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Environmental Effects on Graphite-Epoxy Fatigue Properties

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Effects of torsional and flexural fatigue on the long-time integrity of advanced graphite-epoxy structural composites have been investigated. Torsional fatigue tests were run at stress ratios of $R=0$ (zero to maximum, repeated) and $R=-1$ (zero mean stress) on unidirectional, angleply, and woven graphite fiber materials in air and water at room temperature and at 74°C. Flexural fatigue tests (four-point bending) with $R=-1$ were run in air and water at room temperature, and with $R=0$ in air. Results show that, in torsional cycling, both water environment and higher test temperature contribute to significant degradation of torsional stiffness. The degradation of stiffness from torsional stress cycling was observed to be much greater with $R=-1$ than with simple $R=0$ cycling. The effect of environment also is greater in the fully reversed cycling. Flexural fatigue results on ±30° material show a large fatigue effect, with fatigue limits of less than 50% and 30% of the static failure strength for specimens tested under stress ratios of $R=0$ and $R=-1$, respectively. Compliance measurements indicate that the final failures are preceded by damage initiation and accumulation, which begins at about 1% of the specimen life.

Introduction

INVESTIGATION of the effects of generalized loading and environment on the long-time integrity of advanced graphite-epoxy structural composites has been continued and broadened to include other layups and test conditions. Initial results have been reported previously elsewhere.[1] The study was undertaken initially because it was felt that, if these materials were to achieve their widely heralded potential for applications in aircraft structural use, they must be better characterized. Especially, it must be demonstrated that they have mechanical properties of reasonable predictability over long periods under conditions of anticipated use. Generally, available data on long-time fatigue properties of graphite-epoxy composites have indicated that advanced composites are less susceptible to fatigue damage than are isotropic engineering alloys.[2,3] Results of the first part of the investigation, however, indicated that unidirectional and angleply ±45° graphite-epoxy composites were 1) susceptible to torsional fatigue damage at stress levels as low as 15% of the transverse failure strength of the materials (less than 1% of the longitudinal failure strength), and 2) susceptible to significant flexural fatigue damage in both air and water when subjected to fully reversed plane bending. It appeared to be of value, therefore, to extend the investigation, in order to characterize more completely these potentially significant observations.

The intent of these continued studies was 1) to extend the investigation of torsional fatigue properties to other fiber orientations (±30° and woven fibers) including the effects of environment on the stiffness of carbon-reinforced composites; and 2) to verify the previously observed rapid rate of accumulation of fatigue damage in flexure cycling. Presented herein is a progress report in which representative data from the initial torsional fatigue tests are presented in the form of graphs showing is some detail the type of data obtained and the method of analysis. The results of all tests to date on torsional fatigue testing of the four types (fiber orientations) of graphite-epoxy material are presented in a tabulated summary. Results of flexural fatigue tests in four-point bending of angleply ±30° material are presented as *S-N* curves.

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Index categories: Aircraft Structural Materials; Materials, Properties of; Structural Composite Materials (including Coatings).

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Experimental

The angleply material used in this investigation was formed from Hercules prepreg tapes containing 63±2% volume fraction of Hercules AS fiber in 3501 resin system (Hercules AS/3501). Fiber properties as given by the producer were UTS 448.4 ksi, modulus 32.27 Msi, and density 0.06514 lb/in.[3] The woven composite sheet was formed from Fiberite 934/T300. Material layups studied included the following: $[0,\pm 30,0]_{4s}$, $[0]_{16}$, $[0,\pm 45,0]_{4s}$, and woven. For simplicity in the remainder of this paper, these layups will be referred to as ±30°, 0°, ±45°, and woven materials, respectively. Void content was negligible (0.0 to 0.43%) for all materials as determined by the supplier. The specimen stock was prepared by Lockheed Missiles and Space Company in sheets approximately ⅛ in. thick. The method of preparation is given in detail elsewhere.[1] The sheets as received were machined into specimens having the dimensions indicated in Figs. 1a) and 1b). The specimens with the parallel-gage section were used for the torsion testing, whereas the "dog-bone" specimens were for flexural fatigue tests. The flexural tests that were run in this later part of the study were all four-point bending, and, normally, parallel-sided specimens would be used. However, flexural test specimens were designed and machined initially for cantilever reverse band tests and were used, because of cost and time considerations, after running bend tests which showed that both types had comparable maximum strength

