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Biaxial compression in carbon-fiber-reinforced mortar, sensed by electrical resistance measurement

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Abstract

The stress-sensing behavior of carbon-fiber-reinforced mortar under biaxial compression was found to be different with that under uniaxial compression. For both the case of uniaxial compression and the case of biaxial compression, with an increase in the compressive stress, the fractional change in resistance in any direction decreases gradually at first, and then increases with increasing stress. But the stress level at which the fractional change in resistance starts to increase, referred to as the critical stress in this paper, varies with the loading style and the direction in which the resistance is measured. The critical stress related to the biaxial compression and the stress direction is larger than that related to the uniaxial compression and the stress direction. But on the other hand, the critical stress related to the biaxial compression and the direction other than the two stress directions is less than that related to the uniaxial compression and the direction other than the stress direction. The piezoresistivity of carbon-fiber-reinforced mortar under biaxial compression is more sensitive than that under uniaxial compression.

Keywords: Electrical properties; Carbon fibers; Stress; Uniaxial compression; Biaxial compression

1. Introduction

In recent years, more attention has been paid to the carbon-fiber-reinforced cement composite, not only because it exhibits high flexural strength and toughness and low drying shrinkage [1,3], but also due to its capabilities in nondestructive structural health monitoring in real time [2–4]. Health monitoring of a structure is valuable for hazard mitigation, whether the damage is due to use, earthquake, wind, or ocean waves [7]. Real-time monitoring provides information as soon as damage occurs, thus enabling timely repair or other hazard precaution measures. Carbon-fiber-reinforced cement composite is capable of sensing its own stress/strain due to the effect of stress/strain on the electrical resistance [2–6]. As observed at 28 days of curing, the resistance in the stress direction for carbon-fiber-reinforced cement composite under uniaxial loading increases upon tension, due to slight fiber pullout that accompanies crack opening, and decreases upon compression, due to slight fiber push-in that accompanies crack closing [8–13]. However, little attention has been previously paid to the stress/strain-sensing ability for carbon-fiber-reinforced cement composite under biaxial or triaxial loading. In practical use of carbon-fiber-reinforced cement composite for stress/strain sensing, sometimes multiaxial loading is inevitable. Furthermore, how the resistance changes under multiaxial loading provides valuable insight on the mechanism behind the piezoresistive effect. Therefore, for both technological and scientific reasons, it is important to investigate the resistance of carbon-fiber-reinforced cement composite subject to multiaxial loading. For simplicity, this paper is focused on the resistance of carbon-fiber-reinforced mortar under biaxial compression. However, for the sake of comparison, investigation was also conducted in this work for carbon-fiber-reinforced mortar subject to uniaxial compression.

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2. Experimental methods

The carbon fibers were isotropic PAN-based and unsized, as obtained from Tiantai New Materials (Shandong, P.R. of China). The fiber diameter was 15 μm. The nominal fiber length was 4.5 mm. Fibers in the amount of 0.5 mass% of cement were used. The mechanical/electrical properties of carbon fibers are listed in Table 1. The cement used was Portland cement (42.5R) from Nanfang Jiahua Cement Plant (Guangzhou, P.R. of China). The silica fume with diameter of 0.08 μm and specific gravity of 200–250 kg/m^3 (Muhu Concrete Admixture, Beijing, P.R. of China) was used in the amount of 15 mass% of cement. The methylcellulose from Tianma Chemistry (Guangzhou, P.R. of China) was used in the amount of 0.4 mass% of cement to help disperse the fibers. The defoamer from Chemical Reagent (Shanghai, P.R. of China) was used in the amount of 0.05 mass% of cement. The water-reducing agent (FDN) was used in the amount of 2 mass% of cement. The water/cement ratio was 0.4. The aggregate used was natural sand, 100% of which passed a 2.5-mm sieve. The sand/cement ratio was 1.0.

