase was less relative to displacement and the sample reached at maximum flexural load that it can bear in this stage. Also, micro matrix cracks and delaminations occurred in this stage. In spite of the increasing of displacement the increase in the load was inevitably diminished or becomes a flat form in the third region. In the third stage, previous peak load can never reach because the load that ensure in this stage was carried by only the reinforcement element. At the end, the fibers break apart and the sample cracked as brittle. The flexural strength (σ_f) and flexural modulus (E_f) values obtained from the three point bending tests are given in Table 1 together with the standard deviations.

When the values given for the mechanical properties in Table 1 are examined, it is seen that the values were close to each other in longitudinal fiber and transverse fiber direction. However, the values in longitudinal fiber direction were higher for each mechanical property. In this case it can be said that, similar glass filaments were used in each two directions for glass woven fabric and the number of filaments in the longitudinal fiber direction was many.

Table 1. Mechanical properties of glass/epoxy laminated composites with standard deviation under tensile, compression and three-point bending loading

Test Type	Mechanical Properties Value (MPa)	Standard Deviation Value (MPa)
Longitudinal direction elasticity modulus (E1)	32636.45	580.80
Transverse direction elasticity modulus (E2)	30326.93	780.78
Tensile strength in longitudinal direction (Xt)	360.67	12.19
Tensile strength in transverse direction (Yt)	348.07	7.59
In-plane shear modulus (G12)	2849.50	-
Compression strength in longitudinal direction (Xc)	244.56	15.44
Compression strength in transverse direction (Yc)	238.23	20.70
Flexural modulus (Ef)	30952.65	2823.46
Flexural strength (σ_f)	495.45	11.34

4.2. Fatigue Test Results

Glass/epoxy laminated composites with thermoset matrix structure have a brittle structure. However, depending on loading conditions, brittle fracture damage may not always occur under variable loads. During the flexural fatigue tests, two different damage forms were observed in glass/epoxy laminated composites. Fracture damage occurred in test specimens which were forced to fatigue at the level of stress near the static three-point bending strength. The matrix cracks propagated rapidly by the result of high bending stress and the fiber matrix interface connection weakened. Fatigue damage was spread to the fiber matrix interface by the increase in the number of cycles and caused separation of layers (delamination). Finally, the glass/epoxy composite sample was fractured in a brittle manner. (Figure 8a). The number of cycles until fracture failure was considered as the fatigue life (N_f).

Although, the specimens were forced to fatigue at low stresses until number of cycles of 10^6, which was accepted as theoretical fatigue life for this study, but they did not show any breakage in the samples. In the event of such damage, the stiffness of the test sample decreases as the number of cycles increases. This means that less strain is applied for the same displacement. The loss of rigidity that occur by the time in specimens was taken as the criterion of fatigue, because fatigue fracture was not observed in specimens forced to fatigue at low stress levels. According to the ISO 13003 standards, stiffness reduction between 5% and 20% can be accepted as the fatigue failure in FRP composites [26]. So that 20% stiffness loss was considered as the fatigue damage criterion for non-fractured specimens in the fatigue test. The stress value on the specimen was accepted as fatigue damage stress (σ_{FD}) when 20% stiffness loss occurred. For non-fractured samples, the number of cycles passed for a 20% stiffness loss was considered as fatigue life (N_f).

Matrix cracks and fiber-matrix interface damage progress more slowly in variable loads at low stress levels. Tensile and compressive stresses, which were occurred by bending, cause stiffness loss in the sample. However, delamination damage take place with starting from weak edges of the test sample to center of sample. Despite of the losing the strength of the composite specimen with delamination, low stress does not cause fracture of the fibers, radically (Figure 8b).

Fig. 8 Fatigue damage of glass/epoxy composite (a) crack and (b) delamination

Load value that corresponding to each cycle was recorded, thanks to the software of the developed fatigue device. So that, the fatigue strength corresponding to each cycle was calculated with the help of Equation (6). In figure 9 have presented loss of stiffness that occurred with the increasing of number of cycles in the test specimen. Accordingly, the decrease in stiffness loss is clearly seen by increasing of the stress amplitude. Such that, in 50,000 cycles, the glass / epoxy specimen lost 7%, 18%, 20%, 26% and 29% of the stiffness at 40%, 50%, 60%, 70% and 80% of stress amplitude, respectively.

