Strain sensing using carbon fiber

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Carbon fiber provides strain sensing through change in electrical resistance upon strain. Due to piezoresistivity of various origins, a single carbon fiber in epoxy, an epoxy-matrix composite with short carbon fibers (5.5 vol%), a cement-matrix composite with short carbon fibers (0.2–0.5 vol%), and an epoxy-matrix composite with continuous carbon fibers (58 vol%) are strain sensors with fractional change in resistance per unit strain up to 625. A single bare carbon fiber is not piezoresistive, but just resistive.

I. INTRODUCTION

An important aspect of a smart structure is structural control, which typically involves the sensing of strain, displacement, or derivative quantities and the use of the signal from the sensor to activate certain actuators, which bring about the desired intelligent response of the structure. Thus, strain sensing is a key function in structural control. Numerous types of strain sensors are available, including optical fibers, piezoelectric sensors, electrostrictive sensors, magnetostriuctive sensors, and piezoresistive sensors. The sensors are usually attached to or embedded in the structure.

Composite materials involving fiber reinforcements have become common structural materials. Among the various types of fibers, carbon fibers have become quite dominant due to their high strength, high modulus, low density, and temperature resistance. Carbon fibers are used to reinforce polymers, carbon, cement, and metals. If the carbon fibers in the composite provide strain sensing, then the conventional attached or embedded sensors are not necessary. This would mean reduced cost, greater durability, larger sensing volume, and absence of mechanical property degradation (due to embedded sensors). Therefore, this paper addresses strain sensing using carbon fibers.

Carbon fibers are electrically conductive. This behavior causes a change in electrical resistance in response to strain, thus enabling strain sensing. The nature of the electromechanical behavior depends on whether the fibers are continuous or discontinuous and depends on the matrix around the fibers. This paper provides a systematic study of the electromechanical behavior by considering (i) a single bare carbon fiber, (ii) a single carbon fiber in a matrix, (iii) a polymer-matrix composite containing randomly oriented short carbon fibers, (iv) a cement-matrix composite containing randomly oriented short carbon fibers, and (v) a polymer-matrix composite containing continuous unidirectional carbon fibers.

II. A SINGLE BARE CARBON FIBER

Previous electromechanical study of carbon fibers reported that, for low-modulus carbon fibers, the electrical resistance increases reversibly with tensile strain and decreases reversibly with compressive strain, mainly due to dimensional change rather than resistivity change. The objective of this section is to investigate the electromechanical behavior of a single bare carbon fiber of the same type that is used in most of the following sections. In other words, this section provides baseline information that is needed for the following sections.

The carbon fiber used was 10E-Torayca T-300 (unsized, PAN-based) of diameter 7 μm, density 1.76 g/cm³, tensile modulus 221 ± 4 GPa, tensile strength 3.1 ± 0.2 GPa, and ultimate elongation 1.4%. The electrical resistivity was (2.2 ± 0.5) × 10⁻³ Ω cm, as measured by using the four-probe method and silver paint electrical contacts on single fibers. Single fiber electromechanical testing was conducted by measuring the electrical resistance during static and cyclic tension. The dc resistance was measured by using the four-probe method, using silver paint for the electrical contacts. The outer two contacts (50 mm apart) were for passing a current; the inner two contacts (40 mm apart) were for voltage measurement (Fig. 1). A Keithley 2001 multimeter was used. Away from the four contacts, the single fiber was attached vertically with adhesive (60 mm apart) to a piece of paper with a rectangular hole cut in it (Fig. 1). Prior to vertical tension application, the paper was cut horizontally along the dashed lines shown in Fig. 1. The tension was under load control, as provided by a screw-type mechanical testing system (Sintech 2/D). The crosshead speed was 0.1 mm/min. The strain was obtained from the crosshead displacement.

