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An improved design of apparatus for multi-specimen bending fatigue and fatigue behaviour for laminated composites

İrfan Ay [a,*], Raif Sakin [b], Güven Okoldan [b]

[a] Department of Mechanical Engineering, Balikesir University, 10145 Balikesir, Turkey
[b] Edremit Technical Vocational School of Higher Education, Balikesir University, Edremit, Turkey

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Abstract

A previously designed fatigue apparatus to test bending fatigue behaviours of glass–fiber reinforced plastic materials is improved in the scope of this research. The advantages of the improved test apparatus are as follows: It can teste 16 samples instead of 10. The square section axis was used to connect the samples more rigid by instead of the round section. So, a good balance and less vibration were obtained on the apparatus. More functional infrared sensors were used instead of proximity sensors that are sensitive to repeated cycling. While the load stress ratio is $R = 0$ or 1 (two alternative), with a developed adjustable support device, it is $R = -1$, 0 and 1 (three alternatives). The fatigue behaviours of two groups (A and E) of composite fiber samples which have different directions but the same volumes were tested by this new apparatus. As a result, it was observed that the directions of the fibers have an important effect on the fatigue strength.

Keywords: Multi-specimen bending fatigue test apparatus; Glass–fiber reinforced plastic (GFRP); Fatigue life; *S–N* plots

1. Introduction

The usage of composite materials as construction materials in industries is increasing more and more. The material of fan blades used in cold storage depots is generally made of aluminum and their alloys. In this study, the usage of laminated composite materials instead of aluminum has been considered, due to the fact that of the composite material density (0.7 g/cm^3) is lower than that of aluminium (2.7 g/cm^3) (see Table 1) [1].

The fan blades operate under cyclic loads that mostly cause fatigue damages. When the fatigue damage stresses are compared with the ultimate stress of the fan blade material, it is indicated that the fatigue damage stresses are very low [2]. After reaching a certain number of load cycles, a crack starts, and then it grows, and eventually, the fan blade is broken. The fan blades are subjected to the gravitational force, a centrifugal force and a wind force. A wind force has a relatively low frequency and a high amplitude and it is the most dominant force on the fatigue damage. This also generates alternating bending stresses (tension–compression) [1].

It is very well known that fatigue tests have some difficulties. Many specimens have to be tested to obtain reliable results. Thus, much time is required. Test frequency may be increased, but this causes some overheating problems.

An apparatus is needed to decide whether the usage of composite material is suitable or not instead of aluminum. This apparatus will be used to test the fatigue properties of composite materials. The multi-specimen fatigue apparatus was previously both designed and produced by Kim et al. [2]. Later, this apparatus was examined by us and we decided to make improvements as seen in Table 2.

* Corresponding author. Tel.: +90 266 612 11 94; fax: +90 266 612 12 57.
E-mail address: ay@balikesir.edu.tr (İ. Ay).

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Table 1
Comparison of aluminum and glass fiber reinforced polyester composite materials for thermal and mechanical properties

Material	Density (g/cm^3)	Elasticity module (MPa)	Tensile strength (MPa)	Compression strength (MPa)	Maximum working temperature (°C)	Thermal conductivity (W/m°K)
Aluminum	2.7	69	417	–	200	200
Laminated composite (Glass fiber reinforced)	1.5–2.2	7–53	80–900	130–520	170–250	0.2–0.3

Table 2
Comparing of Kim's study and present study

Features	Kim's study (4)	Present authors' study
Number of specimens	10	16
Cross section of axis	Circle	Square
Type of sensors	Proximity sensor	Infrared sensors
Counting unit	By switch	By personal computer
Load ratio adjustment (R)	0 or 1	−1, 0, 1
Frequency adjustment	Not available	Between 0 and 93 rpm
Observation of rigidity	Not available	By pen plotting device

In this study, this new fatigue apparatus will be introduced. Moreover, the fatigue test results achieved by this new apparatus will be explained for two groups of composite samples which have two different directions but the same volumes.

2. Materials and methods

2.1. Fatigue testing apparatus

This new test apparatus is shown in Figs. 1a–c. The multi-specimen rotating bending fatigue test apparatus consists of four main sections:

A motor and sample holders.
A sensor and counting unit.
A Computer and software.
A water bath.