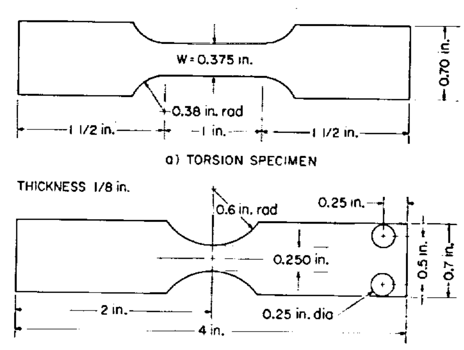

Fig. 1 Test specimens.

properties. Five specimens of the dog-bone type averaged 169-ksi maximum fiber strength (range 156-175 ksi); five specimens of the parallel-side type averaged 154 ksi (range 128-176 ksi).

Torsional fatigue tests were conducted at a frequency of approximately 1 Hz under conditions of controlled torsional deflection using an MTS Systems Corporation torsional materials testing system. In this system, a constant torsional force was applied at one end of the specimen, and the torque developed is measured by the output of a strain-gaged torque cell at the other end. The angular deflection or degree of twist ($\pm$ angleθ) was set at the beginning of the test and maintained constant thereafter. The resulting initial value of the maximum shear stress τ_0 and subsequent values, of course, were calculated from the measured torque and specimen dimensions.[4,5] This maximum shearing stress is found at the middle of the longer side (width) of the rectangular cross section according to the solution of Saint Venant and is given by the equation

$$\tau_{max} = T/\propto bc^2 \tag{1}$$

in which b is the width and c is the thickness of the rectangular cross section, and $\propto$ is a numerical factor that depends upon the ratio b/c.[4] For specimens of the nominal dimensions used in this investigation (⅜ in. width, ⅛ in. thickness), maximum shear determined by Eq. (1) amounts to 639 T psi, with the torque T measured in units of inch-pound. Using an empirical equation given by Singer,[5]

$$\tau_{max} = (T/bc^2[3+1.8(c/b)] \tag{2}$$

the maximum shear is 614 T psi, again with torque T measured in units of inch-pound. Maximum shear values calculated by the two methods are in good agreement; values calculated by Eq. (2) are 3.9% smaller than by Eq.(1). For example, τ_0 of 11,2000 psi used in most of the torsion tests, e.g., Fig. 3, resulted from a measured torque of 17.5 in.-lb or 280 in-oz calculated with Eq. (1); with Eq.(2), τ_0 amounts to 10,745 psi. For the purpose of this investigation, either equation is satisfactory if used consistently, inasmuch as the objective of the study was to determine comparative properties showing the effect of environment, and not to generate mechanical properties design data.

For most of the testing, the initially applied torque stress was 50% of the maximum static failure strength for the woven material and approximately 40% of the failure strength for the other three fiber orientations. For one series of tests to be described, the initial stress was varied from 28 to 51% of the failure strength in order to determine the effect of this parameter. Maximum static torsional strengths for the four materials were 13,000, 16,000, 28,000, and 27,000 psi for woven, 0°, ±30°, and ±45°, respectively. The tests were continued until the torque had decreased to some predetermined level or until a sufficient number (1×10^5 or greater) of stress cycles had accumulated. Tests were run in four enviornments: room-temperature (24°C) air and water, and hot (74°C) air and water. Some of the angleply ±30° and the woven materials were tested at stress ratios $R(\tau_{min}/\tau_{max})$ of both $R=0$ and $R=-1$, whereas the other materials all were cycled at $R=-1$.

After the torsional fatigue tests were completed, the specimens were subjected to a four-point bend test (to fracture) using an MTS Systems Corporation hydraulic testing machine. The bend tests were conducted to measure the residual longitudinal strength of the specimens and were performed with a lenght-to-center span ratio of 16:1. Data were obtained in the form of bend vs deflection curves from which maximum bend strengths, compliances, and failure energies could be calculated.

