Pergamon

Cement and Concrete Research, Vol. 26, No. 1, pp. 15-20, 1996

0008-8846/96 $15.00 + .00

0008-8846(95)00184-0

SELF-MONITORING OF FATIGUE DAMAGE IN CARBON FIBER REINFORCED CEMENT

Xuli Fu and D.D.L. Chung
Composite Materials Research Laboratory
State University of New York at Buffalo
Buffalo, NY 14260-4400, U.S.A.

(Communicated by D.M. Roy)
(Received October 23; in final form November 6, 1995)

ABSTRACT

Self-monitoring of slight fatigue damage was demonstrated in cement mortar containing short carbon fibers (0.24 vol.%), as damage (occurring in the first < 10% of the tensile or compressive fatigue life) caused the volume electrical resistivity to decrease irreversibly by up to 2%. The greater the stress amplitude, the greater the damage, the greater the resistivity decrease and the greater the number of stress cycles for which the resistivity decrease monotonically occurred. The resistivity decrease is attributed to the damage of the cement matrix separating adjacent fibers at their junction.

Introduction

Damage monitoring is needed for critical civil infrastructure systems in order to enhance safety and provide timely repair. For some structures, such as dams and nuclear power plants, even slight damage may cause hazards. Thus, the monitoring of both slight and severe damage is relevant, even though slight damage may not lead to fracture. The monitoring of severe damage is technically easier than that of slight damage. For example, acoustic emission or visual inspection provide detection of severe damage, but not slight damage. This paper provides a method for detecting slight fatigue damage.

A self-monitoring material refers to a structural material that can monitor itself without the need for embedded, attached or remote sensors. This is possible because the self-monitoring material is itself a sensor. Compared to structural materials which require sensor addition in order to monitor, self-monitoring materials are advantageous in their durability, low cost, large sensing volume and good mechanical properties. Self-monitoring of reversible strain has been previously reported in concrete containing short carbon fibers [1-3]; this ability stems from the reversible increase in the volume electrical resistivity of the concrete due to the reversible increase in the contact electrical resistivity between fiber and matrix during reversible straining [2]. This paper describes the self-monitoring of fatigue damage rather than reversible strain in the same material.

The method of damage monitoring provided by this paper also involves monitoring the volume electrical resistivity. Damage affects the resistivity of materials which are at least slightly electrically conducting. For example, cracks, which are electrically insulating, cause the resistivity to increase. However, a simple calculation shows that the resistivity increase is negligible unless the cracks constitute a significant fraction of the volume of the material. When cracks are so plentiful, damage is severe. As a result, this mechanism does not provide the ability to monitor slight damage. In the case of a composite material with fibers that are more electrically conducting than the matrix, damage in the form of degradation of the fiber-matrix interface also causes the resistivity to increase. However, this interface degradation occurs only in the first cycle of fatigue testing [1-3], so that this mechanism only provides a memory of the first cycle and does not allow the monitoring of damage in excess of what occurs in the first cycle. In contrast to these two mechanisms, this paper exploits a new mechanism which allows the monitoring of slight fatigue damage, including damage from the first cycle up to 350 cycles. This new mechanism is based on the decrease in resistivity in a composite material with short and randomly oriented fibers that are more electrically conducting than the matrix (e.g., concrete with short carbon fibers) upon damage of the matrix separating the adjacent fibers at their junction. This damage (probably in the form of microcracks in the case of a brittle matrix, such as cement) increases the chance of adjacent fibers to touch one another, thus causing the resistivity of the composite to decrease. The damage due to this mechanism causes the resistivity to decrease, whereas that due to the two other mechanisms causes the resistivity to increase.

Carbon fiber reinforced concrete is attractive technologically due to its high flexural strength, high flexural toughness, low drying shrinkage [4] and strain sensing ability [1-3]. This paper describes the damage sensing ability of this material. The objectives of the paper are (i) to characterize the fatigue damage sensing ability of carbon fiber reinforced concrete, (ii) to provide a concrete which has the ability to sense its own fatigue damage, and (iii) to provide a method for assessing slight fatigue damage in carbon fiber reinforced concrete.