2.2. Motor and sample holder

During the test, the motor was attached to a worm gear whose power was 0.5 HP, the speed was 1390 rpm, and the gear ratio was 15:1. When the motor frequency was 50 Hz, the worm gear output gave 93 rpm. So, the output speed can change between 0 and 93 rpm by frequency adjustment in the main panel.

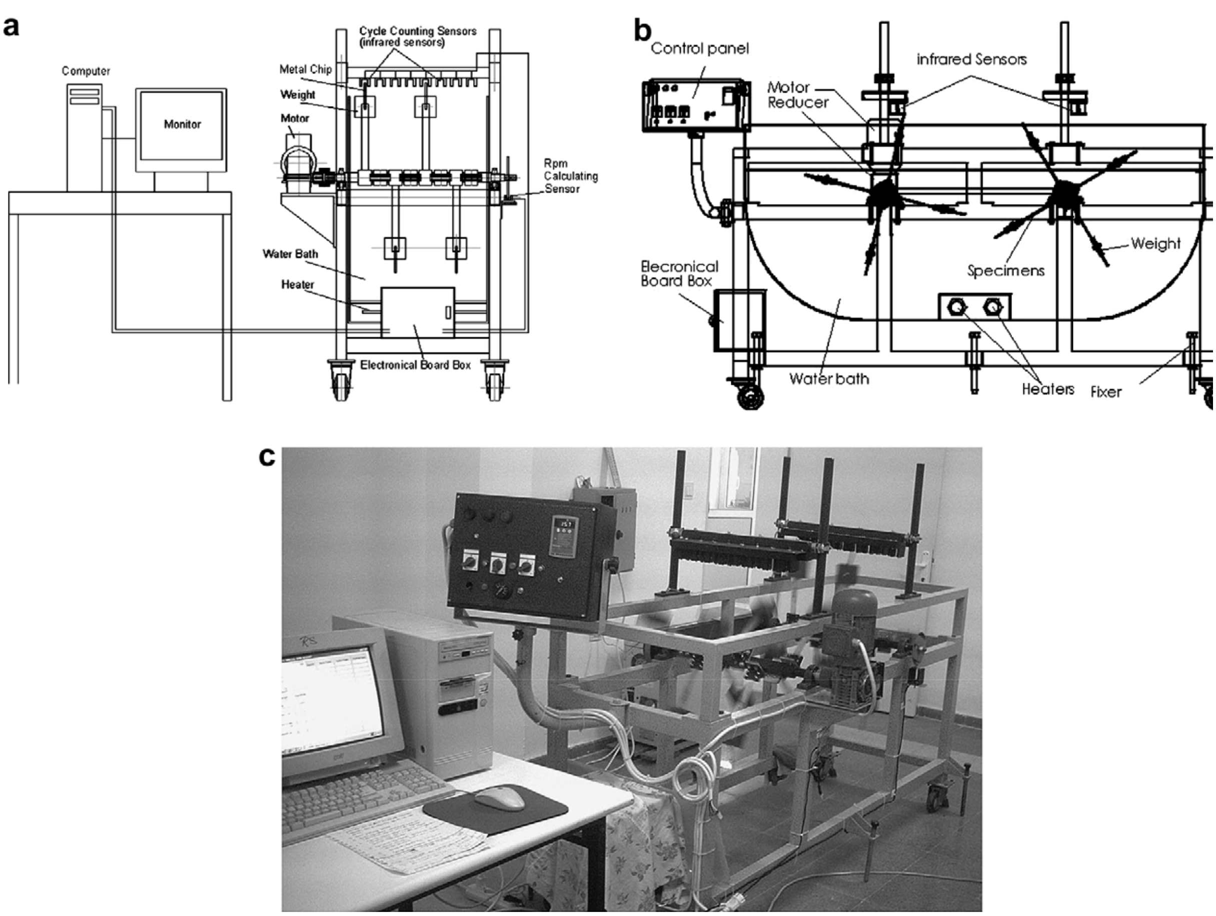


Fig. 1. Rotating fatigue test machine: (a) front view of the apparatus (schematic), (b) left side view of the apparatus (schematic) and (c) photography of the test machine.