The flexural fatigue studies were run using an MTS Systems Corporation hydraulic testing machine having a linear actuator. The test specimen was placed in a test fixture (Fig. 2) that kept the ends in fixed position while allowing the center span to be actuated by the hydraulic ram in reverse cycling. Most tests were run in either fully reversed bending with a stress ratio $R=-1$, or repeated bending with $R=0$. In the flexural fatigue studies, the load was kept constant and controlled by a load signal from a load cell while the specimen was undergoing cyclic strain or deflection. Load and deflection both were recorded periodically on a high-speed, strip chart recorder and/or recorded with an electronic data-acquisition system by which the load-deflection or flexural compliance relationship could be continuously monitored, stored, and plotted. Deflection limit detectors could be set to terminate the test at fracture or when the specimen deflection exceeded the initial value by any selected amount. However, in order to follow the complete compliance response, most specimens were tested to fracture. In addition to the periodic recording of the load and deflection, full hysteresis curves were recorded at intervals during the test. Tests were run at frequencies of 10 to 30 Hz. Some specimens were tested in water environment by placing a small amount of water-absorbent cotton around the gage section. The cotton was moistened with water before the test began, and this environment was maintained throughout the test by dripping water onto the cotton.

Results and Discussion

The results of the torsional fatigue tests are shown in Figs. 3 and 4 and Table 1. Figures 3 and 4 are results for ±45° material presented as curves that show specimen stiffness τ/θ as a function of the number of applied stress cycles N, where

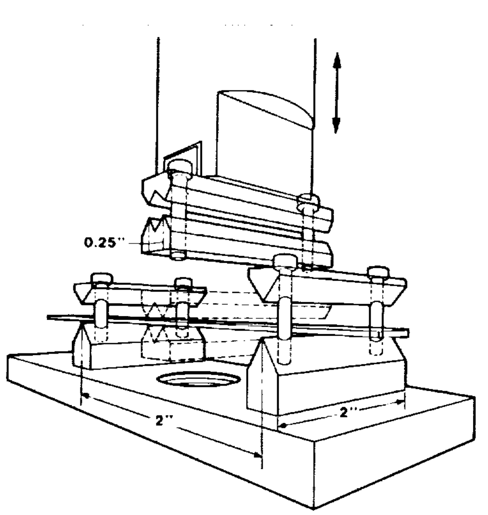

Fig. 2 Fatigue fixture.

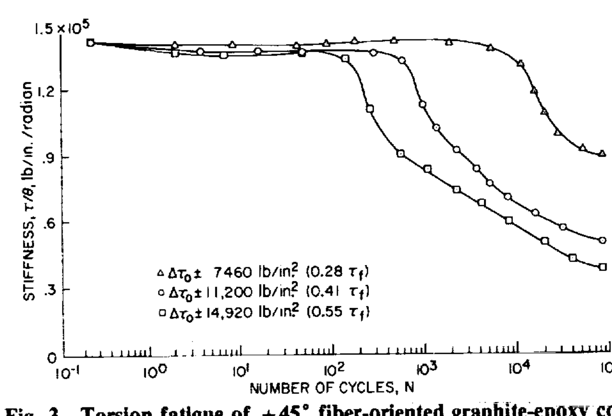

Fig. 3 Torsion fatigue of ±45° fiber-oriented graphite-epoxy composite. Decrease in stiffness [τ/θ] with number of cycles (log N) as a function of initial applied stress [τ_0].