Methylcellulose was dissolved in water and then fibers and defoamer were added and stirred by hand for about 5 min. Then, this mixture, cement, sand, water, water-reducing agent and silica fume were mixed in a mixer for 5 min. The mixer had a flat beater. After pouring the mix into oiled molds (10×10×10 cm), a vibrator was used to facilitate compaction and decrease the amount of air bubbles. The specimens were demolded after 1 day and then allowed to cure at room temperature in air (relative humidity ≥90%) for 28 days. The average resistivity of the 28-day carbon-fiber-reinforced mortar, measured using the two-probe method, was $7.26\times10^3\ \Omega\cdot$cm. It should be noted that the two-probe method produces values which may be higher than the true resistance of the specimens, due to the influence of the contact resistance between the electrical contacts and the specimens, but this does not affect the ability of the two-probe method to detect changes due to internal processes within the specimens under compressive loading [15].

Samples for both uniaxial and biaxial compression were in the form of cubes of size 10×10×10 cm. Three specimens for uniaxial compression (Specimen 1–Specimen 3) and five specimens for biaxial compression (Specimen 4–Specimen 8) were tested in the experiment.

For uniaxial compressive testing, compressive stress was applied to the specimen in the *x* direction. During the loading process, the compressive stress at first increased at a rate of 2 MPa/min until it reached 2 MPa, and then the compressive stress increased at a rate of 4 MPa/min. During static loading to failure, electrical resistance measurement was made in the *x*, *y* and *z* direction independently, using the two-probe method, in which thin copper sheets (6×8 cm) in conjunction with copper wires served as electrical contacts. The copper wires were soldered on the copper sheets. Conductive paste was used to bond six electrical contacts to the six surfaces of the specimen. The mixture proportion of the conductive paste was as follows:

Table 1
Mechanical/electrical properties of carbon fibers

Tensile strength	Tensile modulus	Elongation at break	Electrical resistivity
3200 MPa	220 GPa	1.0%	$6\times10^{-3}\ \Omega\cdot$cm

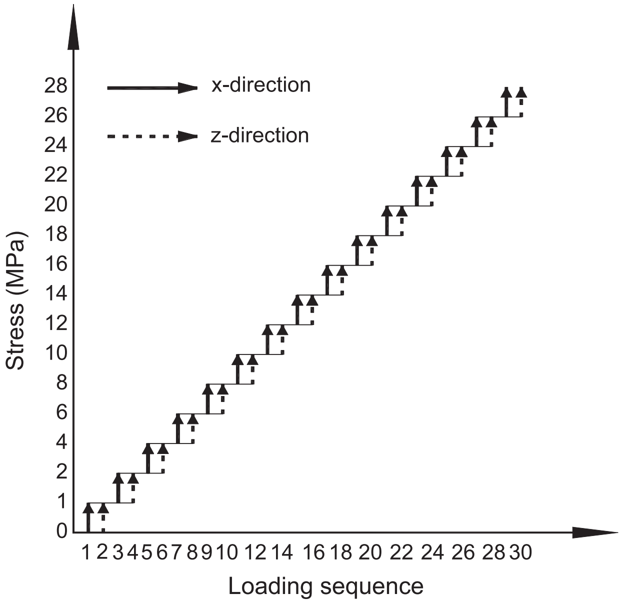

Fig. 1. Loading process for biaxial compression.

$$\begin{aligned}&\mathrm{E}-44\ \text{ epoxide resin : dibutylphthalate : divinyltrilamine}\\&:\gamma-\text{aminopropyl}-\text{triethoxysilane : copper powder}\\&=100:20:12:13:300\end{aligned}$$

For biaxial compressive testing, compressive stresses were applied to the specimen in the *x* and *z* directions, respectively. The compressive stress in the *z* direction increased step by step with increasing of the compressive stress in the *x* direction. The loading process for biaxial compression is shown in Fig. 1. During the loading process, the loading rates in the *x* and *z* directions were, respectively, identical to that for uniaxial compressive testing. During static loading, electrical resistance measurement was made in the *x*, *y* and *z* direction independently, using the two-probe method, in which thin copper sheets (6×8 cm) in conjunction with copper wires served as electrical contacts. Conductive paste was used to bond six electrical contacts to the six surfaces of the specimen. The way the copper sheets connected with the copper wires, and the mixture proportion of the conductive paste were the same as those for uniaxial compressive testing.

