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Short carbon fiber reinforced epoxy coating as a piezoresistive strain sensor for cement mortar

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Abstract

Epoxy containing 10 vol.% short carbon fibers and applied as a coating (0.2 mm thick) directly on cement mortar was found to be an effective piezoresistive strain sensor for tensile strain up to 0.042% and compressive strain down to −0.11%. Exceeding these strain limits caused damage in the coating. The strain sensitivity (reversible fractional increase in electrical resistance per unit strain) was 94–97 and 20–24 when the strain was contraction and expansion, respectively. The irreversible fractional increase in resistance per unit strain was 0.5–2.3 and 15–69 when the strain was contraction and expansion, respectively; it increased with increasing magnitude of strain. The resistance change was almost totally reversible when the strain was contraction, but was only partly reversible when the strain was expansion. The sensor in coating form was similar to that in bulk form in the electromechanical behavior.

Keywords: Piezoresistive; Strain sensor; Carbon fibers; Composite; Polymer; Epoxy; Cement; Coating

1. Introduction

Polymer–matrix composites containing short carbon fibers are effective strain sensors ([1,2]) due to piezoresistivity, which results from the electrically conductive nature of carbon fibers and the change in proximity between adjacent fibers upon strain. Short carbon fibers as the filler ([2]) gave higher strain sensitivity than carbon black ([3]) or continuous carbon fibers ([4]) as the filler. The discontinuous nature of short carbon fibers allows the composite to be used as a coating, which can be applied like a paint on any part, the strain of which needs to be monitored. Previous work on this composite is limited to the bulk form of the composite. This work extends the technology from bulk form to coating form for the purpose of providing an inexpensive strain sensor technology.

Epoxy was chosen as the matrix of the composites of this work, due to the adhesive nature of epoxy. Cement mortar was used in this work as the coating's substrate, the strain of which was to be monitored. Cementitious materials are widely used for civil structures, such as bridges and highways. Strain monitoring in real time is important for these structures for the purpose of in situ structural health monitoring, dynamic load monitoring and traffic monitoring. Although the substrate used in this work was cement mortar (with fine aggregate) rather than concrete (with fine and coarse aggregates) and concrete is the commonly used construction material, the results of this work concerning the strain sensing ability of the short carbon fiber polymer–matrix composite coating is expected to apply similarly to mortar and concrete substrates.

2. Experimental methods

The composite strain sensor used epoxy (Epon Resin 862 and curing agent 3274, for room temperature curing, from Shell Chemical) as the matrix and short carbon fibers (5 mm long, resistivity 3×10^{-3} Ω cm, pitch-based, unsized, from Ashland Petroleum, Ashland, KY) as the filler. The composite was fabricated by mixing the fibers with the resin (together with the curing agent) at a weight ratio of 1:12 (corresponding to 10 vol.% fibers after curing) and applying the slurry as a coating on the substrate, using a blade in conjunction with a flat plate to control the coating thickness. The average coating thickness after curing was 0.2 mm, which suggests that the fibers were preferentially oriented in the plane of the coating, in contrast to the random orientation of the fibers in the bulk composite.

The substrate for compressive testing was cement mortar ($2\times2\times2$ in.^{3}) made by mixing water, Portland cement

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(Type I), sand (natural sand, 100% passing #8 US sieve) and a water reducing agent, which was 93–96% sodium salt of a condensed naphthalenesulfonic acid (TAMOL SN, Rohm and Haas, Philadelphia, PA), such that the water/cement weight ratio was 0.400–0.475, the sand/cement ratio was 1.0, and the water-reducing-agent/cement weight ratio was 0.59%. Curing was conducted in room air for 20 days. The electrical resistivity of the mortar was 10^5 Ω cm. The compressive strength of the mortar was 36 ± 8 MPa.

