FATIGUE BEHAVIOR OF GLASS / POLYESTER COMPOSITES

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ABSTRACT

This paper discusses the fatigue behavior of a unidirectional glass / polyester composite in terms of fiber volume fraction and fatigue loading direction (longitudinal and transverse). The polyester base matrix is also included. Static tensile tests are achieved to establish the static fracture strength and stiffness. The fatigue study is performed with cycle ratio R = 0.1. The experimental data points are plotted in the form of maximum fatigue stress versus the fatigue life. The results showed that the increase in fiber volume fraction increases the longitudinal fatigue resistance while it has opposite effect on the transverse fatigue resistance. The matrix properties dominates the static and fatigue behavior of composite material in the transverse direction.

INTRODUCTION

A fundamental problem concerning the engineering uses of fiber reinforced composites is the determination of their resistance to cyclic loading. This problem is of much greater importance for fiber composites than for metals [1]. Previous fatigue studies for composites subjected to tension - tension cycling load have resulted in favorable behavior [2]. Other studies on composites in tension - compression and compression - compression fatigue [3] indicated a substantial reduction in fatigue life as compared to the tension - tension case. The assessment of the material fatigue performance in terms of the well known S - N curves is of critical importance as the material itself is not a conventional one.

The present experimental study is focused on the characterization of the nature and extent of the induced fatigue strength in a polyester resin as well as in a reinforced polyester with E - glass fibers in both longitudinal and transverse directions. For each of the loading directions, longitudinal and transverse, two fiber volume fractions (V_f) are investigated. Tensile tests are first carried out on polyester and glass /polyester composite to establish the static fracture strength and stiffness. The composite stiffness is also evaluated by means of the ultrasonic technique and is predicted by the micromechanics analysis [4]. Then, tension - tension fatigue tests with cycle ratio R = 0.1 and frequency varied form 4 Hz to 15 Hz are preformed. Influence of fiber volume fraction and loading direction on the fatigue behavior is revealed.

MATERIALS AND EXPERIMENTAL WORK

Unidirectional composite materials consisted of a commercial continuous E - glass fibers laid in a thermoset polyester resin (SIROPOL 7440). The prepared composite plates have a fiber volume fractions (V_f) of 28.7% and 42.6% with a nominal thickness of 3.2 mm and 4.5 mm, respectively. The test specimens were cut from the original plates using a diamond - impregnated tool with axis parallel and normal to the fiber direction for longitudinal and transverse specimens, respectively.

Static tensile test specimens were prepared and tested according to the standard specification of ASTM D 5083 for composite tensile test. The fatigue test specimen has a rectangular cross - section with 15 mm width and 180 mm length. A universal testing machine was used with cross - head speed of 1 mm/min. at the ambient conditions. Fatigue tests were performed under cyclic sinusoidal controlled load and the number of load cycles for complete fracture were recorded. Lausenhaussen fatigue testing machine with load capacity of 6.5 tons was used. The cycling frequency was 4 Hz for high fatigue load levels and 15 Hz for low fatigue load levels. The experimental program can be summarized as given in Table (1).

Table 1. Experimental test program.

Material	Reinf. configuration	V_f	V_v	Loading dir.	No. of tested specimens	
					Static	Fatigue
Polyester resin	-	-	-	-	5	19
Unidirectional glass/poly.lamina	R1150	28.7	4.93	Long.	5	17
				Trans.	5	14
	R2310	42.6	3.95	Long.	5	19
				Trans.	5	15