Experimental Methods

The carbon fibers were isotropic pitch based and unsized, as obtained from Ashland Petroleum Co. (Ashland, Kentucky). The fiber diameter was 10 μm. The nominal fiber length was 5 mm. Fibers in the amount of 0.5% by weight of cement (corresponding to 0.24 vol.% of mortar) were used. Cement paste made from Portland cement (Type I) from Lafarge Corp. (Southfield, MI) was used for the cementitious material. The water/cement ratio was 0.35. The aggregate used was natural sand, the particle size analysis of which is shown in Fig. 1 of Ref. 3. The sand/cement ratio was 1.0. No large 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 (Elkem Materials Inc., Pittsburgh, PA) was used in the amount of 15% by weight of cement. Methylcellulose (Methocel A15-LV, Dow Chemical Corporation, Midland, MI) in the amount of 0.4% by weight of cement was used together with a defoamer (Colloids 1010, 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, sand, water, water reducing agent and silica fume were mixed in a Hobart mixer for 5 min. The mixer had a flat beater. The slump was 130 mm. After pouring the mix into oiled molds, a vibrator was used to decrease the amount

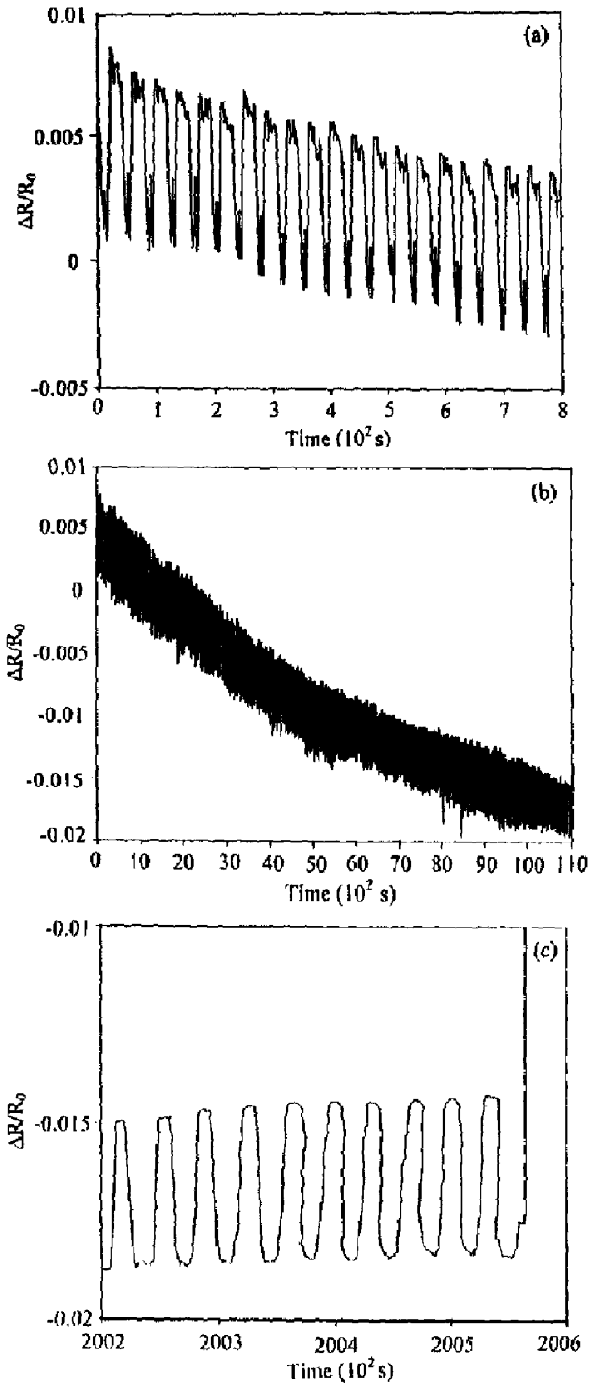

FIG. 1.

Fractional resistance increase ($\Delta R/R_0$) during cyclic compressive loading at a stress amplitude equal to 0.70 of the fracture stress. (a) First 21 cycles. (b) First ~ 300 cycles. (c) Last 11 cycles before fatigue failure at 5263 cycles.

of air bubbles. The specimens were demolded after 1 d and then allowed to cure at room temperature in air for 28 d.