The volume resistivity of the composite coating, as measured by the four-probe method (using silver paint for the electrical contacts) while the coating was in contact with the mortar and by neglecting the non-zero conductivity of the mortar, was 199 ± 31 Ω cm. In contrast, the volume resistivity of the composite in a stand-alone form, as measured by the four-probe method, was 243 ± 20 Ω cm. The difference between these two resistivity values indicates that the conductivity of the mortar affected the measured resistance (apparent resistivity) of the composite coating.

Simultaneous measurements of the uniaxial compressive stress, longitudinal strain (parallel to the stress) and transverse strain (perpendicular to the stress) were made, such that each strain was measured by the composite coating ((A) on the front face of the cube in Fig. 1 for the longitudinal strain and (C) on the right face of the cube in Fig. 1 for the transverse strain) and a resistive strain gage ((B) on the back face of the cube in Fig. 1 for the longitudinal strain and (D) on the left face of the cube in Fig. 1 for the transverse strain). Each patch of composite coating was square (slightly less than 2×2 in., or slightly less than 51×51 mm). On each patch of composite coating were four parallel silver paint electrical contact stripes, as shown by thick lines within (A) and (C) in Fig. 1. The outer two stripes were current contacts, spaced 38 mm apart; the inner two stripes were voltage contacts, spaced 18 mm apart. The strain gages were EA-13-120LZ-120 (gage factor = 2.115 ± 0.5%) from Micromeasurements Group, Inc. (Raleigh, NC). Stress and displacement (0.8 mm/min) were provided by a hydraulic mechanical testing system (MTS Model 810). The stress amplitude ranged from 11 to 27% of the substrate's fracture stress (36 MPa). DC electrical measurements were provided by a Keithley 2001 multimeter. The measured resistances were in the range of 1 to 2 kΩ. Five samples were tested.

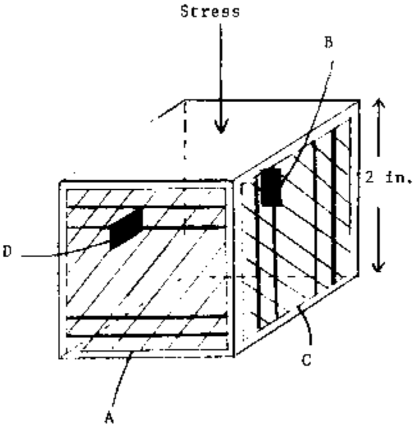

Fig. 1. Compressive testing cement mortar sample. (A) Composite sensor for longitudinal $\Delta R/R_o$ measurement, (B) strain gage for longitudinal strain measurement, (C) composite sensor for transverse $\Delta R/R_o$ measurement and (D) strain gage for transverse strain measurement.

3. Results

Fig. 2 gives the uniaxial compressive stress, longitudinal strain, longitudinal $\Delta R/R_o$ (fractional resistance change), transverse strain and transverse $\Delta R/R_o$ for a stress amplitude of 8 MPa (22% of the compressive strength). Although Fig. 2 shows the result for one sample, similar results were obtained from four other samples. The strains are indicated by the corresponding strain gages ((B) and (D) in Fig. 1) and, as shown in Fig. 2, they are totally reversible. The $\Delta R/R_o$ values are indicated by the corresponding composite sensors ((A) and (C) in Fig. 1). The longitudinal strain is