V_v = Void content R = Roving Fiber

RESULTS AND DISCUSSIONS

Static Tensile Properties

Static tensile tests were conducted on the unidirectional glass / polyester composite as well as the polyester resin. Experimental results were obtained in the form of stress - strain curves as shown in Figure (1), for polyester resin. The tensile stress - strain curves of glass / polyester composite loaded in the longitudinal and transverse directions are presented in Figure (2 (a,b)). Results show that the longitudinal fracture strength (S_L) increases by about 14.5% with increasing the V_f from 28.7% to 42.6%. The corresponding fracture strain is found to be about the same and approximately equals 3%. The longitudinal stiffness (E_L), also, increases by about 23.5% with increasing V_f. In contrast, the transverse fracture strength (S_T) is found to be insensitive to the change in V_f and the corresponding fracture strain is about 2%. The transverse elastic stiffness (E_T) decreases by about 14.3% with increasing V_f. It is noted that, the lowest composite fracture strength value is in general S_T for both values of V_f used and approximately equals 30 MPa and is found to be about half the experimental resin fracture strength (60 MPa). It can be shown that the transverse elastic stiffness is not greatly affected by V_f and is almost equal to that of the experimental polyester stiffness (2450 MPa).

The elastic stiffness of the polyester resin and the unidirectional glass / polyester composites were also determined by the ultrasonic technique and by the micromechanics analysis [4]. Table (2) gives a comparison between the experimental and predicted elastic stiffnesses. It can be seen that the values obtained by the ultrasonic technique and the micromechanics analysis are considered in reasonable agreement for longitudinal direction as well as for polyester resin. On the other hand, the two methods gave higher values than the corresponding stiffness obtained from the tensile test. The table shows clearly that the longitudinal stiffness obtained by different methods (micromechanics, ultrasonic, tensile test) depends on V_f. However, the transverse elastic stiffness obtained by the ultrasonic technique is much higher than the corresponding theoretical and experimental values for the two fiber volume fractions used.

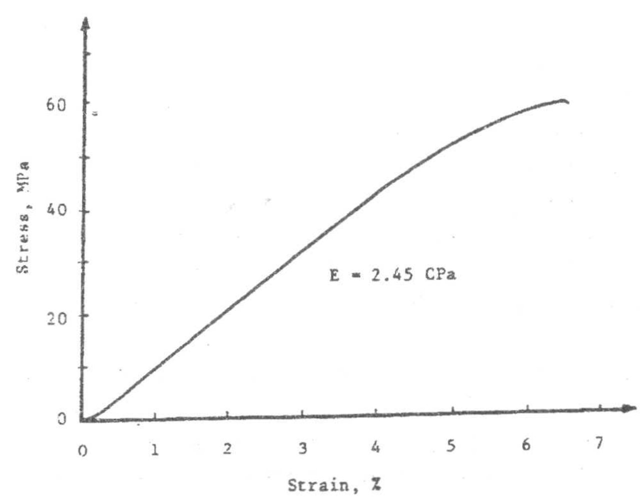

Figure 1. Typical tensile stress-strain curve of polyester.

Table 2. Comparison between experimental and predicted elastic stiffness in MPa.

Material Method	Glass / Polyester Composite				Polyester
	Longitudinal		Transverse		
	Vf=0.287	0.426	0.287	0.426	
Micromechanic analysis [4]	22612	31851	5586	6815	3800
Ultrasonic NDT method	18546	26193	11745	10878	3557
Tensile Test	8213	10147	2469	2116	2450

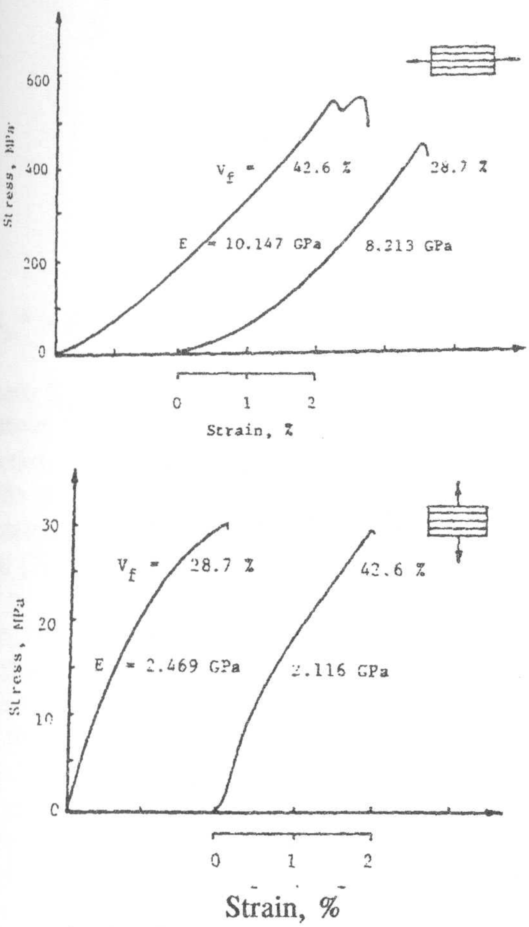

Figure 2. Typical tensile stress-strain curves of glass/polyester composite
a- Longitudinal b- Transverse.

