TECHNICAL NOTE

Real-time monitoring of fatigue damage and dynamic strain in carbon fiber polymer-matrix composite by electrical resistance measurement

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Abstract. Real-time monitoring of fatigue damage and dynamic strain in a continuous unidirectional carbon fiber polymer-matrix composite by longitudinal electrical resistance measurement was achieved. The resistance R decreased reversibly upon tensile loading in every cycle, thus providing dynamic strain monitoring. The peak R in a cycle irreversibly increased as fatigue damage occurred, due to fiber breakage. Fiber breakage started to occur at 50% of the fatigue life, but significant growth of the fraction of fibers broken did not start till 55% of the fatigue life. From 55% to 89% of the fatigue life, more than 1000 fibers broke at a time, but not in every cycle. From 89% to 99.9% of the fatigue life, fiber breakage occurred continuously in every cycle. Beyond 99.9% of the fatigue life, fiber breakage occurred rapidly, both continuously and in spurts, with the last spurt occurring at 99.99% of the fatigue life. Catastrophic failure occurred when 18% of the fibers were broken.

1. Introduction

Fatigue occurs in most materials during dynamic loading at stress amplitudes below the fracture strength. Failure due to fatigue is the cause of numerous disasters in, for example, aeroplanes, automobiles, ships, bridges and machinery, since dynamic loading is commonly encountered. In order to prevent such disasters, fatigue damage is monitored prior to fatigue failure. Another method is to use past experience on other structures to predict the lifetime of the structure under consideration. The former method is more effective for fatigue failure prevention than the latter, but requires more effort. An objective of this paper is to facilitate fatigue monitoring.

Fatigue monitoring is conventionally performed by monitoring at a frequency of at most once a loading cycle (usually once in dozens of cycles) because the monitoring (commonly by acoustic emission) is restricted to the damage only and reversible strain cannot be monitored anyway. Because fatigue monitoring conventionally occurs without dynamic strain monitoring, one cannot determine the loading cycle at which damage occurs unless the loading is periodic in time. In many practical situations, the dynamic loading is not periodic, but occurs at irregular intervals, so that dynamic strain monitoring must be carried out simultaneously with fatigue monitoring in order to

determine the loading cycle and the point in the loading cycle at which damage occurs.

The most commonly used method of fatigue monitoring is acoustic emission [1, 2], which suffers from its inability to monitor dynamic strain. Much less common is the method involving measurement of electrical resistance, which increases due to damage. Previous work using electrical resistance to monitor fatigue was carried out on a CaF_2-matrix SiC-whisker composite [3], but dynamic strain monitoring was not performed, probably because the electrical resistivity of the composite did not change reversibly with reversible strain. In general, dynamic strain monitoring requires a measurand which changes in value reversibly during reversible straining. In addition, in order for both dynamic strain and damage to be simultaneously monitored with a single method, that method must involve a measurand which changes in value reversibly during reversible straining and changes irreversibly during damage. In this work, we have achieved this by using the electrical resistance as the measurand and continuous carbon fiber polymer-matrix composite as the material.

Continuous carbon fiber polymer-matrix composite is an advanced composite which is attractive due to its combination of high strength, high modulus and low density. Previous work on a polymer-matrix composite containing a combination of continuous glass fibers and

Table 1. Carbon fiber and epoxy matrix properties (according to ICI Fiberite).

10E—Torayca T-300 (6K) untwisted, UC-309 sized	
Diameter	7 μm
Density	1.76 g cm^{-3}
Tensile modulus	221 GPa
Tensile strength	3.1 GPa
976 epoxy	
Process temperature	350 °F (177 °C)
Maximum service temperature	350 °F (177 °C) dry
	250 °F (121 °C) wet
Flexural modulus	3.7 GPa
Flexural strength	138 MPa
T_g	232 °C
Density	1.28 g cm^{-3}

Figure 1. Variation of fractional resistance increase ($\Delta R/R_0$), tensile stress and tensile strain with cycle number during the first few cycles of tension–tension fatigue testing.

continuous carbon fibers has shown that the electrical resistance of this composite increases irreversibly upon damage (due to the fracture of the carbon fibers) [4], but fatigue monitoring and reversible resistivity changes (dynamic strain monitoring) were not explored. Our previous work on a continuous carbon fiber polymer-matrix composite [5] has shown that both the longitudinal and transverse (through thickness) electrical resistivities of the composite change reversibly upon dynamic straining and change irreversibly upon damage. However, fatigue monitoring was not explored. This paper is an extension of [5] in that it demonstrates fatigue monitoring (simultaneous to dynamic strain monitoring) by electrical resistance measurement in a continuous carbon fiber polymer-matrix composite.