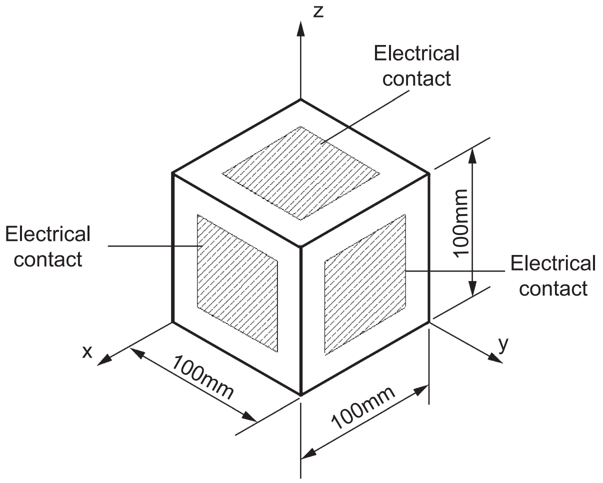

Fig. 2. Sample configuration for measuring the electrical resistance in the x, y and z directions during uniaxial/biaxial compression.

Fig. 2 shows the sample configuration for measuring the electrical resistance in the x, y and z directions during uniaxial/biaxial compression.

3. Results and discussion

Figs. 3 and 4 show the fractional change in resistance in the x and z directions, respectively, for Specimen 1 under uniaxial compression. It can be seen from Figs. 3 and 4 that:

(a) With an increase in the compressive stress, the fractional change in resistance in the stress direction (x direction) decreases gradually at first until the stress reaches 12 MPa (about 40% of the average ultimate compressive strength of the 28-day carbon-fiber-reinforced mortar), and then increases with increasing stress. The resistance decrease at the early stage of loading is mainly attributed to the closing of original microcracks (or damage, defect), as expected, because the loading is compressive. On the other hand, the resistance decrease at the early stage of loading is also perhaps partly due to a decrease in the contact resistance between the copper sheets and the specimen because they touched more closely upon compression. With an increase in the compressive stress, new microcracks, damage or defect will be generated and open. At the middle stage of loading, the closing of the old microcracks and the opening of the new microcracks arrive a dynamic balance, so the curve tends to be plat. But at the late stage of loading, the opening of the new microcracks is quite more than the closing of the old microcracks, so the fractional change in resistance increases dramatically [14].

(b) With an increase in the compressive stress, the fractional change in resistance in the z direction (other than the stress direction) also decreases gradually at first, and then increases with increasing stress. But the resistance in the z direction starts to increase at a stress level of 6 MPa, which is lower than 12 MPa mentioned above for resistance in the stress direction. This may be due to the fiber pullout in the z direction, which is caused by the tensile strain in the z direction during uniaxial compression.

(c) The fractional change in resistance in any direction relative to the stress axis can be used to indicate compressive stress in the stress direction, although the fractional change in resistance in the stress direction is used commonly.

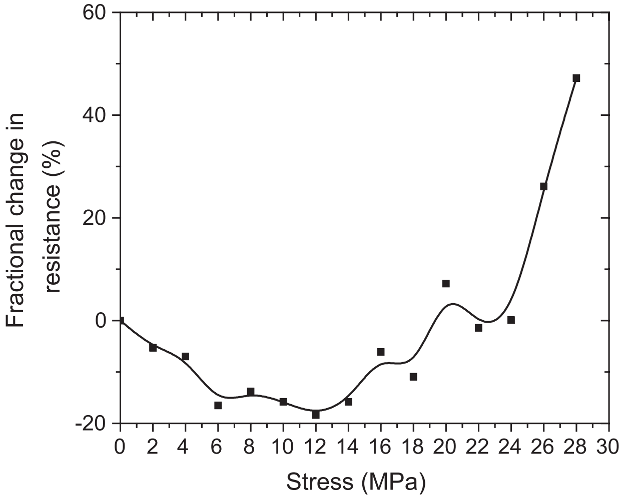

Fig. 3. Fractional change in resistance in the x direction versus compressive stress in the x direction during uniaxial compression.