The micromechanics analysis showed that the predicted longitudinal fracture strength (S_L) for V_f = 28.7% and 42.6% are 572.8 MPa and 831.6 MPa, respectively, while for the predicted transverse fracture strength (S_T) for Vf 28.7% and 42.6% are 30.7 MPa and 31.6 MPa, respectively. The experimental tensile tests revealed that the longitudinal fracture strength (S_L) is lower than the theoretical values. However, the transverse (S_T) fracture strength values obtained both experimentally and theoretically are quite the same.

Fatigue Properties

Fatigue behavior at cycle ratio R = 0.1 is determined for unidirectional glass / polyester composite at five loading levels. Low cycling frequency (4 Hz) is used for the two high load levels, while for the two low load levels high cycling frequency (15 Hz) is applied. The medium load level is performed at frequency of 10 Hz. Experimental data are plotted for the maximum applied fatigue stress versus the fatigue life, (S_{max} - N) diagram, for polyester base matrix and glass / polyester composites as shown in Figure (3) and Figure (4), respectively. Close investigation of Figure (4-a) shows that, for the longitudinal direction, the increase in fiber volume fraction (V_f) shifts the S - N curve upward. Opposite effect of V_f can be observed on Figure (4-b), for the transverse direction, at high stress levels while at low stress levels the S - N curves intersect and the effect is reversed again. This might be due to the effect of void content (V_v) and/or the cycling frequency. Chamis [4] stated that void content directly affects the composite matrix strength which plays a major role in determining the composite transverse strength. The matrix strength in the presence of voids can be calculated by the following equation.