2. Experimental method

Composite samples were constructed from individual layers cut from a 12 inch wide unidirectional carbon fiber prepreg tape manufactured by ICI Fiberite (Tempe, AZ). The product used was Hy-E 1076E, which consisted of a 976 epoxy matrix and 10E carbon fibers. The fiber and matrix properties are shown in Table 1.

The composite laminates were laid up in a 4 inch × 7 inch platten compression mold with laminate configuration [0]$_8$ (i.e. eight unidirectional fiber layers in the laminate). The individual 4 inch × 7 inch fiber layers were cut from the prepreg tape. The layers were stacked in the mold with a mold release film on the top and bottom of the layup. No liquid mold release was necessary. The density and thickness of the laminate were 1.52 ± 0.01 g cm^{-3} and 1.1 mm respectively. The volume fraction of carbon fibers in the composite was 58%. The laminates were cured using a cycle based on the ICI Fiberite C-5 cure cycle. Curing occurred at 355 ± 10 °F (179 ± 6 °C) and 89 psi (0.61 MPa) for 120 min. Afterward, they were cut to pieces of size 160 × 14 mm². Hence, each specimen had 38 bundles of fibers (6000 fibers per bundle, 7 μm diameter for each fiber). Glass fiber reinforced epoxy end tabs were applied to both ends on both sides of each piece, such that each tab was 30 mm long and the inner edges of the end tabs
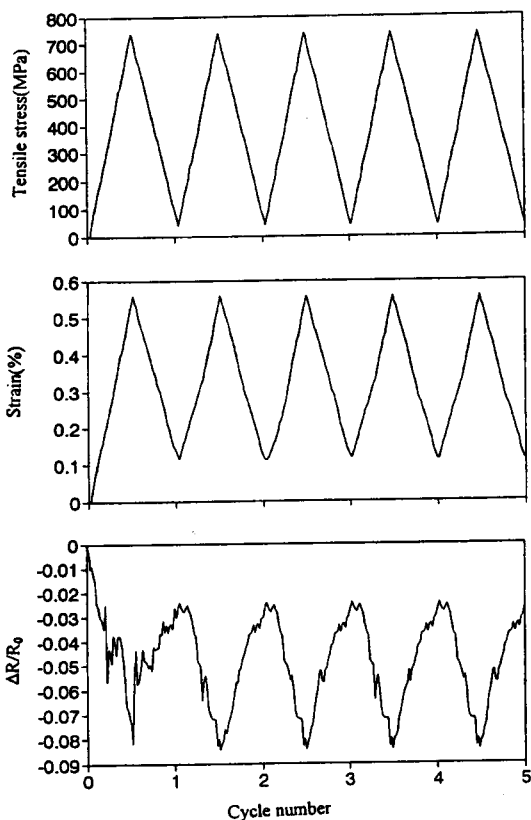
on the same side were 100 mm apart and the outer edges were 160 mm apart.

