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BRIEF COMMUNICATION

Strain sensors based on the electrical resistance change accompanying the reversible pull-out of conducting short fibers in a less conducting matrix

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Abstract. A new class of strain sensors has been discovered. These sensors are short-fiber composites. Their sensing ability is based on the electrical resistance change accompanying the reversible pull-out of conducting short fibers in a less conducting matrix. The fiber pull-out is associated with crack opening; the fiber push-in is associated with crack closing. The fiber pull-out, though slight, causes an increase in the fiber–matrix contact resistivity, thereby increasing the overall resistance of the composite. An example of these sensors is carbon fiber reinforced concrete.

1. Background

A strain sensor provides an electrical or optical response to a strain stimulus, such that the response is reversible when the stimulus vanishes. Strain sensors are needed for smart structures. The relationship between strain and stress, if known, allows strain sensors to serve as stress sensors as well.

Conventional strain sensors include strain gages, optical fibers, and piezoelectric and electrostrictive sensors. Some strain gages are in the form of a metal wire or film, which changes in electrical resistance as its dimensions change. Some other strain gages are piezoresistive materials, which are composites comprising conducting fillers and non-conducting matrices; the electrical resistivity of the composite increases as the separation between adjacent filler units increases upon tensile straining and decreases as the separation decreases upon compressive straining. Piezoelectric and electrostrictive sensors work because the electrical dipole moment per unit volume changes upon straining. Optical fibers can function as strain sensors because the light throughput of the fiber is decreased upon deformation.

2. A description of new strain sensor technology

This paper describes a new class of sensors, which are based on the electrical resistance change accompanying the reversible pull-out of electrically conducting short fibers in a less conducting (but somewhat conducting) matrix. The fiber pull-out is activated by straining and accompanies crack opening. The reverse, fiber push-in, accompanies crack closing. As the amount of fiber pull-out ($< 1\,\mu$m) is negligible compared to the fiber length (5 mm), the fiber–matrix interface area is essentially unaffected by the fiber pull-out, but the fiber–matrix contact resistivity is increased upon fiber pull-out, thus causing the overall resistivity of the composite to increase. The reversibility of the fiber pull-out is associated with the reversibility of the crack opening. This reversibility is made possible by the fact that the fiber bridges the crack.

In order for a short-fiber composite to have strain sensing ability using the above mentioned mechanism, the fibers must be more conducting than the matrix, of diameter smaller than the crack length, and well dispersed. Their orientations can be random and they do not need to touch one another (i.e., percolation is not needed). Percolation refers to the situation in which the fibers touch one another, thus allowing electrical conduction to occur from one fiber directly to another fiber.

The above mentioned sensing mechanism was discovered in work on carbon fiber reinforced concrete, in which the fibers were of diameter $10\,\mu$m, length 5 mm, and resistivity $10^{-3}\,\Omega$ cm (compared to a resistivity of

10^5–$10^6\,\Omega\,cm$ for plain concrete). The sensing ability of such a short-fiber composite had been previously reported [1], but the mechanism behind the sensing ability had not been previously elucidated. Although [1] alluded to reversible crack opening, it did not associated the reversible crack opening with reversible fiber pull-out. The crack volume increase along just cannot explain the large increase in the electrical resistance.

The evidence that supports the above mentioned sensing mechanism includes the following. (Refer to [2] for details of the evidence).

(i) The sensing ability was present when the fibers were conducting (i.e., carbon or steel) and absent when the fibers were non-conducting (i.e., polyethylene).

(ii) The sensing ability was absent when fibers were absent.

(iii) The sensing ability occurred at low carbon fiber volume fractions which are associated with little effect of the fiber addition on the concrete's volume electrical resistivity.

(iv) There was no maximum volume electrical resistivity required in order for the sensing ability to be present.

(v) The sensing ability was present when the carbon fiber volume fraction was as low as 0.2%—way below the percolation threshold, which was 1 vol.% or above, depending on the ingredients (e.g., silica fume against latex) used to help disperse the fibers.

(vi) Fracture surface examination showed that the fibers were separate from one another.

(vii) The fractional increase in electrical resistance ($\Delta R/R_0$) upon straining did not increase with increasing carbon fiber volume fraction, even though the increase in fiber volume fraction beyond the percolation threshold caused a large decrease (by orders of magnitude) in the volume electrical resistivity.

(viii) The electrical resistance increased upon straining, whether in tension or compression. In contrast, in piezoresistivity, the resistance increases in tension and decreases in compression.

(ix) The presence of carbon fibers caused the crack height to decrease by orders of magnitude. For example, the irreversible crack height observed after deformation to 70% of the compressive strength was decreased from 100 to 1 μm by the addition of carbon fibers in the amount of 0.37 vol.%, even though the compressive strength was essentially unaffected by the fiber addition.