Figure 2 shows typical plots of the fractional increase in resistance (ΔR/R₀), stress, and strain simultaneously obtained during static tensile testing up to failure. ΔR/R₀ increased monotonically with strain/stress.
configuration for bare single fiber electromechanical testing. The single fiber is adhered to a sheet of paper using adhesive such that points of adhesion are 40 mm apart. The four silver paint electrical contacts are such that the outer contacts are 34 mm apart and the inner contacts are 14 mm apart. The sheet of paper has a rectangular hole in its middle. The inner contacts are within the hole.

With a slight negative deviation from linearity. The gage factor (or strain sensitivity), given by the measured \( R/R_0 \) divided by the strain, was 1.8–1.9 throughout the whole range of strain. The \( \Delta R/R_0 \) calculated from the change in dimensions was less than but quite close to the measured \( \Delta R/R_0 \) at every strain value.

Figure 3 shows plots of \( \Delta R/R_0 \) versus time and strain versus time, simultaneously obtained during the first two cycles of tensile loading at stress amplitudes equal to 18.8, 58.1, and 83.0% of the fracture stress, respectively. The strain and \( \Delta R/R_0 \) were totally reversible at low values of the stress amplitude (up to 58.1% of the fracture stress), but their irreversible components increased with stress amplitude at high values of the stress amplitude. At the highest stress amplitude of 83.0% of the fracture stress, the extent of irreversibility of strain and \( \Delta R/R_0 \) increased slightly with cycle number [Fig. 3(c)]. At the intermediate stress amplitude of 58.1% of the fracture stress, the strain was totally reversible but \( \Delta R/R_0 \) was not [Fig. 3(b)]. A nonzero irreversible portion of \( \Delta R/R_0 \) was associated with a nonzero fractional decrease in the elastic modulus from the first cycle to the second cycle. The greater the irreversible portion of \( \Delta R/R_0 \), the greater was the fractional decrease in modulus. The gage factor, given by the reversible portion of \( \Delta R/R_0 \) divided by the reversible...
strain, was 1.9–2.3 at all stress amplitudes for both cycles 1 and 2. The \( \Delta R/R_0 \) calculated from the change in dimensions was less than the measured reversible \( \Delta R/R_0 \) at every stress amplitude.

Comparison of the calculated and measured reversible \( \Delta R/R_0 \) shows that dimensional change is the main cause of the observed reversible resistance change. The observed irreversible resistance change is attributed to damage, as supported by the accompanying decrease in the elastic modulus.

Even at a stress amplitude of 83.0% of the fracture stress, the irreversible portion of \( \Delta R/R_0 \) is much smaller than the reversible portion. Therefore, the use of the carbon fiber as a strain/stress sensor is possible. The irreversible portion, on the other hand, can be useful as an indicator of the amount of damage, so that the carbon fiber becomes a sensor of its own damage. This damage should be distinguished from fiber breakage, which would cause the irreversible \( \Delta R/R_0 \) to be \( \infty \).

III. A SINGLE CARBON FIBER IN A MATRIX

In a composite, a carbon fiber is not bare but is embedded in a matrix. The objective of this section is to investigate the electromechanical behavior of a single carbon fiber embedded in a matrix. Two matrices are included, namely a polymer (i.e., epoxy) and a cement (i.e., portland cement, Type I).

A. In a polymer matrix

Resistive and piezoresistive behaviors are to be distinguished. Resistive behavior pertains to the reversible increase of the electrical resistance (not resistivity) of a fiber upon tensile strain, as described in Sec. II for a single bare carbon fiber. The piezoresistive behavior pertains to the reversible change in the electrical resistivity upon strain, as reported in this section for a single carbon fiber in epoxy.

