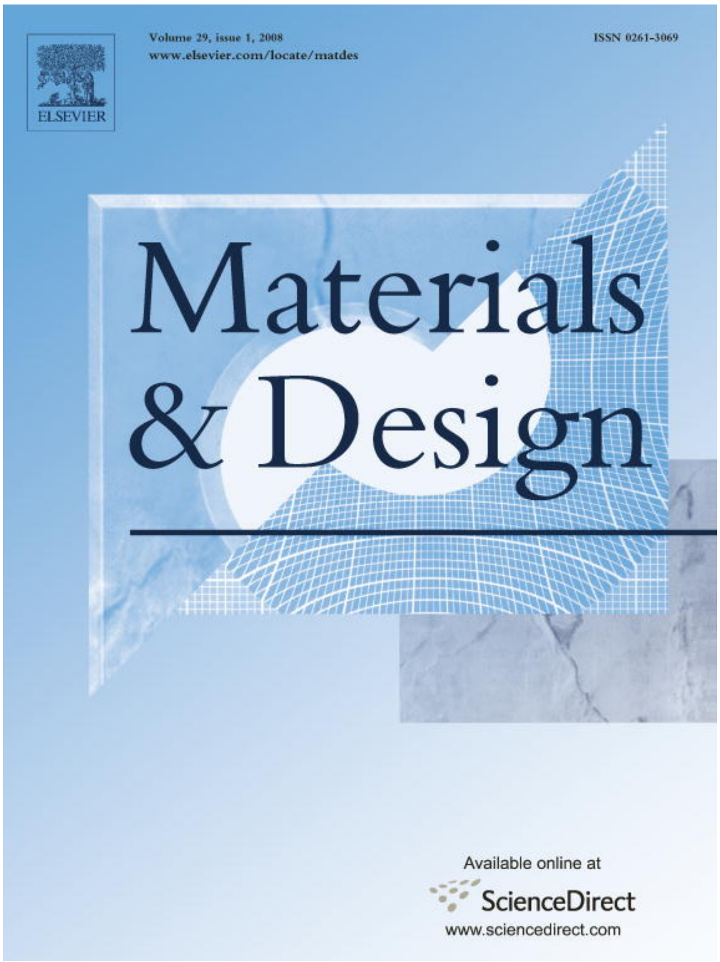
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Technical Report

An investigation of bending fatigue behavior for glass-fiber reinforced polyester composite materials

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Abstract

To investigate bending fatigue behaviors for glass-fiber reinforced polyester composite material, 800 g/m^2, 500 g/m^2, 300 g/m^2, and 200 g/m^2 glass-fiber woven and 225 g/m^2, 450 g/m^2, and 600 g/m^2 randomly distributed glass-fiber mat samples with polyester resin have been used. The samples have been produced by the RTM (Resin Transfer Molding) method and the samples have been cut down with directions of 0/90°, ±45°. As results of the combinations from the samples, nine different structures has been obtained. Furthermore, a new mold have been designed for the RTM method. To provide a full infiltration (wetting) of fibers, a simple method has been applied in this new mold system. A new computer aided and multiple-specimen test apparatus have been designed and constructed to simulate load and stress behavior of axial fan blades on the wind tribunes. This multiple specimen apparatus has a big advantage to shorten test time and to test 16 specimens at the same time. Firstly, composite specimens have been applied to the three-point bending test. Later, fatigue tests have been carried out. For the bending fatigue test, "fixed stress" fatigue type has been used. To determine the fatigue limit of all the specimens, S–N diagrams (Wöhler plots) have been derived from experimental results.

According to the test results, the highest fatigue life has been obtained from 800 g/m^2 fiber glass woven specimens with 0/90° (group E). The property of anisotropy of the GFRP (Glass Fiber Reinforced Plastic) material is dominant on the fatigue strength which has been clearly observed from the experiments. In the test results, the effective parameters are density of fiber distribution on the area, fiber angle, resin permeability of woven fiber, full infiltration (wetting) or without infiltration of fibers.

1. Introduction

Glass-fiber reinforced polyester composite materials are used instead of metallic materials because of their low density, high strength, and high rigidity. Because of such properties, GFRP materials are preferably used in wind turbine blades, in air, sea and land transportation. Most of these materials are subjected to a cycle loading during the service condition.

The mechanisms of composite materials under cycling loading and their fracture behaviors are really complex. For this reason, the study which has been done to identify the fatigue behavior under the cycling loading is essential for using composite materials safely [1–4].