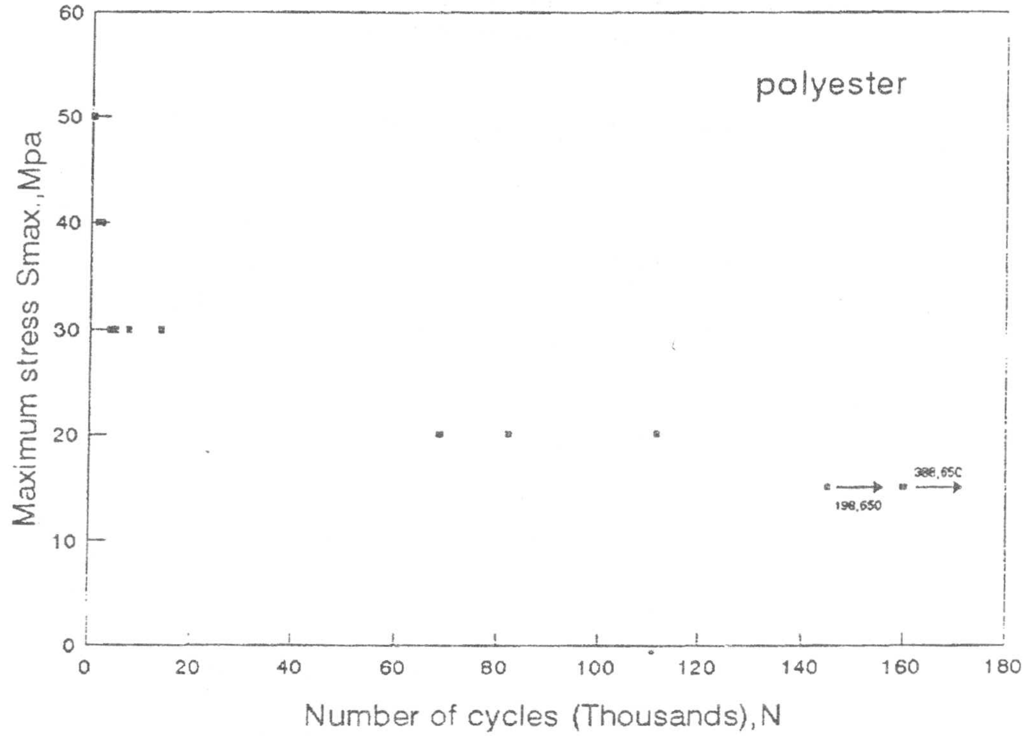

Figure 3. Polyester fatigue S_{max} - N curve.

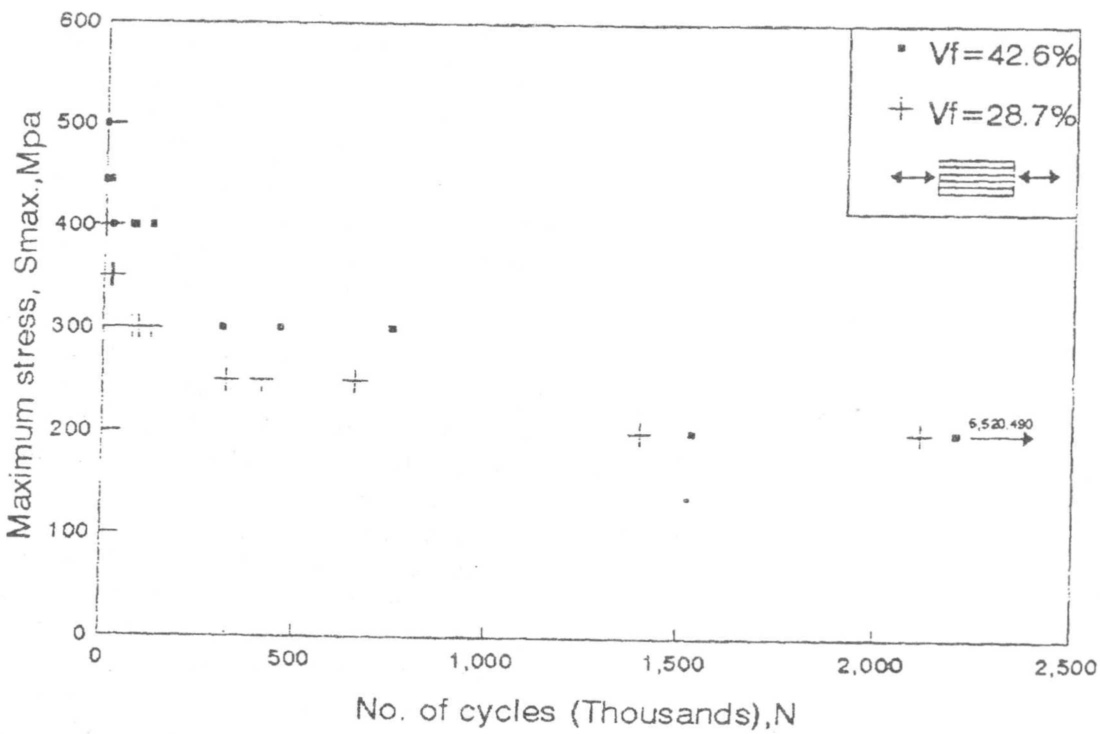

Figure 4-a. Longitudinal glass/polyester fatigue S_{max}-N curve.