τ is the applied shear stress and θ is the torsional deflection angle in radians per unit gage length. The curves shown are for one of three specimens tested under identical conditions; an example of the good agreement between triplicate tests has been given previously.[1] Reproducibility for the uniaxial and the angleply material was approximately $\pm 5\%$, and for the woven fiber material $\pm 10\%$. Figure 3 shows the effect of initial stress on the torsional fatigue behavior of angleply $\pm 45°$ composite specimens. The material under-goes a decrease in stiffness on cycling for each of the three different initial stress levels applied; these levels were selected to be 28%, 41%, and 55% of the static torsional stress limit τ_f. The point (number of cycles N) at which the rapid decrease in stiffness begins (failure point N_f) and the level to which the stiffness decreases in a given number of cycles are dependent upon the initial stress level. N_f values for the stress levels of 0.28, 0.41, and 55 τ_f are approximately 6×10^3, 6×10^2, and 1×10^2, respectively. The corresponding stiffness values at 10^5 cycles were approximately 62, 36, and 28% of the initial values. Inasmuch as these tests were run under conditions of constant torsional deflection, this means that, for all three tests, the torsional stresses decreased in 10^5 cycles to a nearly constant stress of about 4000 psi, approximately 15% of the static torsional failure stress. All three curves indicate that they may be approaching a "fatigue limit" near 10^5 cycles. Subsequent testing of a limited number of specimens to more than 10^6 cycles indicated that this fatigue limit was similar to the limit noted for nonferrous metals (no sharp plateau, but instead a gradual leveling) rather than the sharp limit noted for ferrous alloys.

Results of fully reversed torsional cycling of $\pm 45°$ angleply material shown in Fig. 4 are, in general, representative of the response of the other three materials tested: angleply $\pm 30°$, unidirectional, and woven. In general, the specimens undergo a relatively slight decrease in stiffness (dependent on environment) on cycling up to the failure point N_f. The rapid dropoff in stiffness which identifies the failure point continues to a leveling-off value, which again is dependent upon the test environment. The $\pm 45°$ and woven specimens tested in hot water generally undergo an immediate and continuing degradation of stiffness with progressive cycling, rather than the "incubation" or relatively damage-free period noted for all other tests. For the specimens that did not exhibit the incubation period but instead showed an immediate decrease in stiffness with cycling, N_f was designated arbitrarily as the number of cycles at which τ/θ had decreased by 15%. In cycling of angleply $\pm 30°$ and the woven fiber materials, at $R = 0$, all specimens showed a greatly reduced stiffness degradation rate compared to specimens subjected to $R = 1$ torsion cycling. Results of all torsional fatigue tests are presented in Table 1. Column 1 gives the fiber orientation of the test specimens; column 2 gives the test environment; column 3 lists the initial stiffness τ_0/θ; column 4 gives the number of cycles at failure N_f; column 5 gives the stiffness at $N = 10^5$ cycles.

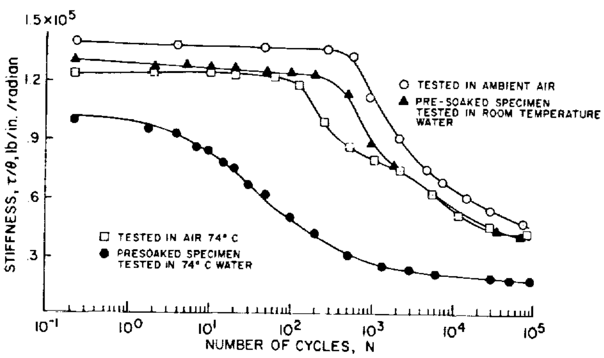

Fig. 4 Torsion fatigue of $\pm 45°$ fiber-oriented graphite-epoxy composite. Decrease in stiffness $[\tau/\theta]$ with number of cycles ($\log N$) as a function of environment. $\pm 45°$ fiber orientation. $\Delta\tau_0 = \pm 11{,}2000$. Test frequency 1 Hz.