In industrial applications, most materials are subjected to cycling loading and deformation in the lower value of ultimate strength. For this reason, usability of these materials can be decided in a better way by knowing their fatigue behaviors. For this aim, generally S–N diagrams are used [1–5].

Long testing time is one of the most difficult step in the fatigue test. This long test time can be reduced by increasing the test frequency. However, increasing the test frequency produces some problems such as mechanical failure by hysteric heating [6].

As it is also mentioned in the literature, different loading frequencies are obtained for fatigue tests of composite

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material by fatigue apparatus. Generally, 10 Hz or lower frequency is used to minimize heating [6]. These problems are especially important in polymer materials. Testing conditions should be similar to service conditions as much as possible.

The aim of this study, is to investigate the failure which is caused by bending fatigue in axial fan blades and wind turbines made by composite materials. In this study 800 g/m^2, 500 g/m^2, 300 g/m^2 and 200 g/m^2 glass-fiber woven, and 200 g/m^2, 450 g/m^2 and 600 g/m^2 randomly distributed glass-fiber mat samples with polyester resin have been used. The production of test samples have been done in a special mold system by the method of RTM (Resin Transfer Molding).

The samples have been subjected to bending fatigue in a computer aided multi-specimen fatigue tester which has been improved by us [7].

2. Materials and methods

In this study, general purpose unsaturated polyester resin CE 92 N8 type as shown in Table 1 and woven glass-fiber as shown with its mechanical properties in Table 2 have been used [8,9]. A schematic representation of woven glass-fiber is given in Fig. 1. In order to obtain the GFRP sample by the RTM method a heated mold system was constructed as shown in Fig. 2.

First, the mold was sprayed with a mold release agent to facilitate the later removal of the molding. Then, one layer of woven glass-fiber and one layer of mat glass-fiber were put into the mold as shown in Fig. 3. Special transparent silicon was used to prevent leakage in the mold. Fifteen percent stren was added into polyester resin to reduce viscosity in accordance with RTM [7,8]. Cobalt catalyst (0.2%) and 0.7% MEKP curing were added to a 1000 ml mixture of polyester and stren [7]. Then, the mixture prepared was injected into the mold at a pressure between 0.5 and 1 bar.

The injection cycle was repeated 5–7 times to prevent bubbles and for homogeneous wetting of plates in the mold. About 12 h later, the mold was opened and a plate with dimensions of 320 × 600 × 3.25 mm was removed out of the mold. In this way, nine different material combinations were obtained (see Table 3). Fatigue test samples were prepared from these plates with dimensions of 25 × 250 × 3.25 mm similar to the ASTM 3039 tensile standard dimensions (see Fig. 4) [7,10]. By preparing samples from the same plates with dimensions of 18 × 140 × 3.25 mm according to the ASTM 790-00, three point bending tests were carried out to obtain the maximum bending strength [12].

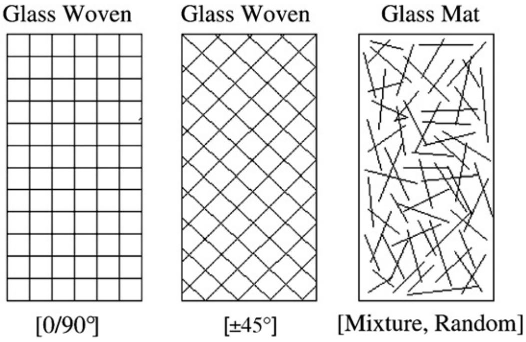


Fig. 1. Schematic representation of used glass-fiber.

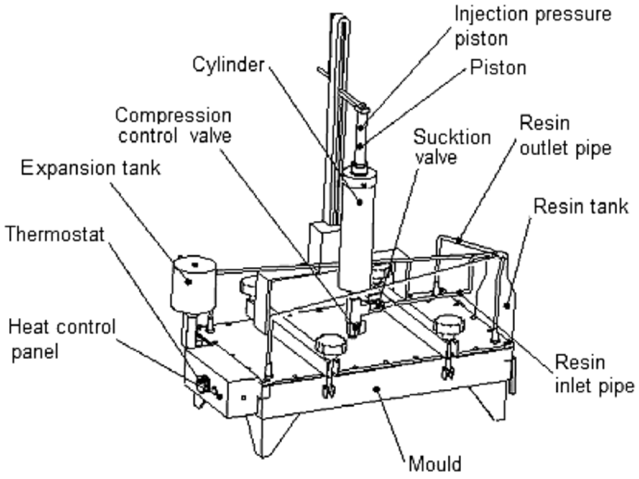


Fig. 2. Application and schematic picture of RTM mould system.