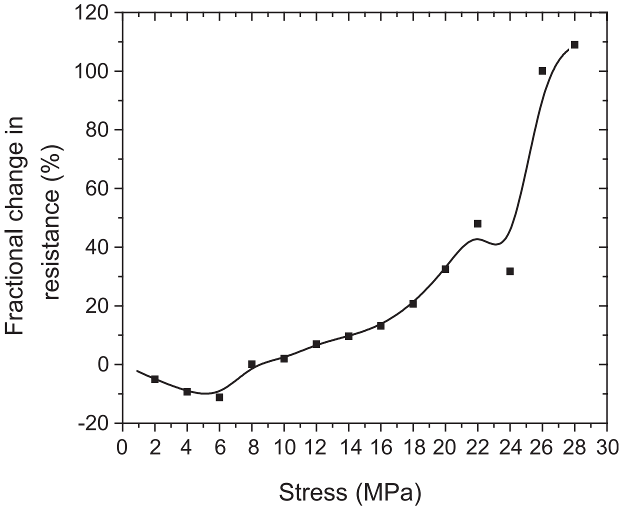

Fig. 4. Fractional change in resistance in the z direction versus compressive stress in the x direction during uniaxial compression.

Test results of Specimen 2 and Specimen 3 are similar to those of Specimen 1. The stress level at which the fractional change in resistance starts to increase is referred to as the critical stress in this paper. For uniaxial compressive testing, the average critical stress for Specimens 1–3 in the stress direction is 11 MPa, and the maximum error of the critical stress of any specimen in the stress direction with respect to 11 MPa is 9.1%.

Figs. 5, 6 and 7 show the fractional change in resistance in the *x*, *y* and *z* directions, respectively, for Specimen 4 under biaxial compression. It can be seen from Figs. 1, 5, 6, and 7 that:

(a) With an increase in the compressive stresses, the fractional change in resistance in the *x* direction (stress direction) and that in the *z* direction (stress direction) decrease gradually at first until the stresses reach 16–20 MPa (about 53–67% of the average ultimate compressive strength of the 28-day carbon-fiber-reinforced mortar), and then increase with increasing stresses. Comparing with Fig. 3, the resistance in any stress direction during biaxial compression starts to increase at a stress level that is higher than 12 MPa mentioned above for resistance in the stress direction during uniaxial compression. This may be due to the effect of biaxial compression on postponing the emergence of new cracks, damage and defect and hindering them from opening.

(b) In comparison with Fig. 3, the piezoresistivity in any stress direction (i.e., the *x* or *z* direction) during biaxial compression is more sensitive than that in the stress direction during uniaxial compression. For biaxial compressive testing, the fractional change in resistance in the *x* direction (stress direction) decreases from 0.0 to about −60% while the compressive stresses in the *x* and *z* directions increase from 0.0 to about 16 MPa (the ratio of −60% to 16 MPa is −3.75%/MPa), and the fractional change in resistance in the *z* direction (stress direction) decreases from 0.0 to about −88% while the compressive stresses in the *x* and *z* directions increase from 0.0 to about 20 MPa (the ratio of −88% to 20 MPa is −4.40%/MPa). But for uniaxial compressive testing, the fractional change in resistance in the *x* direction (stress direction) only decreases from 0.0 to about −20% while the compressive stress in the *x* direction increases from 0.0 to about 12 MPa (the ratio of −20% to 12 MPa is only −1.67%/MPa).