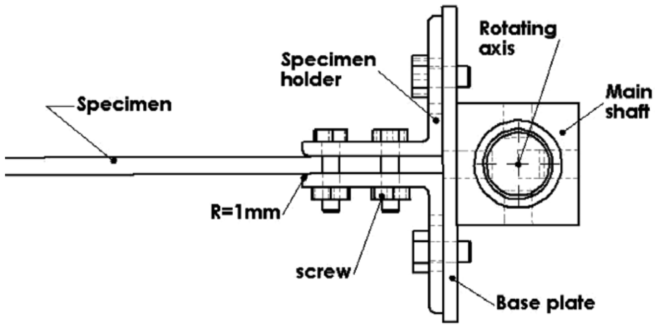


Fig. 2. Clamping apparatus for a specimen.

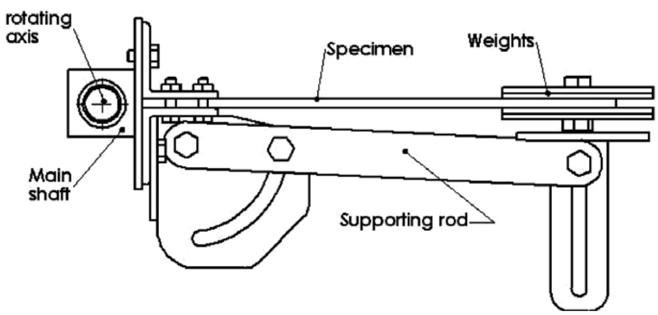


Fig. 3. Supporting apparatus for different stress ratios (R).

There are two axes with square cross sections for sample holders in the test apparatus. One of them is a direct connection to the output axis by the worm gear, and the other is driven by the chain gear. Their rotating speeds are the same as that of the worm gear output. Eight samples are fixed on each rotating axis. The total number of samples that can be tested at a time is 16. The specimens are located on each side of the axis in a helical form and the second axis has a 45° position difference than the first one. This positioning form makes the test rig more balanced .The details of the sample holder unit can be seen in Figs. 1 and 2. Each sample has been fixed on the axis by two screws and two angle brackets. The other side of the specimen carries a proper weight. This causes the required stress (stress controlled mode). Furthermore, a metal chip is attached to the end of the specimen for producing signals to the sensor. The specimens are connected to a base plate from both sides. Also, the base is connected to the main shaft (see Fig. 2).

To obtain different stress ratios (R), an adjustable load supporting rod has been designed; consequently the stress ratio can be adjusted between 0 and 1 or −1 and 0, rather than −1 and 1 (see Fig. 3).

2.3. Sensors and counting unit

Sixteen infrared sensors (IR-LED sensor and opto-transistor) were placed on a metal cover. Sensitivities of these sensors span up to 40–50 mm horizontally but the present gap is 15 mm, and the vertical gap is not important for sensitivity (see Fig. 1a). In Kim's design, proximity sensors were used and these sensors run per the magnetic principle and in the vertical direction. When the metal chip is not close enough to the sensor, the proximity sensor may not count the revolution data. Problems can occur when an unexpected deformation is caused on a specimen. Consequently, infrared sensors used in the new apparatus have some advantages according to proximity sensors.

When the metal chip passes the gap of an infrared sensor, the sensor produces a signal. The signal is transferred to the interpreter chart and then the signal passes to an LPT port of a computer for counting by a signal processing software (SPS). The SPS saves all the revolution data. When a specimen is broken as a result of fatigue during the testing, it falls down and the related sensor does not produce any signal. The counter shows the failure cycles of that specimen (see Fig. 1c).

2.4. Computer and software

A Pentium III 800 MHz PC was used with which SPS has been used to count and record the data. This software also shows the cycle number and checks the broken specimen.

2.5. Water bath

When the fatigue test is performed in water or other liquid medium at a constant or variable temperature, the temperature of the liquid can be controlled by a thermostat connected to a heater. If needed, the water bath can be connected to the apparatus (see Fig. 1b). In this study, a water bath was not used.