Table 1 Torsional fatigue of graphite-epoxy composites

Fiber orientation	Test Environment	$\tau_0/\theta \times 10^{4\,a}$	N_f,[b] cycles	τ_N/θ^c
$R = -1$				
0°	Air	6.8	1.7×10^4	5.2
	Water	6.8	9×10^3	4.8
	Hot air	5.7	5.3×10^3	4.0
	Hot water	4.1	4.6×10^2	1.9
±45°	Air	14.0	5×10^2	5.0
	Water	13.2	3×10^2	4.5
	Hot air	12.3	10×10^2	4.4
	Hot water	10.0	1×10^1	2.0
±30°	Air	8.0	4×10^3	4.1
	Water	7.8	3×10^3	3.9
	Hot air	6.5	4×10^2	2.0
	Hot water	6.3	4×10^2	2.8
Woven	Air	5.0	9×10^2	2.1
	Water	5.0	2×10^2	1.5
	Hot air	4.0	8×10^2	1.7
	Hot water	3.6	4×10^1	0.7
$R = 0$				
±30°	Air	8.0	1×10^5	7.8
	Water	7.8	2×10^4	7.5
	Hot air	7.5	5×10^3	3.2
	Hot water	7.7	2×10^4	5.7
Woven	Air	6.3	$> 1 \times 10^5$	6.2
	Water	5.8	2×10^4	5.3
	Hot air	4.5	2×10^4	3.4
	Hot water	3.6	4×10^3	1.6

[a] τ_0/θ = initial applied torsion stress per radian, in.-lb/in.^{2}.
[b] N_f = number of cycles at failure as defined in test.
[c] τ_N/θ = applied torsion stress per radian at $N = 10^5$, lb/in.

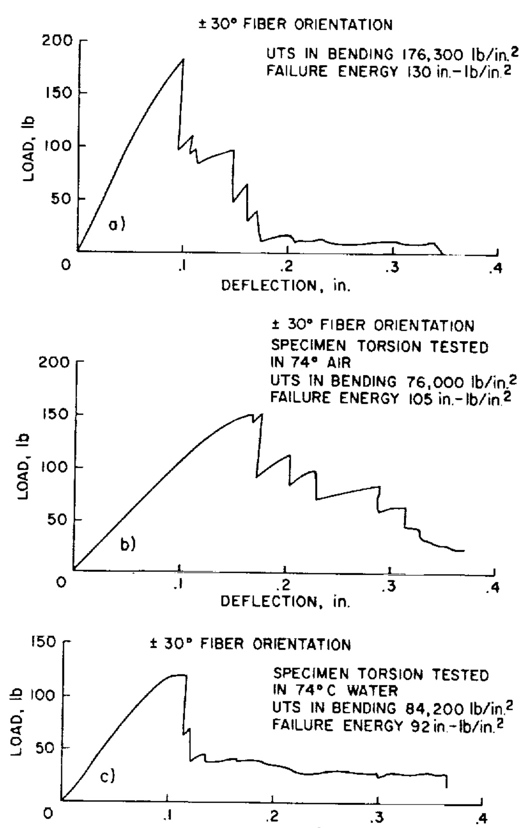

Fig. 5 Bend tests in ambient air of $\pm 30°$ fiber-oriented specimens. a) Specimen not previously tested in torsion. b) Specimen previously torsion-tested in 74°C water at $\Delta\tau_0 = \pm 10{,}8000$ psi. c) Specimen previously torsion-tested in 74° C water at $\Delta\tau_0 = \pm 10{,}8000$ psi.

A number of specimens were tested in four-point bending to determine the effect of prior torsional stress cycling and test environment on the residual properties of the material in the longitudinal direction. Figures 5a-5c show examples of load-deflection curves obtained in these bend tests for angleply material. As shown, torsional stress cycling and environmental exposure cause changes in such longitudinal material properties as flexural stiffness and failure stress in bending; failure energy as determined from the area under the curve for deflections up to the first significant load drop also decreases after stress cycling. A more complete description of these effects for 0° and ±45° can be found elsewhere.[1] Test results for woven fiber material showed similar behavior.

Figure 6 shows results of flexural fatigue tests in four-point bending on angleply ±30° specimens tested at 24°C in air at $R=-1$ and $R=0$. There is obviously a much greater damage accumulation rate in reverse bending ($R=-1$) than in simple bending ($R=0$). For $R=-1$, there is a fatigue limit at a stress of 30% of the static flexural strength. For $R=0$, there is an indicated fatigue limit greater than 50% of the static strength, a difference of over 30 ksi. The fatigue life for $R=-1$ is less by one to two orders of magnitude than for $R=0$ at equivalent stress levels. The effect of moisture is poorly defined as yet; the limited number of data points fall near the lower boundary of the scatter band for ambient air tests but indicate a trend of lower fatigue life for specimens tested in water environments.