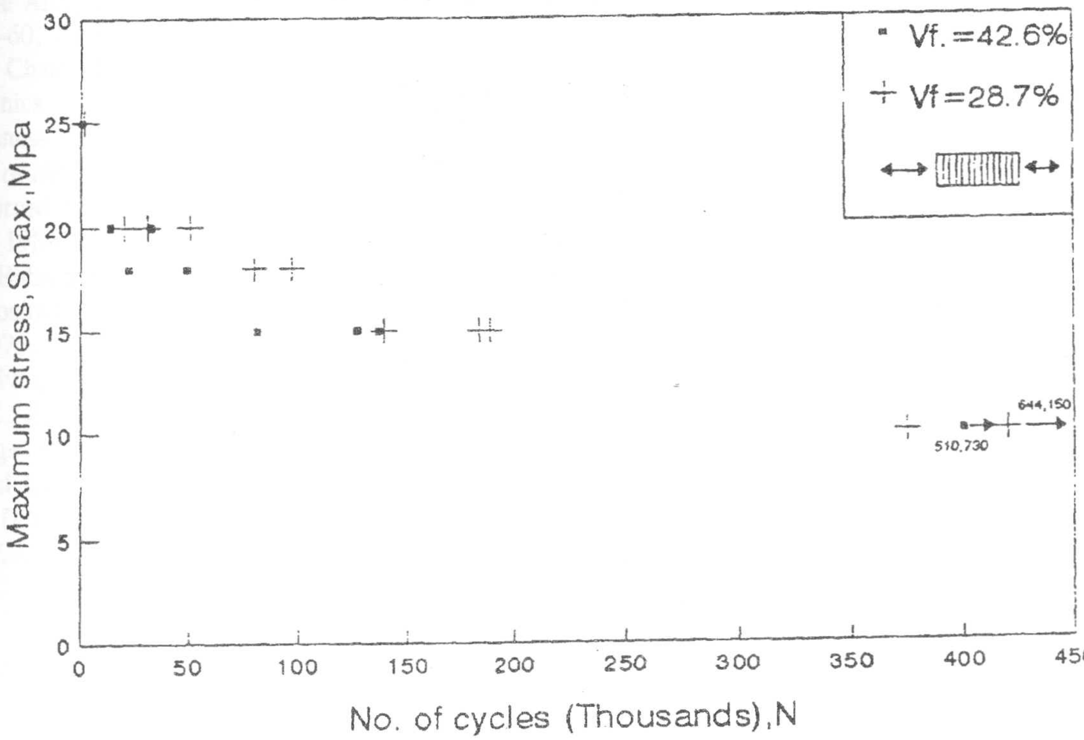

Figure 4-b. Transverse glass/polyester fatigue S_{max}-N curve.

$$S_m^* = [1 - 4V_v / PV_m] S_m \qquad (1)$$

where S_m^* and S_m are the matrix strength with and without void effect and V_m is the matrix volume fraction.

The variation of cycling frequency was selected as explained before to save the fatigue test duration. Hahn et al [5] showed that cycling frequency ranging from 4 Hz to 10 Hz does not affect the fatigue behavior of composite laminates. However, the sensitivity of fatigue data to the frequency of sinusoidal load has been discussed by Brivio et al [6]. They revealed that the 30 Hz S - N curve is shifted of one decade than the 6 Hz S - N curve. This could be explained by the rise of matrix temperature as the loading frequency increases. It could be said that the visible change in frequency during the fatigue test has an influence on the fatigue life particularly for the transverse direction where the matrix properties dominates the behavior of composite material. It is noted that, the increase of V_f improves slightly the longitudinal fatigue resistance, while the transverse fatigue resistance decreases.

To reduce the discrepancies of the experimental fatigue data points, the fatigue results are replotted as (S_{max} / X_o) where X_o is the average static tensile strength and S_{max} is the maximum applied fatigue stress versus the logarithmic fatigue life (log N).

Figure (5) shows the influence of fatigue loading direction for glass / polyester composite with V_f = 28.7% as well as the polyester base matrix. An acceptable fit is obtained by the straight line given by

$$(S_{max} / X_o) = a + b \log N \qquad (2)$$

It is observed that the fatigue stress ratio (S_{max} / X_o) of polyester base matrix at one million cycles is about 11.7%. However, at the same fatigue life for the reinforced polyester with V_f = 28.7%, the fatigue stress ratio is influenced strongly by the loading direction. The fatigue stress ratio (S_{max} / X_o) is about 50% and 31.8% for the longitudinal and transverse directions, respectively. The constant term (b) of equation (2) which represent the slope of the straight line, for the transverse direction is in agreement with the corresponding value of the polyester base matrix. This confirm that the matrix properties has a great influence on the transverse composite fatigue behavior.