3. Preparation of the test specimens

Laminated composites which consist of polyester as the matrix structure were obtained from Sisecam Co. (Turkey) (general purpose unsaturated polyester resin CE 92 N8 type), 1% cobalt as the catalyst, MEK peroxide as the hardener, stren to reduce the viscosity, woven glass fiber (800 g/m^2) and random mat glass (225 g/m^2) as reinforcement from Fibroteks Co. (Turkey). The RTM (Resin Transfer Molding) method was used for the production of the laminated composite plates and the dimensions of the plates were $320 \times 600 \times 3.25$ mm. The test specimens were cut from these plates according to the standard ASTM 3039 specifications so as to have with dimensions of $25 \times 250 \times 3.25$ mm (Fig. 4) [3]. The properties of the laminated composite specimen are given in Table 3.

4. Fatigue tests

For the minimization of heat effects on the composite material during the fatigue tests, the test frequency is kept less than 10 Hz [4]. In this study, the practical test frequency

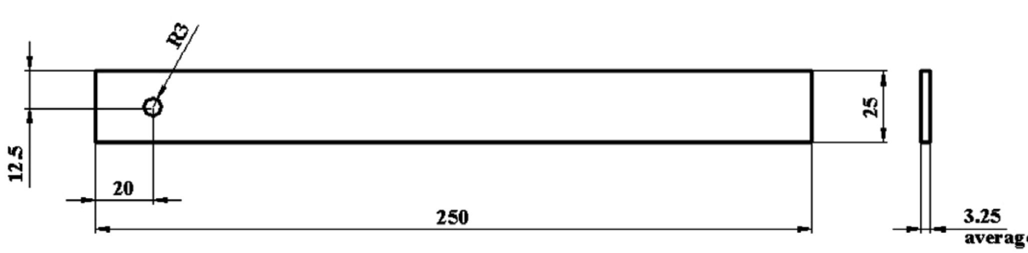


Fig. 4. Dimensions of a fatigue specimen.

Table 3
The specimens groups and their properties

Group	Fiber orientations	Glass fiber volume	Glass–fiber combination
A	±45	44.00%	3 Ply 800 g/m^2, Woven 4 Ply 225 g/m^2, Random mat
E	0/90	44.00%	3 Ply 800 g/m^2, Woven 4 Ply 225 g/m^2, Random mat

was 2 Hz, test temperature was room temperature (about 20 °C). In the maximum load calculations, Eq. (1) was used [2]. The gravitational and centrifugal forces were neglected to simplify Eq. (1):

$$\sigma_{\max} = -\sigma_{\min} = \frac{6FL}{BH^2} \tag{1}$$

where $\sigma_{\max}$ is the maximum strength value (MPa), F is the applied load (N), L is the distance from the applied load point to the fracture area (mm), B is the sample width (mm) and H is the sample thickness (mm). The slotted weights of various thicknesses were used to apply load to the specimens.

As seen in Figs. 4 and 5, a tension-compression fully reversed load ($R = -1$) was applied to the specimens. Different slotted metal weight combinations were used to apply the required loads to the specimens. The weights were mounted on the specimens as seen in Fig. 6. The fatigue tests were carried out until all the specimens fractured or the cycles passed 1 million [2,5,6]. The *S–N* plots were drawn from the test results of *A–E* group laminated composites.

5. Results and discussion

The biggest difficulty for the fatigue test of a material is its long testing time. For example, if a single laminated composite specimen is tested at a low frequency (as 2 Hz), the test time takes as long as 23 days for 1 million cycles. To obtain eight points in the *S–N* plot (each point requires four specimens), the total number of the specimens is 32, and their total test time is about 736 days. Sixteen specimens can be tested at a time with the test apparatus improved by the authors. With this improvement, the test time has been reduced to 46 days for 32 specimens.

For *S–N* plots, according to the ASTM 790-00, three point bending tests were carried out for each group composite specimens and their maximum bending strengths were obtained [8]. The maximum bending strengths were 203.12 MPa and 353.54 MPa for groups *A* and *E*, respectively. These values were accepted as fatigue strength against 1 cycle in the *S–N* plot [2,9], and were decreased 10% for each following stage of the *S–N* plot point (second, third, etc.). Consequently, *S–N* plots were completed with 7 or 8 points. As accepted failure cycles (Endurance limits is after 1 million cycles) of test groups (*A* and *E*) are 53.044 MPa and 85.139 MPa respectively. The difference in the values is 62.3%; this is the evidence of changing in the fatigue strength with the direction of the glass fiber.