The electrical resistance R was measured in the longitudinal direction using the four-probe method while cyclic tension–tension was applied in the longitudinal direction. Silver paint was used for all electrical contacts. The four probes consisted of two outer current probes and two inner voltage probes. The resistance R refers to the sample resistance between the inner probes. The four electrical contacts were around the whole perimeter of the sample in four parallel planes that were perpendicular to the stress axis, such that the inner probes were 60 mm apart and the outer probes were 78 mm apart. A strain gage was attached to the center of one of the largest opposite faces. A Keithley 2001 multimeter was used for DC resistance measurement. The displacement rate was 1.0 mm min^{-1}. A hydraulic mechanical testing system (MTS 810) was used for cyclic tension–tension loading in the longitudinal direction, with a stress ratio (minimum stress to maximum stress in a cycle) of 0.05 and maximum stress 740 MPa (at which strain = 0.56%). The fatigue test was run at a constant amplitude load level (load control). Each cycle took 1 s. A total of 396 854 cycles took place before fatigue failure. Although the results shown in this paper are for one particular fatigue test, testing of similar samples confirmed that the results presented here are reproducible.
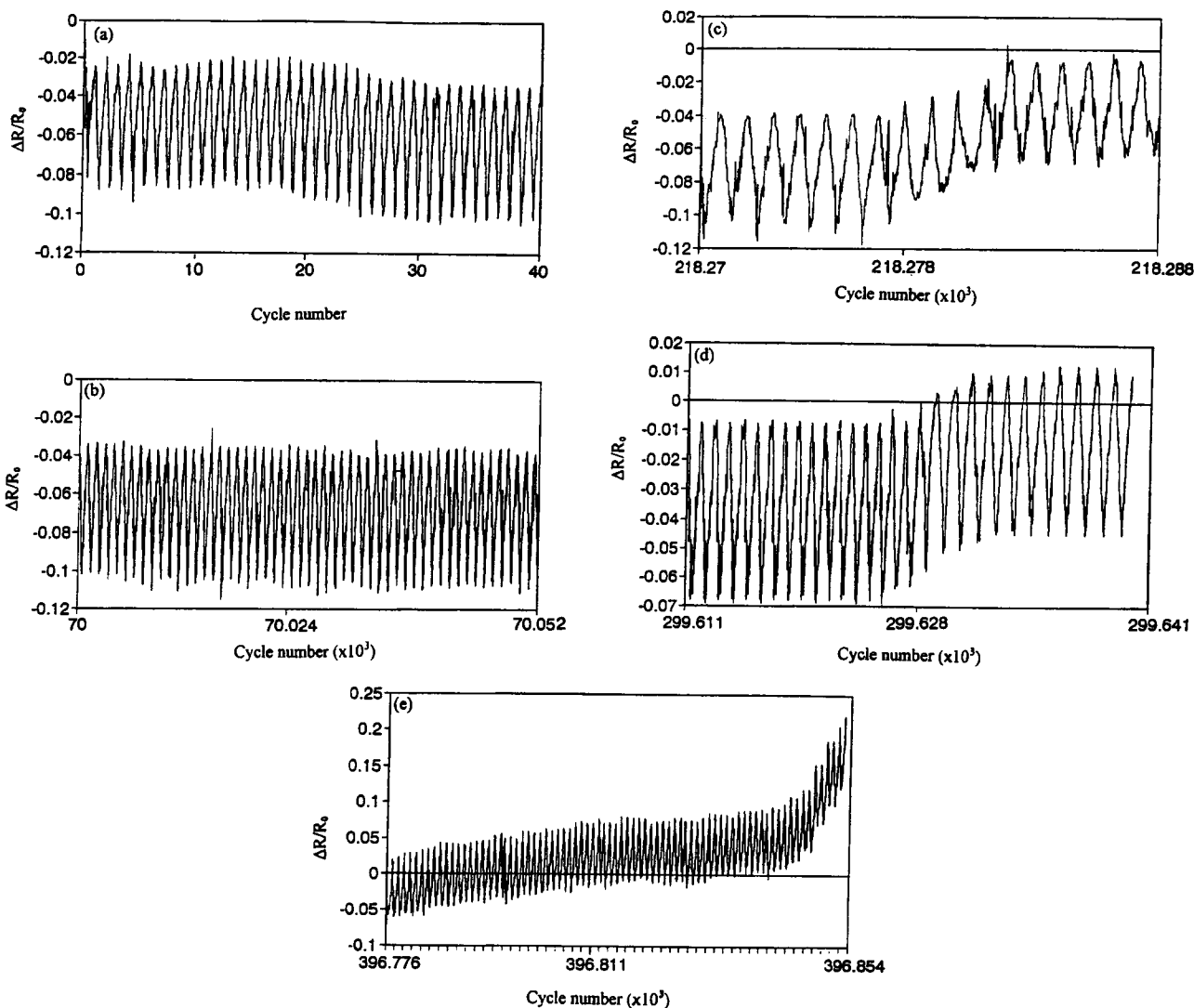
Figure 2. Variation of $\Delta R/R_0$ with cycle number during tension–tension fatigue testing up to failure at 396 854 cycles.

3. Results and discussion

Figure 1 shows the fractional resistance increase ($\Delta R/R_0$), tensile stress and tensile strain simultaneously obtained during cyclic tension–tension loading. The strain did not return to zero at the end of each cycle. The resistance R decreased upon loading and increased upon unloading in every cycle, such that R irreversibly decreased after the first cycle, as in [5], which is for the case of the strain being completely reversible. As explained in [5], the irreversible decrease in R after the first cycle (even when the strain is completely reversible) is due to the irreversible decrease in the degree of neatness of the fiber arrangement. A length increase without any resistivity change would have caused R to increase during tensile loading. On the contrary R was observed to decrease (not increase) upon tensile loading. Furthermore, the observed magnitude of $\Delta R/R_0$ was 9–14 times that of $\Delta R/R_0$ calculated by assuming that $\Delta R/R_0$ was only due to length increase and not due to any resistivity change. Hence, the contribution of $\Delta R/R_0$ from the length increase is negligible compared to that from the resistivity change. The reversible decrease in R

was attributed to increase in the degree of fiber alignment (i.e. slightly off-axis fibers becoming more aligned with the stress) in [5], but more recent work has shown that it is also due to the reduction of the residual compressive stress in the fiber [6]. The residual compressive stress occurs after the curing and cooling of the epoxy around the fiber, since the epoxy shrinks upon curing and cooling.