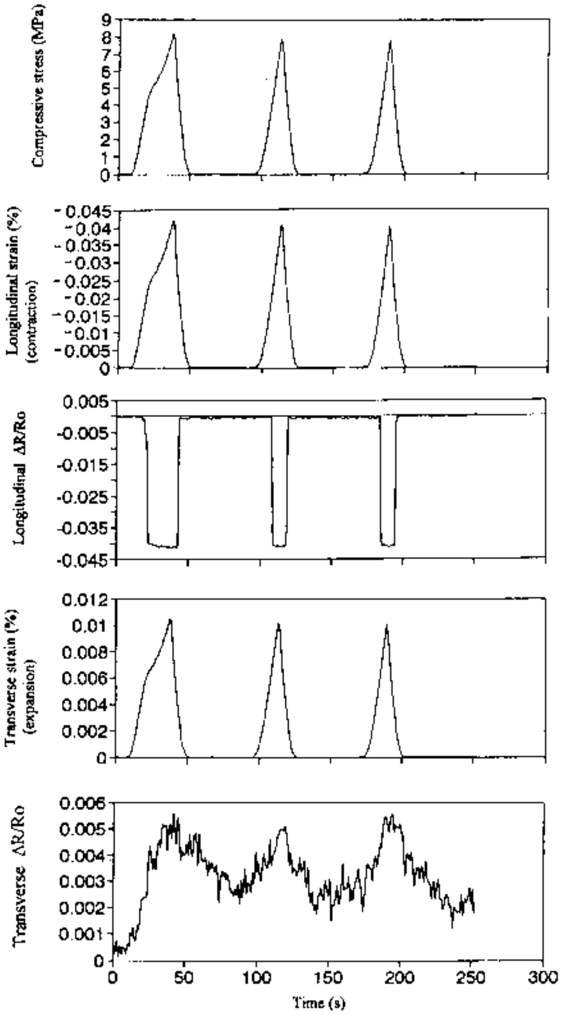

Fig. 2. Plots vs. time of uniaxial compressive stress, longitudinal strain, longitudinal $\Delta R/R_o$, transverse strain and transverse $\Delta R/R_o$ obtained during cyclic compression testing for the composite sensor coating on cement mortar.

Table 1
The reversible and irreversible parts of $\Delta R/R_o$ and of $\Delta R/R_o$ per unit strain

	Maximum stress/fracture stress		
	11%	22%	27%
Strain (%)			
Longitudinal	−0.023	−0.043	−0.052
Transverse	0.0053	0.0105	0.013
$\Delta R/R_o$			
Reversible			
Longitudinal	−0.0216	−0.0415	−0.0497
Transverse	0.0011	0.0021	0.0031
Irreversible			
Longitudinal	−0.00011	−0.0002	−0.0012
Transverse	0.0008	0.0025	0.0090
$\Delta R/R_o$ per unit strain			
Reversible[a]			
Longitudinal	94	97	96
Transverse	21	20	24
Irreversible			
Longitudinal	0.5	0.5	2.3
Transverse	15	24	69

[a] Strain sensitivity (gage factor).

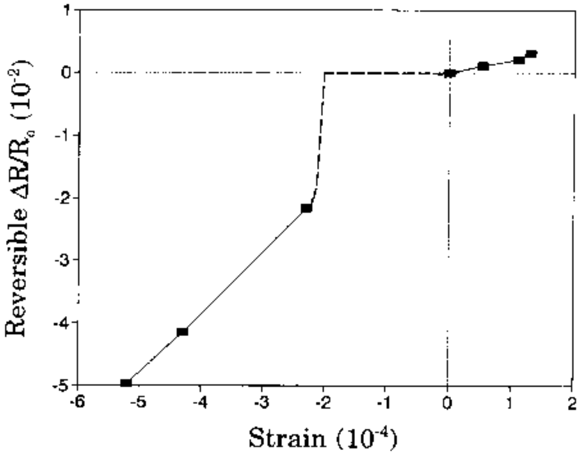

Fig. 3. Plot of reversible part of $\Delta R/R_o$ vs. strain. Negative strain corresponds to contraction, which occurs in the longitudinal direction. Positive strain corresponds to expansion, which occurs in the transverse direction. The dashed line corresponds to the non-linearity shown in the longitudinal $\Delta R/R_o$ in Fig. 2.