(x) The presence of carbon fibers caused the flexural toughness and tensile ductility of the composite to greatly increase.

Items (iii), (iv), (vii) and (viii) are against piezoresistivity as the sensing mechanism. Items (ix) and (x), together with prior knowledge on fiber reinforced concrete [3, 4], suggest the occurrence of fiber bridging. Items (i), (ii), (v) and (vi) suggest that the electrical contact resistance between fiber and matrix plays an important role and that between fiber and fiber does not. All the pieces of evidence together support the proposed mechanism.

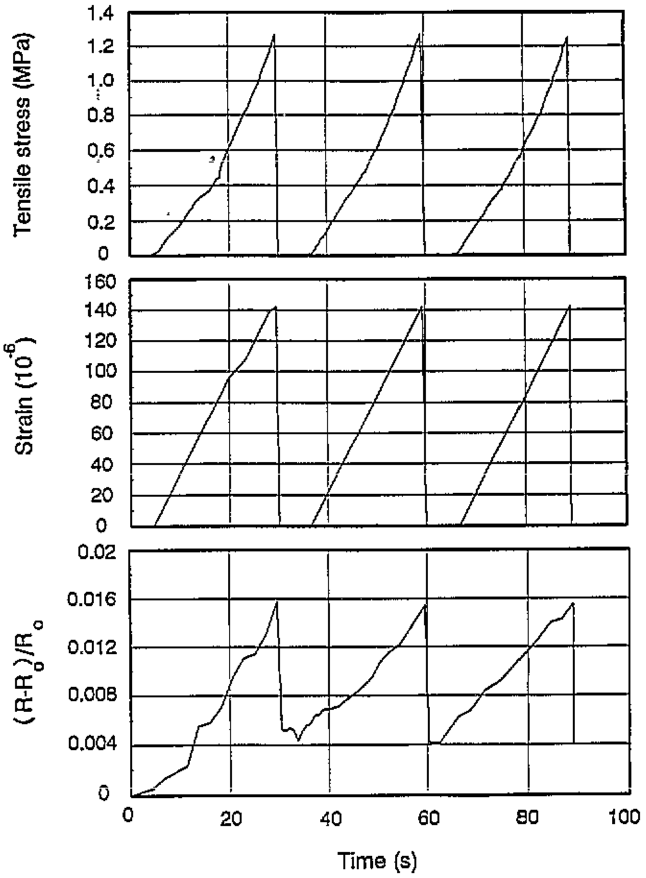

Figure 1. Plots against time of $\Delta R/R_0$, tensile strain and tensile stress obtained during cyclic tensile testing for mortar containing latex and 0.53 vol.% carbon fibers.

3. Performance of the new strain sensor

The strain sensitivity of the new sensor is extraordinarily high, as illustrated in figure 1 for carbon fiber (5 mm long, 0.53 vol.%) reinforced mortar (with sand, but no coarse aggregate) containing latex in the proportion of 0.20 of the cement (Portland cement, type I) weight and subjected to cyclic tension such that the maximum stress was ~ 0.5 of the breaking stress (i.e., loading within the regime where the strain was fully reversible). The smart performance was observed as (i) irreversibly increasing $\Delta R/R_0$ during the initial portion of the first loading, (ii) reversibly increasing $\Delta R/R_0$ during the latter portion of the first loading and during any subsequent loading, (iii) reversibly decreasing $\Delta R/R_0$ during unloading in any cycle. The increase in $\Delta R/R_0$ during loading is attributed to crack opening, whereas the decrease in $\Delta R/R_0$ during unloading is attributed to crack closure. The initial portion of the first loading exhibited an irreversible increase in $\Delta R/R_0$ whereas the latter portion was reversible because the irreversible part is due to permanent damage, probably associated with fiber–matrix interface weakening, whereas the reversible part is due to crack opening. The stress at which the irreversible $\Delta R/R_0$ increase ends and the reversible $\Delta R/R_0$ increase starts is the stress at which the fiber–matrix interface is sufficiently weak for it to not restrain crack opening or fiber pull-out. This stress corresponds to a strain of 48×10^{-6}. The stress/strain at which the irreversible $\Delta R/R_0$ increase starts to occur is the stress/strain at which permanent damage, probably associated with the fiber–matrix interface weakening, starts to occur; this stress is 0.001 MPa and the corresponding strain is 2×10^{-8}. The occurrence of permanent damage at such an early stage of elastic deformation had not been previously observed. Its observation indicates the high sensitivity of the concrete sensor.

The new strain sensing mechanism found in concrete may be found in other brittle matrix composites containing fibers or whiskers that are more conducting than the matrix.

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