As cycling progressed beyond 218 277 cycles (or 55% of fatigue life), the peak R (at the end of a cycle) significantly but gradually increased, such that the increase did not occur in every cycle, but occurred in spurts (figures 2 and 3(a)), e.g. at 218 278 cycles (figure 2(c)) and 229 628 cycles (figure 2(d)). Figure 3 shows the variation of the peak $\Delta R/R_0$ as a function of the percentage of the fatigue life throughout the entire life. Beyond 353 200 cycles (89% of fatigue life), the increase of the peak R occurred continuously from cycle to cycle rather than in spurts (figure 2(e)). At 396 457 cycles (99.9% of fatigue life), the increase became more severe, such that spurts of increase occurred on top of the continuous increase (figure 3(b)). The severity kept increasing until failure at 396 854 cycles, when R abruptly increased. The last spurt
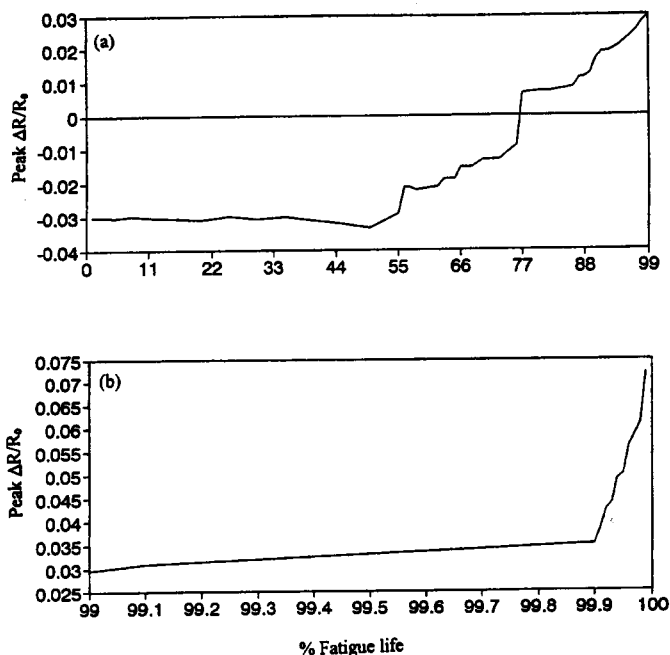
Figure 3. Variation of the peak $\Delta R/R_0$ at the end of a cycle with the percentage of fatigue life during tension–tension fatigue testing up to failure.

before the final abrupt increase occurred at 396 842 cycles (99.997% of the fatigue life) (figure 2(e)).

The early period in which the peak R increased discontinuously in spurts is attributed to minor damage in the form of fiber breakage which did not occur in every cycle. The subsequent period in which the peak R increased continuously but gradually is attributed to fiber breakage which occurred in every cycle. The still subsequent period in which the peak R increased rapidly, both in spurts (which did not occur in every cycle) and continuously (i.e. in every cycle), is attributed to more extensive fiber breakage, which occurred in the final period before failure. Thus, by following the increase in the peak R, the degree of damage can be monitored progressively in real time. Moreover, progressive warning of impending fatigue failure is provided in real time, so disasters due to fatigue failure can be avoided.

Single fibers obtained by dissolving away the polymer from the carbon fiber prepreg were subjected to similar electromechanical testing [7]. The resistance R of a single fiber increased upon tension, such that at a tensile stress equal to 83.0% of the fracture stress, the reversible portion of $\Delta R/R_0$ (due to dimensional change) was 18.4×10^{-3}, while the irreversible portion of $\Delta R/R_0$ (due to damage) was 4.0×10^{-3} [7]. We therefore assume that a fiber prior to fatigue failure has an irreversible $\Delta R/R_0$ of 4.0×10^{-3}. There are two sources of irreversible $\Delta R/R_0$, namely fiber damage and fiber breakage, though the former was almost negligible compared to the latter. The irreversible $\Delta R/R_0$ due to fiber damage was subtracted from the measured irreversible $\Delta R/R_0$ (in the part of the fatigue life in which the irreversible $\Delta R/R_0$ had shown an increase from the initial value) in order to obtain the irreversible $\Delta R/R_0$ due to fiber breakage.