negative, as it corresponds to contraction in the stress direction. It is associated with a negative $\Delta R/R_o$ (i.e., R decreasing), due to piezoresistivity. The transverse strain is positive, due to the Poisson effect. It is associated with a positive $\Delta R/R_o$, due to piezoresistivity. Table 1 shows the reversible and irreversible parts of $\Delta R/R_o$ and of $\Delta R/R_o$ per unit strain for each stress amplitude (expressed as a fraction of the fracture stress of the mortar). The reversible $\Delta R/R_o$ per unit strain is the strain sensitivity (gage factor). It is much larger for negative strain (longitudinal) than for positive strain (transverse), as also shown in Fig. 3. The irreversible part of $\Delta R/R_o$ per unit strain is much smaller than the reversible part of $\Delta R/R_o$ per unit strain when the strain is negative (longitudinal), but these two parts are comparable when the strain is positive (transverse). Hence, the strain sensing ability is much better for negative than for positive strain. Except for the strain range from 0 to −0.02%, the reversible part of the longitudinal $\Delta R/R_o$ is linearly related to the negative strain (Fig. 3). The reversible part of the transverse $\Delta R/R_o$ is linearly related to the positive strain (Fig. 3). Thus, the strain sensitivity is quite independent of the strain amplitude for most strains (Table 1). However, the irreversible $\Delta R/R_o$ per unit strain increases with increasing strain amplitude, suggesting that the irreversible $\Delta R/R_o$ is associated with coating damage. Comparison of the strain data provided by the resistive strain gages (Fig. 2) and the $\Delta R/R_o$ data (Fig. 2) provided by the composite coating shows that the resistive strain gages are more sensitive to strain and more linear with strain than the composite coating. On the other hand, the composite coating is much less expensive than the strain gages.

Figs. 4 and 5 show the longitudinal and transverse $\Delta R/R_o$ during static compression of mortar up to failure (Fig. 1).

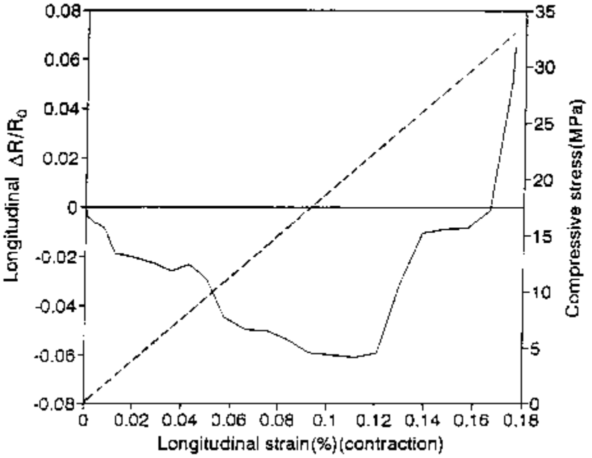

Fig. 4. Compressive stress, longitudinal strain and $\Delta R/R_o$ of the composite coating, obtained simultaneously during static compression up to fracture. Solid curve: longitudinal $\Delta R/R_o$ vs. longitudinal strain. Dashed curve: compressive stress vs. longitudinal strain.

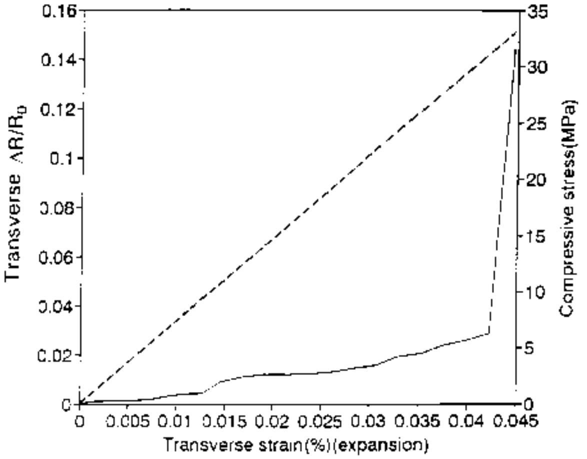

Fig. 5. Compressive stress, transverse strain and $\Delta R/R_o$ of the composite coating, obtained simultaneously during static compression up to fracture. Solid curve: transverse $\Delta R/R_o$ vs. transverse strain. Dashed curve: compressive stress vs. transverse strain.