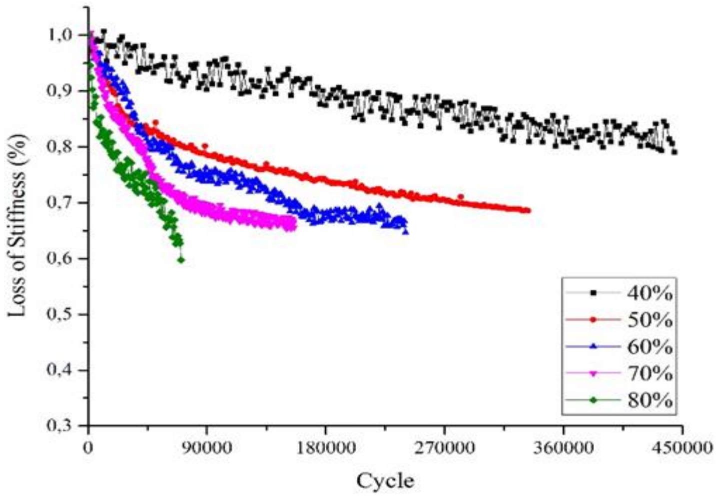


Fig. 9 Stiffness losses of glass/epoxy test samples

Laminated composites are thin-walled structures and thin-walled structural elements are more susceptible to bending and buckling loads. Table 2 shows the flexural strength and fatigue life of layered composites which were loaded static and dynamically at different stress levels with the standard deviations. Hereunder, glass/epoxy composite material has a maximum fatigue life of 354800 cycles under a full variable loading of 218.64 MPa. According to the static situation, the glass/epoxy composite sample lost 55.96% of its strength at the end of the cycle of 354800. If similar comparison is performed for glass/epoxy test specimen that loaded dynamically at a stress level of 80% of static strength, the test specimen is damaged by breaking when the flexural strength of the specimen lost 18.18%. This means that the damage tolerances of the brittle glass / epoxy composites are very low in the dynamic stresses at high stress amplitudes.

The fatigue strength increased by the stress amplitude increased and nevertheless fatigue life decreased. When stress amplitude reached from 40% to 80%, the fatigue strength increased by 85%, while the fatigue life decreased by 557%.

Table 2. The fatigue life corresponding to the fatigue stress in different stress amplitude

Stress Level (%)	**Stress (σ_{FD}) (MPa)**	***Cycle(N_F)***	**Loss of Rigidity According to Static Loading (%)**
40	218.64 (22.17)	354800 (25440.13)	55.96
50	256.78 (17.71)	271100 (19122.63)	48.28
60	308.36 (26.96)	165240 (5035.18)	37.78
70	367.34 (25.97)	113700 (23145.19)	25.86
80	405.70 (23.17)	54000 (4662.62)	18.18
100 (Static)	495.45 (11.34)	1	-

*(Standard deviation)

The S-N curve representing the relation of fatigue strength-fatigue life under different stress amplitude of glass/epoxy laminated composite was given in Figure 10. For glass/epoxy samples, breakage of samples or loss of 20% rigidity was accepted as fatigue damage in this scope of study. Even if the breaking was not observed on samples, the experiment was not continued after 20% rigidity loss. The theoretical fatigue life for polymer matrix composites is 10^6 cycles [8]. The fatigue strength corresponding to the theoretical life was expressed by the Power Law function. The Power Law function, which expresses mathematically the fatigue mechanism, was indicated on the graph. As shown in Fig. 10, the Power Law equation for glass/epoxy samples is expressed in;