It has been reported that a carbon fiber in epoxy increases its electrical resistivity during the curing of the epoxy due to the residual compressive stress resulting from the shrinkage during curing and thermal contraction during cooling of the epoxy. Since the residual compressive stress in the fiber is expected to decrease upon subsequent tension of the fiber, this observation suggests that the electromechanical behavior of a carbon fiber in epoxy may be different from that of a bare carbon fiber. However, Ref. 5 reported the same electromechanical behavior for bare carbon fiber and carbon fiber in epoxy. As the residual compressive stress in a fiber increases with increasing curing temperature, a higher curing temperature than Ref. 5 was used in this work. Consequently, the fiber resistivity (also resistance) increased by 10% after curing of epoxy in this work, whereas the fiber resistance increased by only 0.5% after room temperature curing in Ref. 5. Thus, upon subsequent tension of the fiber in cured epoxy, we observed decrease of the fiber resistance due to reduction of the residual compressive stress, whereas Ref. 5 observed increase of the fiber resistance (as in the case of the bare fiber). Our effect is a piezoresistive effect in which the resistivity of a carbon fiber in cured epoxy decreases reversibly upon tension of the fiber.

The carbon fiber used was 10E-Torayca T-300 (un-sized, PAN-based). The epoxy used was EPON(R) resin 9405 together with curing agent 9470, both from Shell Chemical Co., in weight ratio 70:30. The recommended curing temperature is 150–180 °C for this epoxy.

The electrical resistance of a carbon fiber embedded in epoxy before and after the curing of the epoxy (at 180 °C, without pressure, for 2 h), as well as during subsequent tensile loading, was measured using the sample configuration of Fig. 4. A single fiber was embedded in epoxy for a length of 60 mm and an epoxy coating thickness of 5 mm, such that both ends of the fiber protruded and were bare in order to allow electrical contacts to be made on the fiber using silver paint. Four contacts (labeled A, B, C, and D in Fig. 4) were made. The outer two contacts (A and D) were for passing a current, whereas the inner two contacts (B and C, 80 mm apart) were for measuring the voltage. A Keithley 2001 multimeter was used for dc electrical measurements. The same electrical contact design was used in Sec. II for a single bare carbon fiber.

The electrical resistivity of carbon fiber increased by ~10% after curing and subsequent cooling. The fractional resistance increase was also ~10%.

It is known that the disparate thermal expansion properties of carbon fiber and epoxy leads to a residual thermal stress during the matrix (epoxy) solidification and subsequent cooling. Here we consider only the residual stress along the fiber direction (one dimension).

![Plate with mold release film on top](image_url)

**FIG. 4.** Sketch of the resistance measurement setup for single carbon fiber embedded in epoxy. A, B, C, and D are four probes. A and D are for passing current; B and C are for voltage measurement. Dimensions are in mm.
The experimental configuration is shown in Fig. 4. The thin specimen of a composite material is deformed in a biaxial test in which the strain is measured in two orthogonal directions. The stress-strain relationship is plotted in Fig. 6, showing the tensile and compressive behavior of the material. The Young's modulus and Poisson's ratio are determined from the slope and intercept of the stress-strain curve, respectively. The direction and magnitude of the stress are indicated on the graph. The results are consistent with previous studies and demonstrate the strength and stiffness of the composite material.

In conclusion, the experimental setup allows for the accurate measurement of the material properties under controlled conditions. The results provide valuable insights into the behavior of composite materials under different loading scenarios.
500 under compression or tension, in contrast to values up to 31 for the polymer-matrix counterpart (Sec. IV). The evidence in support of this origin for the cement-matrix composite is summarized below.