Simultaneous to mechanical testing, electrical resistance measurements were made at a DC current ranging from 0.1 to 4 A. For compressive testing according to ASTM C109-80, specimens were prepared by using a 2 × 2 × 2 in. (5.1 × 5.1 × 5.1 cm) mold. Dog-bone shaped specimens were used for tensile testing. They were prepared by using molds of the same shape and size. The strain was measured by the crosshead displacement in compressive testing or by a strain gage in tensile testing, 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 contact increased upon tensile deformation and decreased upon compressive deformation, the increase was so small that the measured resistance remained essentially proportional to the resistivity. Testing was performed under cyclic loading (tensile or compressive) at stress amplitudes equal to 0.30, 0.50 and 0.70 of the fracture stress. For compressive testing, a hydraulic mechanical testing system (MTS Model 810) was used, such that each cycle took 38.1 s. For tensile testing, a screw-action mechanical testing system (Sintech 2/D) was used, such that each cycle took 52.2 s.

Results

Fig. 1 gives the fractional resistance increase ($\Delta R/R_0$) during cyclic compressive loading at a stress amplitude equal to 0.70 of the fracture stress. Fig. 1(a) gives the variation during the first 21 cycles; Fig. 1(b) gives the variation during the first ~ 300 cycles; Fig. 1(c) gives the variation during the last 11 cycles before fracture at 5263 cycles. $\Delta R/R_0$ decreased during loading and increased during unloading in each cycle. Fig. 1(b) shows that $\Delta R/R_0$ had a baseline which monotonically decreased as cycling progressed. This decrease occurred up to 306 cycles, at which the baseline became flat. The flat baseline persisted up to a few cycles before fracture. As shown in Fig. 1(c), the baseline showed a slight but consistent increase for a few cycles before fracture. At fracture, $\Delta R/R_0$ abruptly and greatly increased.

Fig. 2 shows results similar to Fig. 1, except that Fig. 2 was obtained under tension rather than compression. The results under tension and compression at various stress amplitudes are summarised in Table 1. The number of cycles for which the $\Delta R/R_0$ baseline monotonically lowered increased with increasing stress amplitude and the lowest point of the $\Delta R/R_0$ baseline decreased (i.e., became more negative) with increasing stress amplitude, whether under tension or compression. Obviously, the greater the stress amplitude, the greater the damage.

Discussion

The $\Delta R/R_0$ baseline monotonically decreased upon cyclic loading from the first cycle up to a cycle number ranging from 123 to 347 (depending mainly on the stress amplitude). This decrease is attributed to the damage of the cement matrix separating adjacent fibers at their junction. This damage enhanced the chance for adjacent fibers to touch one another, thereby causing the $\Delta R/R_0$ baseline to decrease. It occurred only in the early fatigue life, i.e., 5.8% of compressive fatigue life at a stress amplitude of 0.70 of fracture stress, or 9.2% of tensile fatigue life at a stress amplitude of 0.70 of fracture stress. Although the $\Delta R/R_0$ baseline decrease was clear and monotonic, it was not linear with cycle number. Nevertheless, it provides an indication of the extent of damage in the regime of slight damage.