$$\sigma_F = 15791N^{-0.33}$$

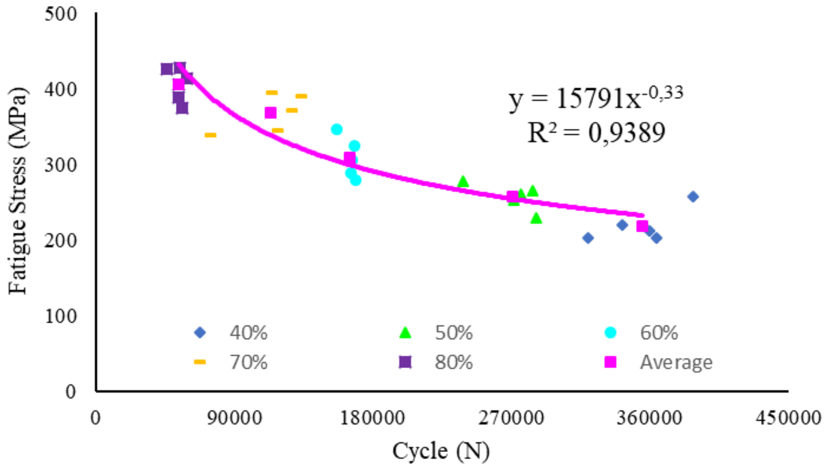


Fig. 10 S-N curve of glass/epoxy laminated composites

Table 3 shows the comparison of fatigue strength values corresponding to the number of different cycles estimated by the Power Law function with experimental data. When look at the error percentages in Table 3, it seen that the maximum error percentage for predicted values was 7.76%.

Table 3. Comparison of experimental and predictive values

Cycle	Power Law Func.		Fatigue Strength (Experimental)	Fatigue Strength (Prediction)	Error (%)
	A	B			
354800			218.64	232.76	6.46
271100			256.78	254.38	0.94
165240	15791	-0,33	308.36	299.52	2.87
113700			367.34	338.85	7.76
54000			405.7	433.23	6.79

Figure 11 showed the S-N curves obtained by experimental and the Power Law function. If assume there was no breakage, the maximum flexural fatigue stress that the glass/epoxy laminated composite could hold would have been 165.35MPa. In this case, the glass/epoxy laminated composites which were subjected to full variable bending loading up to 106 cycles lost 66.67% of their static bending strength.

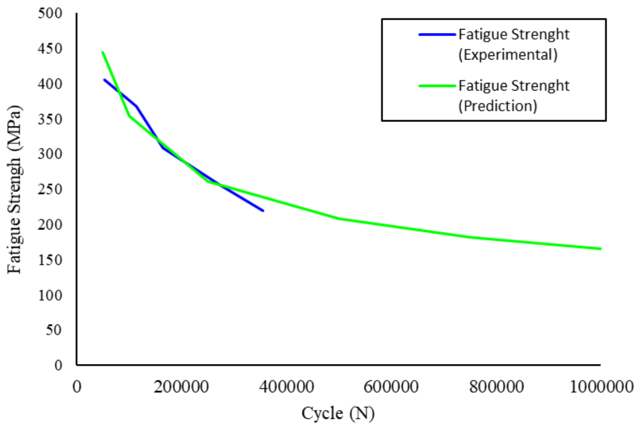


Fig. 11 Comparison of experimental and predictive of S-N curve

5. Conclusion

In this study, the static and dynamic behavior of glass/epoxy laminated composites were investigated. Tensile, compressive and flexural behavior were determined in static tests. Computer-controlled multi sample fatigue test machine, which can tire ten fatigue samples at the same time under flexural loading, have been developed for dynamic tests. Flexural fatigue strength, stiffness loss and fatigue life were determined in fatigue tests. In addition,

The general evaluations obtained in this context were given below.

- When the standard deviation values of the data obtained from the static tests were examined, it is seen that the scattering values of the data for the same experiment type are at acceptable levels. The standard deviation results show that hand lay-up is suitable for laminated composites.
- It has been found that fiber orientation directly influences the tensile and compressive strength of the material according to the tensile and compression tests. The reason for that, the density of fiber in the structure of the woven glass fabric reinforcement material is different along fiber and transverse fiber directions.
- According to the fatigue test results, it was seen that the designed flexural fatigue device is practicable for the low frequency fatigue test of plastic and composites materials. The test time per unit sample was shortened due to fatigue test capacity for 10 samples at the same time and useful software interface.
- According to the results obtained from the dynamic tests, the fatigue life decreases as the applied stress amplitude value increases. The high stress amplitude forces the material to more deformation. The increase in the amount of deformation causes the weakening of the bonds at the fiber-matrix interface. The cracks starting from the matrix material are progressed over time, causing the material to get tired earlier. In addition, the stress amplitude directly affects the form of fatigue damage such as fatigue fracture or delamination.

- Material constants for S–N power equation have been estimated for the two composite types and the agreement between this equation and the experimental data has been noticed. Based on 20% reduction of initial flexural stiffness taken as a failure criterion, the safe fatigue life areas representing the fatigue workability for glass/epoxy composite laminates have been determined.
- The Power Law function was found to be successful in predicting experimental fatigue data. It is foreseen that glass / epoxy composites which continue to 10^6 cycles without breakage damage can carry fatigue load of 165,35 MPa.

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