(c) With an increase in the compressive stresses, the fractional change in resistance in the *y* direction (other than the two stress directions) decreases only at the first step, and then increases with increasing stresses. Comparing with Fig. 4, the resistance in the *y* direction during biaxial compression starts to increase at a stress level that is lower than 6 MPa mentioned above for resistance in the *z* direction (other than the stress direction) during uniaxial compression, because biaxial compression induces larger tensile strain in direction other than the two stress directions, this makes fiber pullout in direction other than the two stress directions during biaxial compression severer

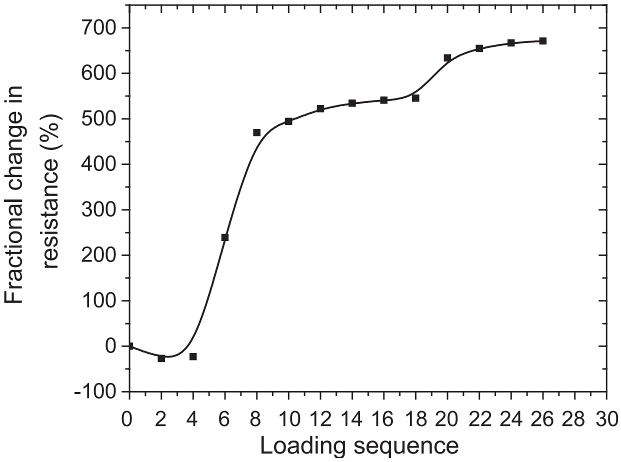

Fig. 6. Fractional change in resistance in the *y* direction versus the loading sequence during biaxial compression.

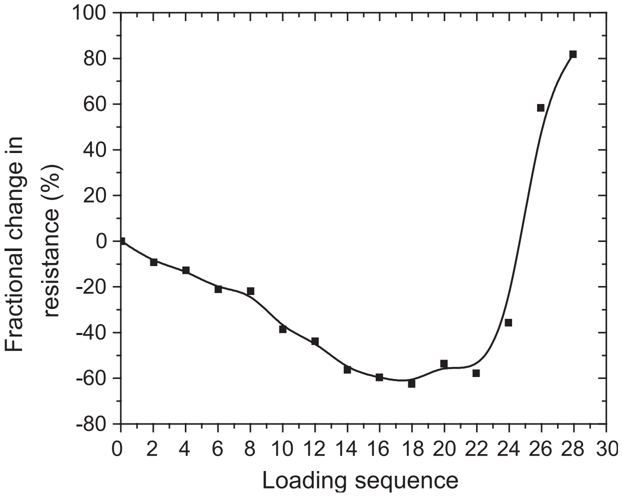

Fig. 5. Fractional change in resistance in the *x* direction versus the loading sequence during biaxial compression.

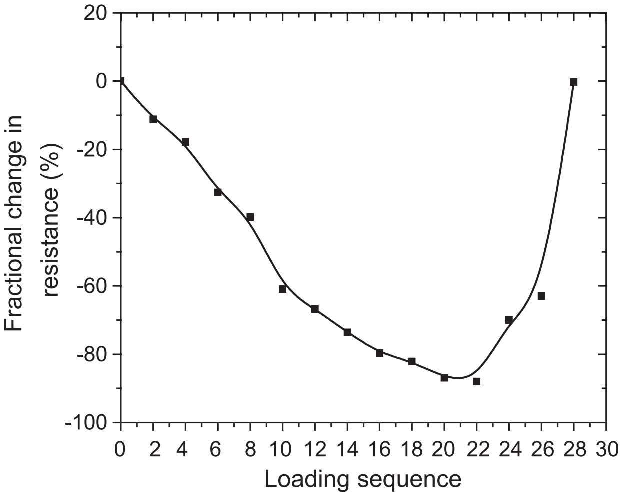

Fig. 7. Fractional change in resistance in the *z* direction versus the loading sequence during biaxial compression.

than fiber pullout in direction other than the stress direction during uniaxial compression.

(d) In comparison with Fig. 4, the ascending branch of the fractional change in resistance–loading sequence curve in the *y* direction during biaxial compression is steeper than that of the fractional change in resistance–compressive stress curve in the *z* direction during uniaxial compression. The maximum fractional change in resistance in Fig. 6 is much larger than that in Fig. 4. It is clear that the piezoresistivity in direction other than the two stress directions during biaxial compression is still more sensitive than that in direction other than the stress direction during uniaxial compression.