The coating in the transverse direction experienced expansion during uniaxial compression. The transverse $\Delta R/R_o$ (Fig. 5) was observed to increase non-linearly to 0.03 with strain up to 0.04% and then jump to 0.14 upon failure, which was due to coating fracture (not coating debonding or mortar fracture, as observed visually). The transverse $\Delta R/R_o$ of the coating in Fig. 5 exhibited the same trend with strain as the bulk composite under tension (Fig. 5 in the work of Wang and Chung [2]). On the other hand, the coating in the longitudinal direction contracted under compression. The longitudinal $\Delta R/R_o$ (Fig. 4) was observed to decrease initially with strain up to 0.11%, and then increase sharply until coating fracture. The behavior of the longitudinal $\Delta R/R_o$ of the coating is similar to that of the bulk composite under compression (Fig. 10 in the work of Wang and Chung [2]), but the strain at which $\Delta R/R_o$ is minimum is 0.12% for the coating and 2.5% for the bulk. This is probably because coating damage (i.e., sensor damage) occurs more readily than bulk damage, and damage causes the resistance to increase. This is also probably because debonding of the coating from the mortar causes the resistance to increase (since the mortar is more conducting than air). Because of damage in the coating, the coating is an effective strain sensor up to a strain of 0.042% (expansion, Fig. 5) and down to a strain of −0.11% (contraction, Fig. 4). The change of $\Delta R/R_o$ under static loading (Figs. 4 and 5) is consistent with that under cyclic loading (Fig. 2).

The strain sensitivities reported in Ref. [2] for the bulk composite were obtained at much higher strains than those in Table 1 for the composite in coating form. In order to compare the performance of composites in bulk and coating forms, measurement of the bulk composite by Wang and Chung [2] (with 5.5 vol.% carbon fibers) was made at strains as low as those of Table 1 under static compression and tension. The measurement procedure is as described by Wang and Chung [2]. As shown in Figs. 6 and 7 for the bulk composite under compression and tension, respectively, the strain sensitivities are 82 and 20 under compression and tension, respectively. These values are not too far from the corresponding values in Table 1 for the composite in coating form. Hence, the electromechanical behavior of the composite in bulk and coating forms are similar, in spite of the absence of fiber alignment in the bulk form and the presence of fiber alignment in the coating form.

The strain limits of 0.042% under tension and 0.11% under compression for the composite coating strain sensor are lower than the practical requirement for concrete (0.5% strain). Nevertheless, this sensor is applicable for local strain testing and dynamic testing of concrete.

The gage length for sensing the strain of concrete should be larger than three times that of the coarse aggregate. As the composite coating can be applied over a large area, the gage length on the coating can be much larger than the above requirement.

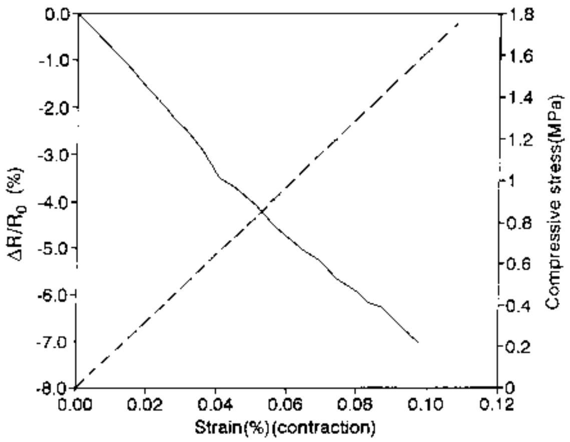

Fig. 6. Compressive stress, longitudinal strain and $\Delta R/R_o$ of bulk composite. Solid curve: $\Delta R/R_o$ vs. strain. Dashed curve: compressive strain vs. strain.