Table 1
Liquid CE 92 N8 Polyester resin properties [8,11]

Properties	Unit	Value of specifications
Viscosity	Cps	400 ± 60
Jell time (25 °C)	min.	8 ± 2
Specific density	g/cm^3	1.2
Hardness	Barcol	Minimum 45
Bending strength	MPa	Minimum 85
Ultimate strength	MPa	Minimum 45

Table 2
Approximate mechanical properties of glass-fiber (E–Glass) [10]

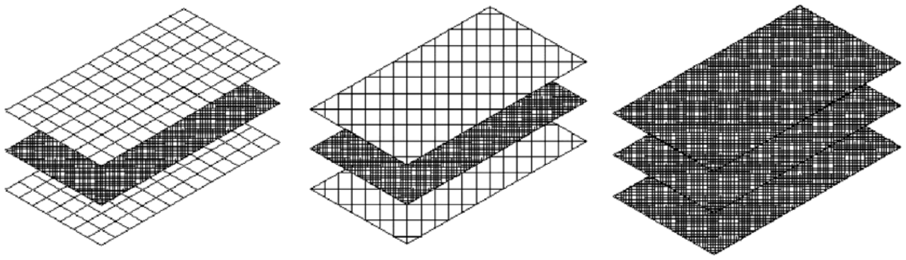
Material type	Ultimate strength (MPa)	Tensile module (GPa)	Typical density (g/cm^3)
Glass fiber–E Glass	2400	69	2.5

Fatigue samples shown in Fig. 4 were tested in a fatigue apparatus which was specially designed and improved by us as shown in Fig. 5. During the test the motor power was 0.5 HP, its speed was 1390 rpm, the speed of the worm gear was 30 rpm, the test frequency was 2 Hz, test period was 0.5 s and the test heat was room temperature.

The bending fatigue test is a load control test. The samples were affected by gravitational force, centrifugal force and pushing wind force during the rotation, as in wind turbine blades. The real service conditions were obtained for the samples by the usage of this new test apparatus. However, because of a lower rotating speed, the effects of gravity and centrifugal forces were ignored. Bending stresses were only caused by the weights which were accepted as effective. During the test, when the sample is in a horizontal position (0–180°), maximum stress occurs. The absolute values of these stresses are equal to each other ($\sigma_{\max}$, $-\sigma_{\min}$). During rotation at 0° while the upper fibers are subjected to tension, the lower fibers are subjected to compression when the sample position is 180°, upper fibers are subjected to compression and the lower fibers are subjected to tension. Thus, this stage is tension-compression fully reversed. In this situation the fatigue stress ratio is $R = -1$, as shown in Fig. 5 [7].

3. Results and discussion

Fixed stress fatigue type was used in bending fatigue tests. To identify the fatigue life of all specimens, S–N diagrams (Wöhler plots) were obtained from experimental data.



(a) [0-90°/Mat]$_3$ (b) [±45°/ Mat]$_3$ (c) [Mat]$_3$

Fig. 3. Placement of glass-fiber used in RTM method.

Table 3
Groups and combinations of glass-fiber reinforced composites samples

Group	Woven fiber direction	Glass-fiber volume (%)	Glass-fiber combination (g/m^2)
A	±45	44.00	3 Layers 800 Woven
			4 Layers 225 Mat
			4 Layers 500 Woven
B	±45	44.67	4 Layers 225 Mat
			1 Layer 450 Mat
			5 Layers 300 Woven
C	±45	44.00	4 Layers 225 Mat
			2 Layers 450 Mat
D	±45	42.67	7 Layers 200 Woven
			8 Layers 225 Mat
E	0/90	44.00	3 Layers 800 Woven
			4 Layers 225 Mat
			4 Layers 500 Mat
F	0/90	44.67	4 Layers 225 Woven
			1 Layers 450 Mat
			5 Layers 300 Mat
G	0/90	44.00	4 Layers 225 Woven
			2 Layers 450 Mat
H	0/90	42.67	7 Layers 200 Woven
			8 Layers 225 Mat
K	Random	44.00	6 Layer 450 Mat
			1 Layer 600 Mat

Bending stress corresponding to average $N = 10^6$ cycles were basically considered as a failure criterion [1,2,6] Empirical formulas were derived from S–N diagrams that are drawn for the identification of fatigue life and material constants were calculated. The model used conforms to the models in the literature [1–3,5,6].