Figure 7 shows a representative (schematic) graph of flexural compliance vs number of cycles for crossply ±30° specimens subjected to four-point reverse bend cycling ($R=-1$). Such graphs were obtained when fatigue tests were run with the automated data-acquisition system attached to the test system continuously monitoring and recording flexural deflection for the corresponding controlled load cycle. The negative slope of the first part of the curve (to around 10^2 cycles) indicates, under constant load operation, a decrease in flexural deflection. This is followed by a period of constant deflection with increasing number of cycles, and then by a period of increasing

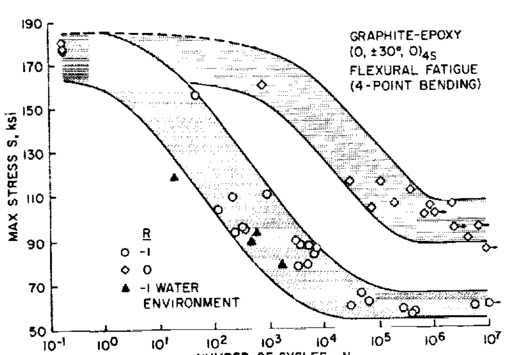

Fig. 6 Flexure fatigue tests of ±30° fiber-oriented specimens in reverse ($R=-1$) and repeated ($R=0$) cycling.

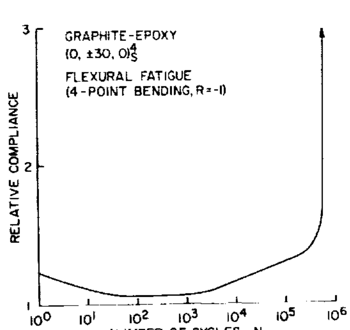

Fig. 7 Relative flexural compliance vs number of cycles (log$N$) of ±30° fiber-oriented specimen in four-point bending ($R=-1$).

deflection (compliance). In this test, as the number of cycles approached 10^6, catastrophic failure (fracture) occurred, as evidenced by the rapid increase in compliance.

The results of this investigation definitely show that graphite-epoxy composite materials of the types tested (0°, ±30°, ±45°, and woven fiber) undergo fatigue damage of varying amounts, depending upon the test parameters of applied cyclic stress, type of stress (torsion, flexure, fully reversed, or repeated), temperature, and environment. As noted earlier, torsional fatigue damage occurred at cyclic stresses as low as 15% of the ambient static torsion strength, or approximately 1% of the longitudinal failure strength of such materials. Since it seems likely that stresses of this magnitude will occur in actual service applications of structural composites, the results of this investigation would seem to be of importance in aerospace applications for composite materials. Useful mechanical properties data for design purposes can be developed by generating torsional fatigue *S-N* curves for the materials of interest. Data for these curves could be obtained from torsion fatigue curves using fatigue life values as determined by the defined failure points.

The torsional fatigue characteristics observed were, in general, similar for the four different fiber orientations and the four test environments investigated. Referring to Fig. 4, for most test conditions there was an initial incubation period during which there was only a slight decrease in stiffness of the specimen. This was followed by a period of very rapid damage accumulation, the transition being evidenced by a sharp drop in τ/θ. This transition point was taken as the failure point of the specimen on the basis that most composite structures will be required to maintain constant stiffness. This period of rapid stiffness decrease was followed by one in which the damage accumulation rate leveled off and the stiffness approached a stable level. This final stiffness was, in most cases, significantly lower than the initial τ_0/θ, as can be seen in Table 1. There were two exceptions to this generalized torsional fatigue damage profile: angleply ±45° and woven specimens tested in 74°C water. These did not have an incubation period but underwent an immediate and continuing rapid decrease in τ/θ with progressive cycling. The comparative torsional fatigue characteristics of the four materials investigated in the four test environments can be noted in Table 1 by comparing the fatigue lives (N_f, number of cycles to failure). The τ_N^*/θ values in the last column give an indication of the degree of damage suffered in each instance. The following significant points can be noted in the data of Table 1:

1) Cyclic torsional fatigue damage occurs to some extent in all four materials in fully reversed ($R=-1$) cycling.