1. The sensing ability was present when the fibers were conducting (i.e., carbon or steel) and absent when the fibers were nonconductive (i.e., polyethylene). 11
2. The sensing ability was absent when fibers were absent. 12
3. The sensing ability occurred even at low carbon fiber volume fractions, which were associated with little effect of the fiber addition on the concrete's volume electrical resistivity. 13,14,16
4. There was no maximum volume electrical resistivity required in order for the sensing ability to be present. 11
5. The sensing ability was present when the carbon fiber volume fraction was as low as 0.2% (below the percolation threshold). 14,15
6. Fracture surface examination showed that the fibers were separate from one another. 16
7. The fractional increase in electrical resistance (ΔR/R0) upon straining essentially did not increase with increasing carbon fiber volume fraction, even though the increase in fiber volume fraction caused large decrease (by orders of magnitude) in the volume electrical resistivity. 11
8. The electrical resistance increased upon tension (fiber pullout) and decreased upon compression (fiber push-in) at any curing age, except for the first compressive strain cycle at less than 14 days of curing in which the resistance increased (Fig. 11). The resistance change during the first strain cycle was consistent with the need to weaken the fiber-matrix interface prior to fiber pullout in case the interface was strong to start with. 16,19
9. The presence of carbon fibers caused the crack height to decrease by orders of magnitude, as observed after deformation to 70% of the compressive strength. 11
10. The presence of carbon fibers caused the fracture toughness and tensile ductility of the composite to greatly increase. 16,19
11. The stress required for fiber pullout in the short fiber composite was consistent with the shear bond strength of carbon fiber and cement paste, as obtained by single fiber pullout testing. 26
12. The contact electrical resistivity between carbon fiber and cement paste increased during dehiscing. 25
13. The residual stress in a single carbon fiber embedded in cement paste is negligible (Sec. III).

Carbon fibers (same type and length as in Sec. IV) in the amount of 0.5% by weight of cement (corresponding to 0.51 vol% of composite) were used. Cement paste (Type I) from Lafarge Corp. (Southfield, MI) was used for the cementitious material. The water/cement ratio was 0.35. No aggregate was used. The water-reducing agent used in the amount of 3% by weight of cement was TAMOL SN (Rohm and Haas Co., Philadelphia, PA), which contained 93-96% sodium salt of a condensed naphthalenesulfonic acid. Methylcellulose and silica fume were added to help disperse the fibers. Silica fume (Eikem Materials Inc., Pittsburgh, PA, H#65) was used in the amount of 15% by weight of cement. Methylcellulose (Michelcel A15-LV, Dow Chemical Company, Midland, MI) in the amount of 0.4% by weight of cement was used together with a defoamer (Colloids Inc., Marietta, GA) in the amount of 0.13 vol%. Methylcellulose was dissolved in water and then fibers and defoamer were added and stirred by hand for about 2 min. Then this mixture, cement, water, water-reducing agent, silica fume, and sand (cement/sand ratio = 1:0. particle size analysis shown in Fig. 1 of Ref. 12; only for mortar, not for cement paste) were mixed in a Hobart mixer for 5 min. The mixer had a flat beater. After pouring the mix into molded molds, a vibrator was used to decrease the amount of air bubbles. The specimens were demolded after 1 day and then allowed to cure at room temperature in air at a relative humidity of 40% for 28 days.

Simultaneous to mechanical testing, dc electrical resistance measurements were made (as measurements that showed resistance and resistance varied with strain in qualitatively similar fashions). For compressive testing according to ASTM C109-80, specimens were prepared by using a 2 x 2 x 2 in. (5.1 x 5.1 x 5.1 cm) mold. Dog-bone-shaped specimens were used for tensile testing, as prepared by using molds of the same shape and size. The strain was measured by a strain gage under tension and by the crosshead displacement under compression, while the fractional change in electrical resistance along the stress axis was measured using the four-probe method. The electrical contacts were made by silver paint. Although the spacing between the contacts changed upon deformation, the change was so small that the measured resistance remained essentially proportional to the resistivity.

Figure 11 gives the fractional dc resistance increase (ΔR/R0) during first tensile loading of cement paste with 0.51 vol% carbon fibers at a stress amplitude of 0.9 MPa, or a strain amplitude of 4.8 x 10^-3, which was within the elastic regime, at 28 days of curing. (The tensile strength was 1.97 MPa.) The resistance was in the stress direction. Both the strain and strain rate were zero at the end of each cycle. The ΔR/R0 increased during tensile loading in each cycle and decreased during unloading in each cycle, with a gain factor of 0.25. This is due to fiber pullout during testing and fiber push-in during unloading. At the end of the first cycle, ΔR/R0 was positive rather than zero. This resistance increase is attributed to damage of the fiber- cement interface due to the fiber pullout and push-in. As cycling progressed, both the maximum ΔR/R0 and minimum ΔR/R0 in a cycle decreased. This is attributed to damage of the cement matrix separating adjacent fibers at their junction; this damage increased the chance for adjacent fibers to touch one another, thereby decreasing the resistivity.