The main feature of a multi-sample fatigue apparatus is to test 16 samples at a time and it can monitor all of its test data and parameters from a computer. Although the apparatus runs at a low frequency during the test, as 16 samples were tested at a time, the overall test periods were greatly reduced. The software was used in the monitoring of test data. The possibility of failure was reduced to a minimum level. As a result of the tests, the usability of the improved apparatus was proved for fatigue tests on plastics and composite materials which need a low frequency and a low applied stress level [7].

When S–N diagrams in Figs. 6 and 7 are examined, 0/90° fiber directional samples clearly have a higher life time than that of ±45° samples.

When Fig. 8 is examined, life progressive percentage and their reliability of all group samples can be seen. For example, under a 100 MPa stress, life progressive possibility of all samples are as follows: $A = 40.26\%$ $C = 46.81\%$ $D = 42.24\%$ $B = 50.21\%$ $H = 63.82\%$ $G = 63.97\%$ $E = 65.45\%$ $F = 70.09\%$. These results approved that the mechanical properties of glass-fiber reinforced composites have changed depending on the directions of the fiber.

As shown in Fig. 9 samples in group E have the maximum and samples in group A have the minimum bending fatigue stress. The samples in group K have almost the same values as the samples in groups B and C.

Maximum fatigue life/Maximum bending stress ratio is shown in Table 4. According to this evaluation, while the samples in group A have the lowest performance in other evaluation criteria, they have the highest performance as considered in the maximum fatigue life/maximum bending stress ratio, as shown in Fig. 9 and Table 4. So, this is a considerable result. Ratios when considered, are between 25% and 20%. This leads us to know one of the rough values (fatigue or bending strength) according to the other. An empirical formula can be derived from these data. However, interpretations are open to discussions.

As a result, the maximum fatigue life has been determined in the composites of group E, which is composed

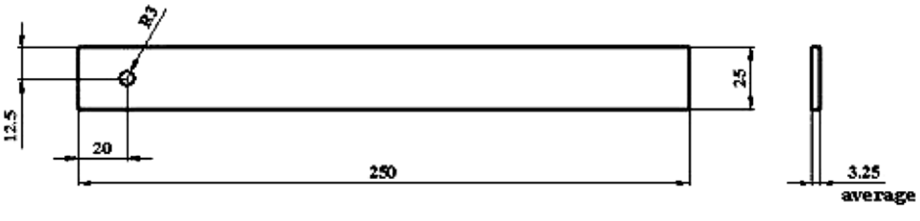
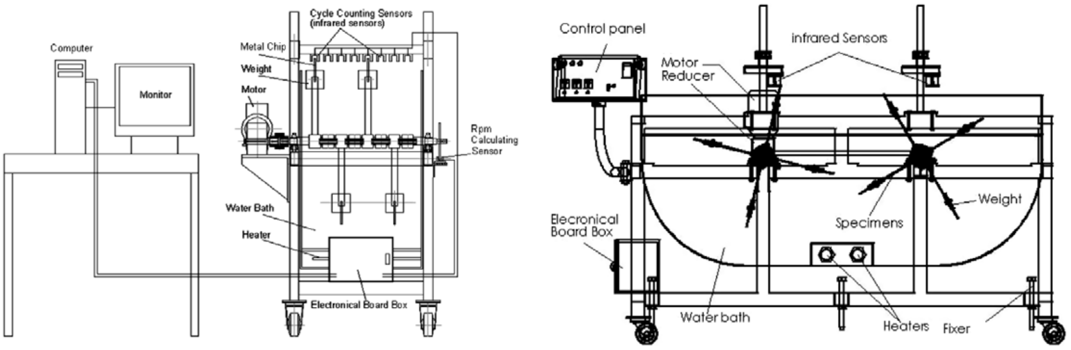


Fig. 4. Dimensions of fatigue samples [12].



(a) Front view of test apparatus (schematic)

(b) Left side view of apparatus. (schematic)

Fig. 5. Schematic view of multi-specimen and fixed stress bending fatigue test apparatus.