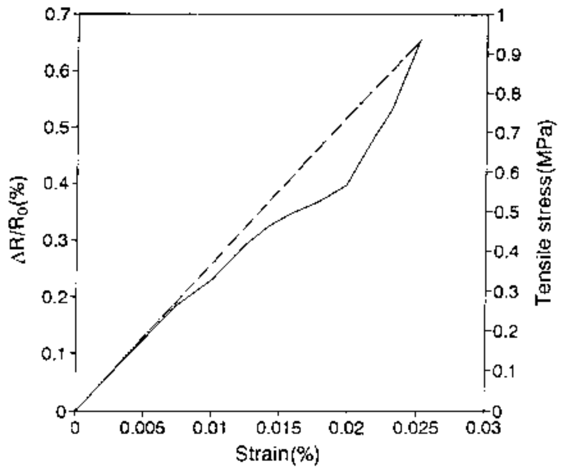

Fig. 7. Tensile stress, longitudinal strain and $\Delta R/R_o$ of bulk composite. Solid curve: $\Delta R/R_o$ vs. strain. Dashed curve: tensile stress vs. strain.

4. Conclusion

Epoxy containing 10 vol.% short carbon fibers and applied as a coating on cement mortar was found to be an effective piezoresistive strain sensor with strain sensitivity 94–97 and 20–24 for negative and positive strains, respectively. Positive strains up to 0.042% and negative strains down to −0.11% were detected; excessive damage in the coating occurs when these limits are exceeded. The resistance change of the sensor is almost totally reversible when the strain is negative, but is only partly reversible when the strain is positive. The irreversible part of the fractional resistance change per unit strain increases with the magnitude of strain. The electromechanical behavior of the composite in coating form is consistent with that of the composite in bulk form.

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References

[1] P.K. Pramanik, D. Khastgir, S.K. De, T.N. Saha, J. Mater. Sci. 25 (1990) 3848–3853.

[2] X. Wang, D.D.L. Chung, Smart Mater. Struct. 4 (1995) 363–367.

[3] J. Kost, M. Narkis, A. Foux, J. Appl. Polym. Sci. 29 (1984) 3937–3946.

[4] N. Muto, H. Yanagida, M. Miyayama, T. Nakatsuji, M. Sugita, Y. Ohtsuka, J. Ceramic Soc. Jpn. (Int. Edn.) 100 (1992) 582–585.

Biographies

D.D.L. Chung is Niagara Mohawk Power Endowed Chair Professor (since 1991), Director of the Composite Materials Research Laboratory (since 1989) and Professor of Mechanical and Aerospace Engineering (since 1986) in the State University of New York at Buffalo. She was Associate Professor of Metallurgical Engineering and Material Science (1982–1986) and Assistant Professor (1977–1982) in Carnegie Mellon University. She holds a PhD degree (1977) in Materials Science and a MS degree (1975) from Massachusetts Institute of Technology, and a MS degree in Engineering Science (1973) and a BS degree in Engineering and Applied Science (1973) from California Institute of Technology. Awards received include Fellow conferral from ASM International (1998), the 'Teacher of the Year' Award from Tau Beta Pi, New York Nu (1992–1993), the Teetor Educational Award from the Society of Automotive Engineers (1987), the Hardy Gold Medal from the American Institute of Mining, Metallurgical, and Petroleum Engineers (1980), and the Ladd Award from Carnegie Mellon University (1979). Chung has been active in composites research since 1986, although she has been active in carbon research since 1975. Her work in composites includes the fabrication and characterization of composites with polymers, cement and metals as matrices. Her composites research accomplishments include intrinsically smart structural materials, fiber–matrix interface characterization by electromechanical pull-out testings, and composites for electronic packaging. She has authored three books, which include *Carbon Fiber Composites* (Butterworth, 1994) and *Science of Smart Materials* (Prentice Hall, in press). In addition, she has authored or co-authored over 200 papers that have been published in archival journals, and has edited a book on *Materials for Electronic Packaging* (Butterworth, 1995).

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