Figure 12 gives ΔR/R0 during first cyclic compressive loading of mortar with 0.24 vol% carbon fibers at a stress amplitude of 16 MPa, or a strain amplitude of 8 x 10^-4, which was within the elastic regime, at 28 days of curing. (The compressive strength was 45 MPa.) The resistance was in the stress direction. Both strain and strain returned to zero at the end of each cycle. The ΔR/R0 decreased during compressive unloading in each cycle and increased during unloading in each cycle, with a gain factor of 0.50. This is due to fiber push-in during loading and fiber pullout during unloading. At the end of the first cycle, ΔR/R0 was positive rather than zero. The resistance increase is attributed to damage of the fiber cement interface due to the fiber push-in and pullout. A cycling progressed, both the maximum ΔR/R0 and minimum ΔR/R0 in a cycle decreased. This is attributed to damage of the cement matrix separating adjacent fibers at their junction, as explained above. This decrease from cycle to cycle persisted for the first ~150 cycle.

![Diagram](image-url)
or through-thickness) under tension is irreversibly decreased after the first cycle. This behavior is attributed to the irreversible disturbance to the fiber arrangement at the end of the first cycle, such that the fiber arrangement becomes less neat. A less neat fiber arrangement means more chance for the adjacent fiber layers to touch one another.

The stepwise increase of the longitudinal $\Delta R/R_0$ in the large strain regime (Fig. 14) is attributed to fiber breakage, which probably occurs in spurs. Such a stepwise increase had been previously observed and is also attributed to fiber breakage.\(^{23}\)

The through-thickness $\Delta R/R_0$ increases abruptly at intermediate strains but increases gradually at high strains (Fig. 16). This is because only a small change in the degree of fiber alignment causes a large change in the chance of adjacent fiber layers to touch one another. Moreover, fiber breakage, which occurs at high strains, essentially does not affect transverse $\Delta R/R_0$ (Fig. 16), but affects longitudinal $\Delta R/R_0$ (Fig. 14).

VII. CONCLUSION

Because of its electrical conductivity, carbon fiber provides strain sensing through the change in electrical resistance/resistivity upon strain. However, the nature and origin of the electromechanical effect depend on the matrix around the fiber and the continuity of the fiber. A single bare carbon fiber is a resistive strain sensor with a gage factor of 1.9–2.3. The effect is merely due to a change in dimensions of the fiber upon tension; it is not due to a change in resistivity. A single carbon fiber embedded in epoxy is a piezoresistive strain sensor with a gage factor of −17. The effect is due to a reduction in the residual compressive stress in the fiber upon tension; the residual stress is caused by the shrinkage of the epoxy during curing and subsequent cooling. A single carbon fiber embedded in cement does not experience this residual stress. An epoxy-matrix composite containing randomly oriented short carbon fibers (5.5 vol%) is a piezoresistive strain sensor with a gage factor of 6–23 under tension and 29–31 under compression; the effect is due to the change in proximity between adjacent fibers upon strain. A cement-matrix composite containing randomly oriented short carbon fibers (0.2–0.5 vol%) is a piezoresistive strain sensor with a gage factor of at least 500 under compression or tension; the effect is due to slight fiber pullout upon tension and slight fiber pull-in upon compression. An epoxy-matrix composite containing continuous unidirectional carbon fibers (58 vol%) is a piezoresistive strain sensor with a gage factor from −12 to −18 in the longitudinal direction and from 17 to 24 in the through-thickness direction under longitudinal tension, and from 1.1 to 1.3 in the longitudinal direction under longitudinal compression; effects in both directions are tentatively due to an increase in the degree of fiber alignment and decrease in fiber residual stress upon longitudinal tension.

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