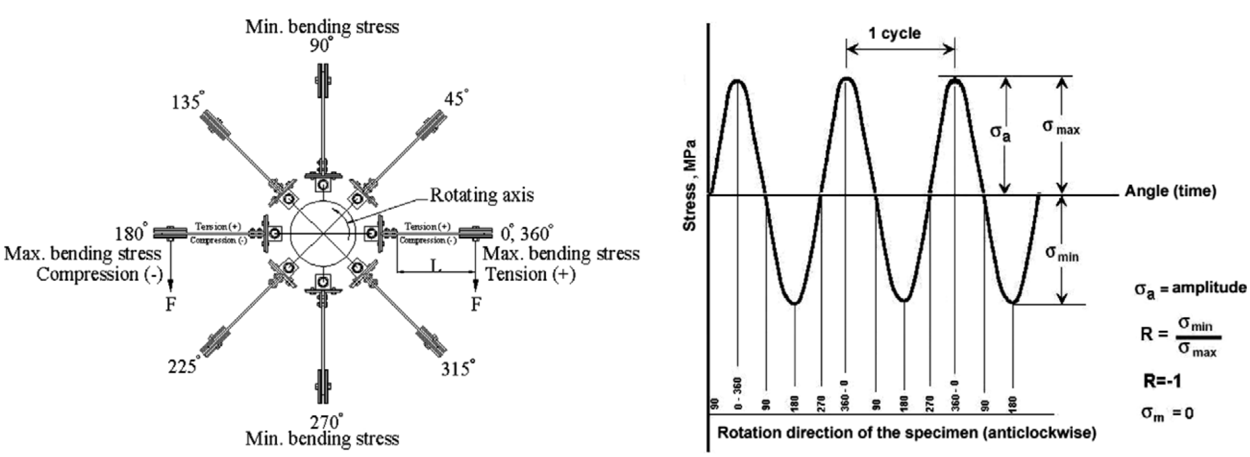
The experimental fatigue curves are characterized with the power function (Eq. (2)) [9,10].

$$S_a = A(N_f)^{-B}, \tag{2}$$

where N_f is the number of cycles (cycle), S_a is the stress amplitude (MPa), A and B are the material coefficients.

Table 4 shows the fatigue strength values corresponding to 1 million cycles. The regression coefficient (R^2) is considerably satisfactory. *S–N* plots for *A* and *E* groups' specimens were drawn and compared to each other in Fig. 7.

In recent years, the real parts are used (with shape, size, conditions, and material) rather than standard specimens for testing the fatigue properties of important parts. The fatigue of the fan blades used in real service conditions occurs from mainly the pushing wind forces. These real service conditions match exactly with the forces applied in the new test apparatus [7]. So, it can be said that this new appa-



Loads of the rotating system   Sinusoidal loading.

Fig. 5. Stress distribution during the rotation.