Assuming that the resistivity of the undamaged portion of the composite does not change during testing, the
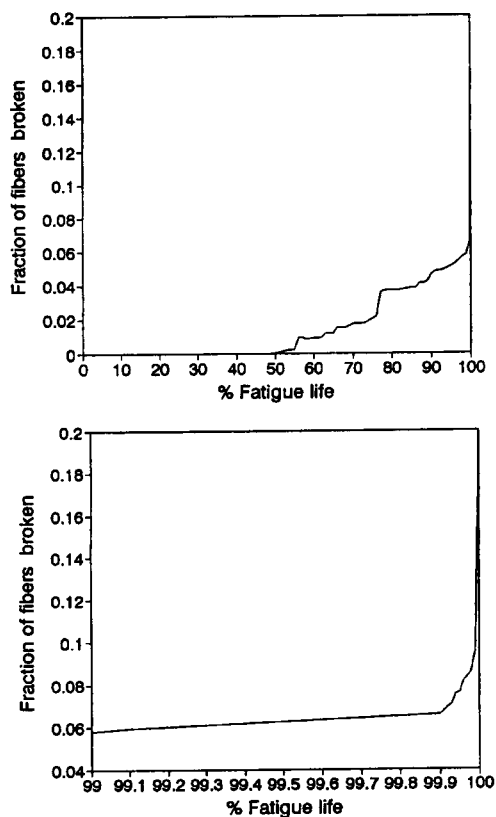

Figure 4. Variation of the fraction of fibers broken with the percentage of fatigue life during tension–tension fatigue testing up to failure. Top, from 0% to 100% of fatigue life. Bottom, from 99% to 100% of fatigue life.

fraction of fibers broken is equal to the fractional decrease in the effective cross sectional area of the unidirectional composite. Hence, in the part of the fatigue life in which the peak R at the end of a cycle had shown an increase from

its value R_0' at the end of the first cycle ($R_0' = R_0 + (\Delta R)_0$, where R_0 is the initial resistance and $(\Delta R)_0$ is the ΔR at the end of the first cycle)

$$\text{fraction of fibers broken} = Q/(1 + Q) \qquad (1)$$

where $Q = (R - R_0')/R_0' - 4.0 \times 10^{-3}$, R is the peak R at the end of the cycle, and 4.0×10^{-3} is the contribution from fiber damage. Figure 4 shows a plot of the fraction of fibers broken as a function of the percentage of fatigue life, as obtained by using equation (1). Fiber breakage started to occur at 50% of the fatigue life, though appreciable growth of the fraction of fibers broken did not start till 55% of the fatigue life. Fiber breakage occurred in spurts from 55% to 89% of the fatigue life, due to fiber breakage not occurring in every cycle. The smallest spurt involved 0.006 of the fibers breaking. This corresponds to 1020 fibers breaking. Thus, each spurt involved the breaking of multiple fibers. This is reasonable since the fibers were in bundles of 6000 fibers. The smallest spurt involved the breaking of a fraction of a fiber bundle. At 89% of the fatigue life, fiber breakage started to occur continuously rather than in spurts. Catastrophic failure occurred when 18% of the fibers were broken.

4. Conclusion

Real-time monitoring of fatigue damage and dynamic strain in a continuous unidirectional carbon fiber polymer-matrix composite by longitudinal electrical resistance measurement has been demonstrated. The resistance R decreased reversibly upon tensile loading in every cycle, thus providing dynamic strain monitoring. The peak R in a cycle irreversibly increased as fatigue damage occurred, due mainly to breakage of the carbon fibers. The degree of damage was indicated by the extent of the increase of the peak R at the end of a cycle. Fiber breakage started at 50% of the fatigue life, but significant growth of the fraction of fibers broken did not start till 55% of the fatigue life. From 55% to 89% of the fatigue life, fiber breakage occurred in spurts (i.e. *not continuously* from cycle to cycle), such that each spurt involved the breaking of at least 1000 fibers. At 89% of the fatigue life, damage started to occur continuously from cycle to cycle, but gradually. At 99.9% of the fatigue life, damage started to occur increasingly rapidly, both continuously and in spurts, and this persisted until failure. The last spurt occurred at 99.99% of the fatigue life. Catastrophic failure occurred when 18% of the fibers were broken. Hence, a progressive indication of the amount of remaining fatigue life was obtained in real time.

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