2) There is relatively little effect of room-temperature water environment; values are very similar to room-temperature air.

3) The two materials tested in repeated $R=0$ cycling (±30° and woven fiber) showed no significant damage in 24°C tests in air or water.

4) Damage suffered by all four material types in 74°C water at $R=-1$ was severe, and for ±30° and woven also was severe at $R=0$.

The observation that water at 24°C had relatively little effect on the torsional fatigue properties of graphite-epoxy composites is consistent with the small changes noted by other investigators.[2] These data make it seem likely that the absorption rate of water by the epoxy at room temperature is not sufficiently rapid to cause any significant changes in material properties. In contrast, the results of the present study show a large effect on initial torsional stiffness when tested in water at 74°C; these tests were not started until 1 hr after the specimen was place in 74°C water. Beaumont and Harris[2] found that torsional fatigue behavior was affected much less significantly by pretest exposure to 100°C steam. These results suggest that there is a synergistic effect of loading the material in the test environment, probably caused by the stress-assisted absorption of water by the epoxy. In this respect, the findings of McKague et al.[6] may be significant. They reported that supersonic service (simulated thermal dashes) caused permanent changes in the moisture diffusion behavior of fiber-reinforced epoxy composites in that absorptivity was doubled. Absorbed moisture was removed by drying at 82°C, but the diffusion behavior was changed permanently. It could well be that the in-flight environment, including high temperature and stresses followed by subsequent exposure to high humidity (water environment), could with repeated cycles result in significant degradation of fatigue properties comparable to that noted in fatigue tests in 74°C water. This effect should be investigated further and considered when characterizing composite materials for use in anticipated service environments.

Flexural fatigue results for angleply ±30° and woven fiber composites tested in four-point bending were in general agreement with previously reported tests for angleply ±45° and 0° specimens tested in reverse cycling of cantilever specimens. Results for the ±30° material data (Fig. 6) show significant fatigue damage in $R = -1$ testing at stress levels as low as 30% of the static flexural failure stress. The cantilever ±45° material data[1] showed no indication of a fatigue limit, whereas the data for four-point bend testing of ±30° material show a fatigue limit at approximately 30% (for $R = -1$) of the static flexural failure stress. Earlier investigators[2,3] who had performed flexural fatigue work generally found that composite materials are relatively insensitive to damage so long as the flexural stresses are applied perpendicular to the longitudinal axis of the fibers. They also reported no appreciable effect of water at room temperature on fatigue properties. However, these investigators used wither three-or four-point simple cyclic bend testing ($R = 0$).

Although the greater fatigue damage observed at $R = -1$ than at $R = 0$ is typical fatigue behavior, the significant increase in the rate of damage accumulation experienced under $R = -1$ cycling needs to be emphasized. With few exceptions, published data on fatigue of graphite-epoxy composites are the results of $R = -0$ testing, and the generally accepted concept that resin matrix composites are relatively undamaged in fatigue cycling is based upon these data.