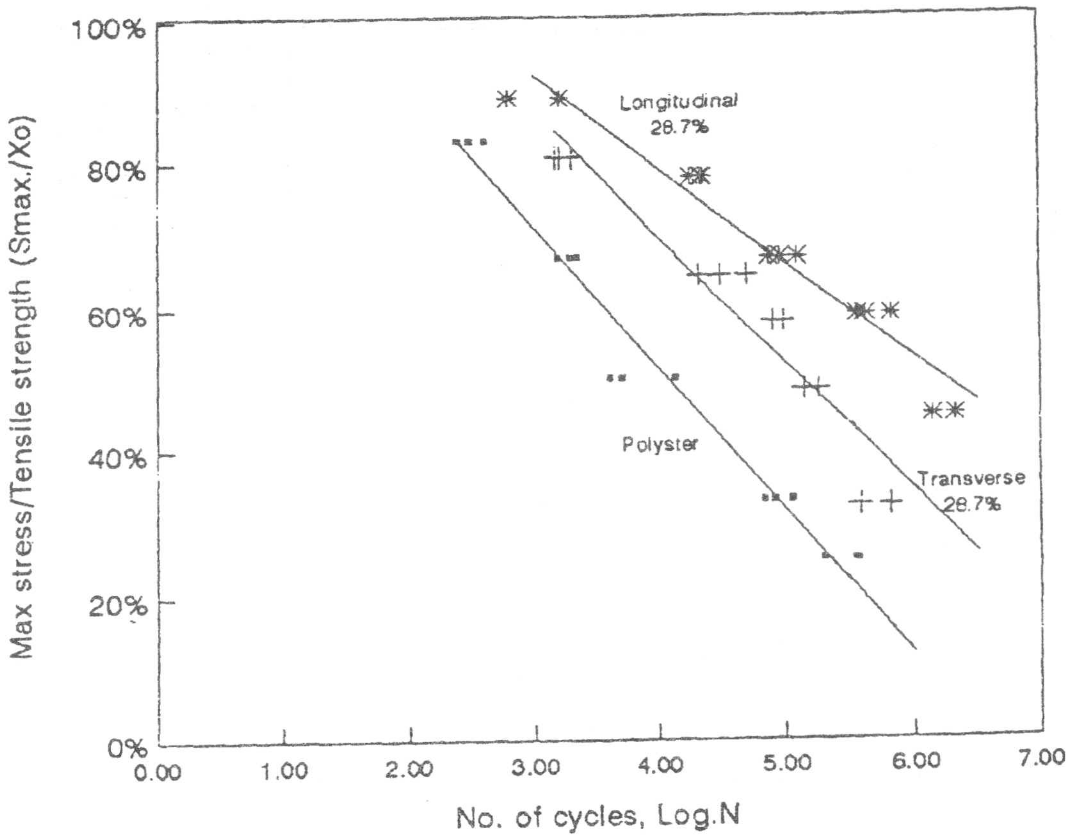

Figure 5. Stress ratio (S_{max} /X_o) versus the logarithmic fatigue life of the reinforced polyester with 28.7% glass fiber.

CONCLUSIONS

Fatigue behavior of unidirectional glass / polyester composite was investigated in terms of static properties, S_{max} - N relationship, fiber volume fraction and loading direction. The resulting conclusions are as follows.

1- Micromechanics analysis are still recommended for predicting the static properties (strength and stiffness) of the tested glass / polyester composite.
2- The fatigue loading direction has a great effect on the composite fatigue strength. The longitudinal fatigue strength, for fatigue life of one million cycles, is found to be about 1.57 times the corresponding transverse values for V_f = 28.7%.
3- The transverse static and fatigue strengthes are found to depend strongly on the matrix properties. Moreover, the increase of V_f improves the longitudinal fatigue strength rather than the transverse one.
4- The change of loading frequency from 4 Hz to 15 Hz is found to affect the transverse fatigue life. So, the fatigue loading frequency must be minimized as can as possible to detract the softening of the composite base matrix.

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