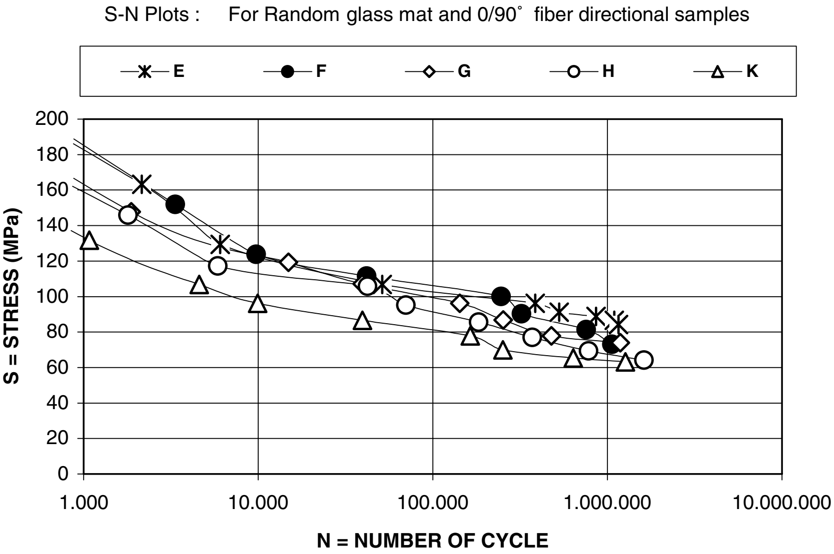


Fig. 6. Comparison of S–N plots for glass-fiber having 90° direction samples.

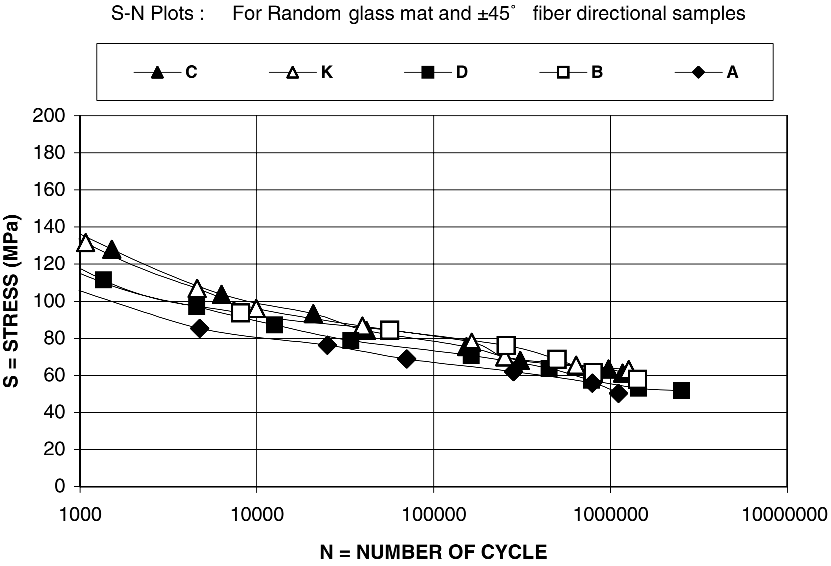


Fig. 7. Comparison of S–N plots for glass-fiber having ±45° direction samples.

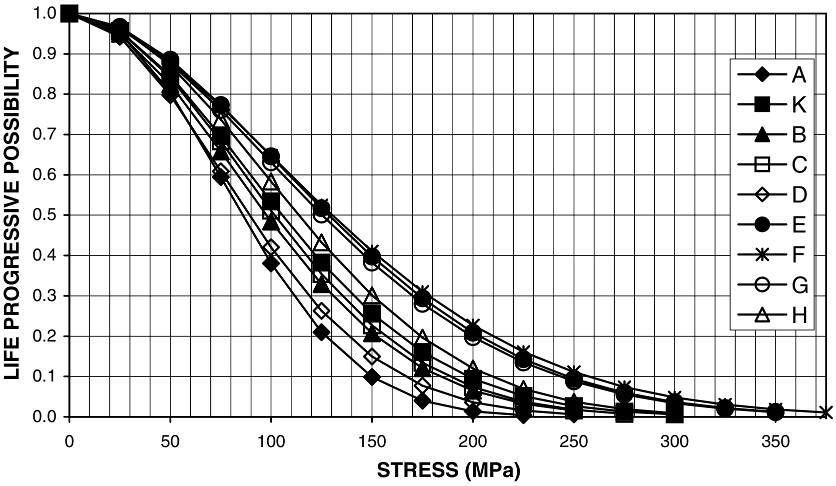


Fig. 8. Graph of life progressive possibility for all group samples.