In the earlier part of the present study, the unidirectional 0° material and, to a lesser extent, the angleply ±45° material both showed a significant effect of testing in water at room temperature. The effect of water on the angleply ±30° material (Fig. 6), as noted earlier, is defined poorly in testing to date in that the limited number of data points fall on or near the lower boundary of the scatter band for ambient air tests. Nevertheless, the data suggest that testing in water environment does decrease the fatigue life compared to that in air. Data for $R = 0$ flexure fatiguing of the ±30° material lie well above the $R = -1$ data, showing a significant decrease in fatigue life for the reverse bend tests. The preceding evidence strongly suggests that the reason for greater fatigue damage in the flexural tests of the present investigation than in those previously reported by others is that the fully reversed method of loading is more damaging to composite materials than the simple $R = 0$ bend methods generally used. It also appears that the fatigue behavior of composites may be more susceptible to the effects of water environment at room temperature when loaded under fully reversed bending rather than simple bending. The compliance vs cycles curve shown in Fig. 7 for the constant load flexural fatigue tests clearly shows that the composite material undergoes significant property changes prior to final failure. This curve is shown schematically because it is representative of a very large number of observations made on many specimens. Initially, the compliance decreases for a short period are due, probably, to a rearrangement of fibers to a more optimum orientation. Following this hardening, the compliance remains constant for some period that is dependent on the cyclic stress. However, after this stable period (about 1% of the specimen lifetime), the compliance begins to increase again, signaling the onset of some type of damage. The compliance increases in a relatively slow and regular manner until, after about 60% of the specimen life, the rate of change of compliance increases significantly. After this point, the compliance continues to increase relatively rapidly until specimen failure. The observation that the compliance begins to increase at approximately 1% of the specimen life seems very reproducible for nearly all of the tests performed. From a design standpoint, the point at which compliance begins to increase significantly might be considered logically as the failure point. This would, of course, greatly decrease the fatigue life of test specimens and thereby decrease acceptable maximum design loads determined from S-N curves.

In an attempt to identify the various types of damage that result from cycling composite specimens both in torsion and in four-point flexure, we have just begun a program of post-test examination using both optical and scanning electron microscopy. Preliminary examination of sectioned torsion-fatigued specimens has not been highly enlightening. Because failure criterion for torsion tests was degradation of torsional stiffness, fracture or other easily observed damage did not occur. Matrix cracks seldom can be identified, and there is no discernible evidence of interfacial debonding between fibers and matrix. In contrast, examination of specimens tested in flexural fatigue revealed matrix cracks present in angleply, unidirectional, and woven materials. However, interlamellar delamination was the primary failure mode in angleply specimens; it was extensive in unidirectional but not observed in woven specimens so far examined. Fracture of fibers was observed in unidirectional, angleply, and woven materials, but to a very limited extend in the latter.

Conclusions

Both angleply ±30° and woven cloth fiber specimens undergo appreciable fatigue damage (similar to that reported previously for other orientations) when subjected to constant-deflection torsional fatigue cycling. This damage occurs at stress levels as low as about 15-20% of the torsional failure stress and is evidenced by reductions in the torsional stiffness of the material. The fatigue curves are characterized by three separable stages of damage: 1) a "pseudoincubation" stage where the stiffness decreases only slightly with increasing cycles; 2) a stage where the stiffness decreases very rapidly, indicating rapid damage accumulation with increasing cycles; and 3) a final stage where the stiffness approaches a constant value, indicating approach to a fatigue limit. The effect of water on this damage accumulation is very minor at 24°C but significant at 74°C, causing an increase in the rate and extent of stiffness loss. The amount of fatigue damage from torsional cycling in water at 74°C compared to that in water at 24°C or air at 74°C is significantly greater. This is thought to be the result of increased absorptivity of water by the epoxy matrix at the highest temperature in combination with a stress-assisted synergistic effect of loading the test specimens in water at the higher temperature. The stress ratio R has a significant effect on the damage curves, with repeated stress loading of $R = 0$ causing much less damage than fully reversed cycling ($R = -1$). The torsional stress cycling also causes measurable changes in the residual longitudinal failure strength and failure energy of the material. Angleply ±30° specimens subjected to four-point flexural cycling under controlled load conditions undergo fatigue failure at relatively low stress levels, as evidenced by their S-N curves. Specimens subjected to fully reversed cycling ($R = -1$) failed significantly more rapidly and exhibited lower fatigue limit than specimens subjected to $R = 0$ loading. Continuous monitoring of the compliance of specimens under flexural load cycling indicated that the composite material initially undergoes a "strain-hardening," which is postulated to be due to reorientation of load-carrying fibers. The compliance then remains constant until the onset of damage, which occurs at approximately 1% of the specimen life. The damage then accumulates at a relatively slow rate, resulting in further decreases in compliance until some point near 60% of the specimen life. Beyond this point, the compliance increases rapidly until failure. Work is continuing in order to define the microstructural causes of the fatigue damage, and work is planned to extend these studies to sizes and configurations representative of aeronautical structural components.

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