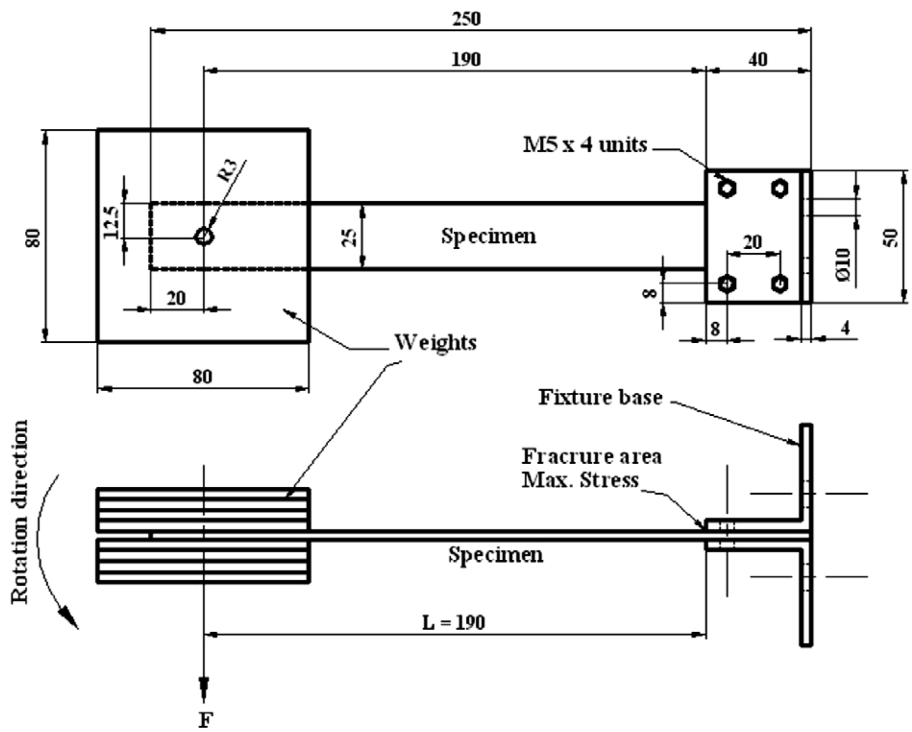


Fig. 6. Schematic view of slotted weights mounted on the specimens [7].

Table 4
Fatigue strength values against 1 million cycles for the *S–N* plots

Group	R^2	*A*	*B*	S_a (MPa)
A	0.9956	202.88	−0.0971	53.044
E	0.9894	342.24	−0.1007	85.139

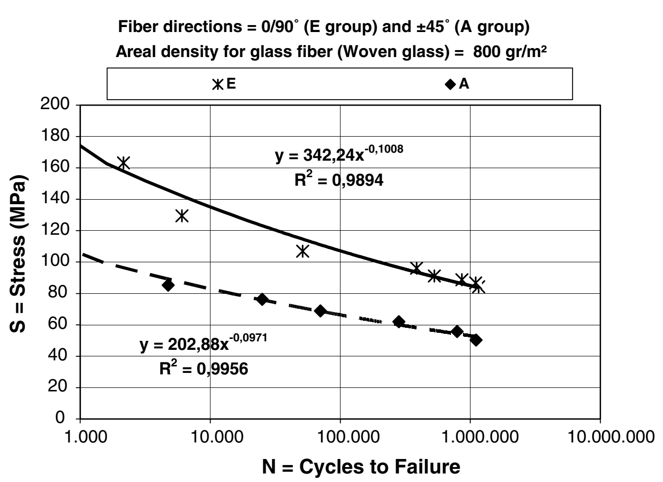


Fig. 7. Comparison of the *S–N* plots obtained for glass-fiber specimens (*A* and *E* Group) [7].

ratus tests are accurate and closer to the fatigue behaviours in real service conditions of the fan blades made of composite material. Thus, it can reach more reliable results [11].

6. Conclusions

A bending fatigue test apparatus designed and produced previously was modified to obtain the following improvements:

1. Total test time has been considerably reduced because of which 16 specimens can be tested at a time.

There has been less vibration on the apparatus during the test because of the fixed placement of the specimen on the square section axis.

The sensitive gap of the sensors has been increased by using a more functional infrared sensor instead of a proximity sensor.

Experimental data and parameters can be monitored by the SPS during the test.

With a developed adjustable support device, the different load stress ratios as $R < 0$ and $R \geqslant 0$ can be obtained rather than only one stress ratio.

By using an out device that indicates "decreasing of rigidity" as a result of fatigue, the real route of the applied load point of the samples operating under constant stress can be drawn. Thus, a mathematical model can be formed easily and the real (*R*) ratio can be calculated. This study should be conducted in the future.

The revolution of these square sectioned axes can be regulated between 0 and 93 rpm by the help of a frequency adjuster.

2. It has been proved that this new apparatus can be used easily for bending fatigue tests at low frequency and low stress conditions for plastics and composites materials.
3. Fatigue strength difference between the GFRP samples in groups *A* and *E* which have different directions but the same volumes goes up to 62.3%. This difference clearly indicates that the anisotropy property of the glass fibers has a considerable effect on the mechanical properties of the laminated composites.

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