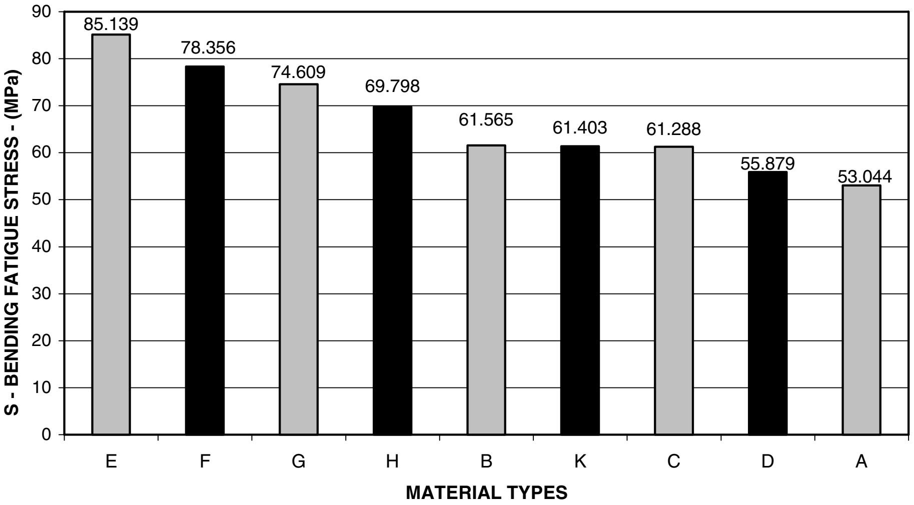


Fig. 9. Average bending stress values obtained for 10^6 cycles in S–N curves.

of 800 g/m^2 glass woven and a 0–90 direction. The test results were influenced by the regional density of glass-fibers on the area, ply angles, suitable placement of glass woven fibers and parameters of RTM methods (injection pressure, suitable placement of fibers, numbers of injection, etc.) and whether these fibers get infiltrated or not [7].

Table 4
Maximum fatigue life/maximum bending stress (% ratio)

Groups	Maximum fatigue life (10^6 equivalent cycle) (MPa)	Maximum bending stress (MPa)	(%) ratio
A	53.044	203.120	26.10
B	61.565	258.287	23.83
C	61.288	278.313	22.02
D	55.879	265.468	21.04
E	85.139	353.540	24.08
F	78.356	375.199	20.88
G	74.609	348.198	21.42
H	69.798	311.503	22.40
K	61.403	295.532	20.77

The reliability of these test results will be confirmed by the usage of Weibull distribution in another study.

4. Conclusions

We can write the following results from bending fatigue test data of glass-fiber reinforced composite laminates produced by the RTM method and considered as wind turbine and fan blade material.

1. The usability of the new apparatus improved by us has been proved in fatigue tests of plastic and composite materials which require a low frequency and stress.
2. It has been determined that samples in group F have the maximum bending strength and the minimum in group A. While the maximum fatigue strength in the samples of group E and group F has been obtained, but the sample in group A has the minimum fatigue strength.

3. More injection cycle has been done in low density fibers for a complete infiltration (wetting). However, this stage increased to the usage of residual polyester because of less injection cycle in the production of the samples in groups E and F as compared to the sample in group D, the usage of residual polyester was reduced.
4. For the same glass-fiber volume, 7 layers of 200 g/m^2 glass woven and 8 layers of 225 g/m^2 glass mat, totally 15 layers of glass-fiber have been used for the samples in group H, 3 layers of 800 g/m^2 glass woven and 4 layers of 225 g/m^2 glass mat have been used for the samples in group E. When the two stages are compared, there has been less workforce in the second stage.
5. In the production of samples in groups E and F by the RTM method, one prefers in the design for having an easier workforce, less usage of residual polyester and a maximum bending and fatigue strength.
6. The strength difference between the samples in group is A and E which have the same fiber density but different directions goes up to 60%. This stage shows that ,the anisotropic property of GFRP obtained by the usage of 800 g/m^2 glass woven-sample is higher than the other glass woven-sample of GFRP.
7. Although maximum fatigue strength values have been obtained from the samples in group E, the usage of 800 g/m^2 glass woven-sample can be risky in design because of having higher anisotropic properties as compared to the other fiber densities. For this reason, the usage of 500 g/m^2 will be more suitable in design. Because, 500 g/m^2 glass-fiber usage decreases the risk of anisotropic property and provides full infiltration.
8. Generally, all the test results have been effected by the regional density of the glass woven fiber area, the directions of fibers, resin permeability of glass-fibers, parameters in the RTM method and whether the fibers are completely infiltrated or not.

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