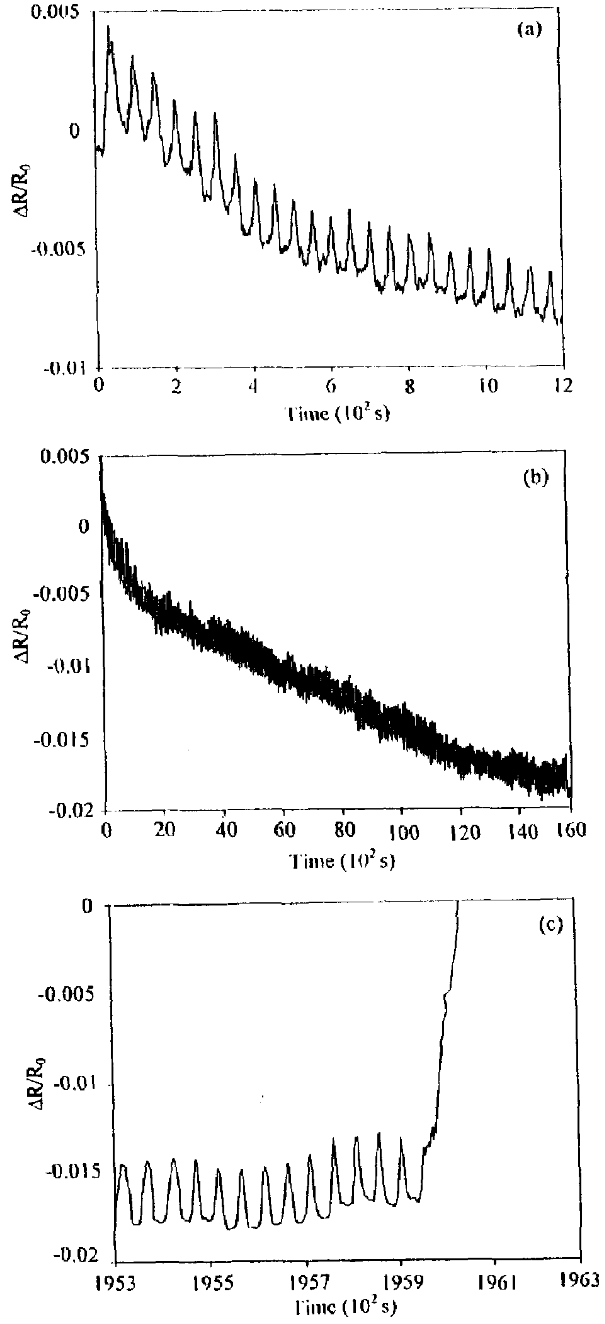

FIG. 2.

Fractional resistance increase ($\Delta R/R_0$) during cyclic tensile loading at a stress amplitude equal to 0.70 of the fracture stress. (a) First 23 cycles. (b) First ~ 300 cycles. (c) Last 11 cycles before fatigue failure at 3756 cycles.

TABLE 1

Effect of damage during cyclic loading on the $\Delta R/R_0$ baseline

Maximum stress / Fracture stress	Minimum $\Delta R/R_0$	No. of cycles to reach minimum $\Delta R/R_0$
Compression		
0.30	-0.003	123
0.50	-0.008	217
0.70	-0.02	306
Tension		
0.30	-0.006	146
0.50	-0.012	252
0.70	-0.02	347

The slight increase in the $\Delta R/R_0$ baseline during a few cycles prior to fracture provides an indication (warning) of the impending fracture. However, due to the slightness of this increase, the warning is not reliable. This slight increase is attributed to cracking. At fracture (fatigue failure), $\Delta R/R_0$ greatly increased, obviously due to cracking.

The damage of the cement matrix between adjacent fibers at their junction occurs upon cyclic loading. This is at least partly because reversible (but very slight) fiber pull-out occurs during each strain cycle [2]. After a certain number of cycles, this damage has stabilised, so that there is no further damage of this type upon further cycling. As a result, the $\Delta R/R_0$ baseline decrease occurs only for a limited number of cycles. Thus, this mechanism provides a means for the mortar to monitor its extent of fatigue damage in the regime of slight damage.

Conclusion

Damage in the early part of fatigue life was found to occur in carbon fiber reinforced mortar such that the damage resulted in an irreversible decrease in the volume electrical resistivity of the mortar. This resistivity decrease is attributed to the damage of the cement matrix separating adjacent fibers at their junction. The phenomenon enables the mortar to self-monitor slight fatigue damage.

References

1. Pu-Woei Chen and D.D.L. Chung, J. Am. Ceram. Soc. 78(3), 816-818 (1995).
2. D.D.L. Chung, Smart Mater. Struct. 4, 59-61 (1995).
3. Pu-Woei Chen and D.D.L. Chung, Smart Mater. Struct. 2, 22-30 (1993).
4. Pu-Woei Chen and D.D.L. Chung, Composites 24, 33-52 (1993).