Test results of Specimens 5, 6, 7 and 8 are similar to those of Specimen 4. For biaxial compressive testing, the average critical stress for Specimens 4–8 in the two stress directions is 18.3 MPa, and the maximum error of the critical stress of any specimen in any stress direction with respect to 18.3 MPa is 20.0%.

4. Conclusion

For both the case of uniaxial compression and the case of biaxial compression, with an increase in the compressive stress, the fractional change in resistance in any direction decreases gradually at first, and then increases with increasing stress. But the stress level at which the fractional change in resistance starts to increase, namely, critical stress in this paper, varies with the loading style and the direction in which the resistance is measured, i.e., the critical stress related to the biaxial compression and the stress direction>the critical stress related to the uniaxial compression and the stress direction>the critical stress related to the uniaxial compression and the direction other than the stress direction>the critical stress related to the biaxial compression and the direction other than the two stress directions. The piezoresistivity in any stress direction during biaxial compression is more sensitive than that in the stress direction during uniaxial compression, and the piezoresistivity in direction other than the two stress directions during biaxial compression is still more sensitive than that in direction other than the stress direction during uniaxial compression.

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References

[1] S.B. Park, B.I. Lee, Y.S. Lim, Experimental study on the engineering properties of carbon fiber reinforced cement composites, Cem. Concr. Res. 21 (4) (1991) 589–600.

[2] P.-W. Chen, D.D.L. Chung, Concrete as a new strain/stress sensor, Composites, Part B 27B (1996) 11–23.

[3] P.-W. Chen, D.D.L. Chung, Carbon fiber reinforced concrete as an intrinsically smart concrete for damage assessment during static and dynamic loading, ACI Mater. J. 93 (4) (1996) 341–350.

[4] X. Wang, X. Fu, D.D.L. Chung, Strain sensing using carbon fiber, J. Mater. Res. 14 (1999) 790–802.

[5] S. Wen, D.D.L. Chung, Uniaxial compression in carbon fiber-reinforced cement, sensed by electrical resistivity measurement in longitudinal and transverse directions, Cem. Concr. Res. 31 (2) (2001) 297–301.

[6] S. Wen, D.D.L. Chung, Uniaxial tension in carbon fiber-reinforced cement, sensed by electrical resistivity measurement in longitudinal and transverse directions, Cem. Concr. Res. 30 (8) (2000) 1289–1294.

[7] D.-M. Bontea, D.D.L. Chung, G.C. Lee, Damage in carbon fiber-reinforced concrete, monitored by electrical resistance measurement, Cem. Concr. Res. 30 (4) (2000) 651–659.

[8] X. Fu, D.D.L. Chung, Self-monitoring of fatigue damage in carbon fiber reinforced cement, Cem. Concr. Res. 26 (1) (1996) 15–20.

[9] X. Fu, E. Ma, D.D.L. Chung, W.A. Anderson, Self-monitoring in carbon fiber reinforced mortar by reactance measurement, Cem. Concr. Res. 27 (6) (1997) 845–852.

[10] X. Fu, D.D.L. Chung, Effect of curing age on the self-monitoring behavior of carbon fiber reinforced mortar, Cem. Concr. Res. 27 (9) (1997) 1313–1318.

[11] X. Fu, W. Lu, D.D.L. Chung, Improving the strain sensing ability of carbon fiber reinforced cement by ozone treatment of the fibers, Cem. Concr. Res. 28 (2) (1998) 183–187.

[12] S. Wang, X. Shui, X. Fu, D.D.L. Chung, Early fatigue damage in carbon-fiber composites observed by electrical resistance measurement, J. Mater. Sci. 33 (1998) 3875–3884.

[13] S. Wen, D.D.L. Chung, Damage monitoring of cement paste by electrical resistance measurement, Cem. Concr. Res. 30 (12) (2000) 1979–1982.

[14] Q. Mao, B. Zhao, D. Shen, Study on the compression sensibility of cement matrix carbon fiber composite, Acta Mater. Compositae Sin. 13 (1996) 8–11.

[15] F. Reza, G.B. Batson, J.A. Yamamuro, J.S. Lee, Resistance changes during compression of carbon fiber cement composites, J. Mater. Civ. Eng., ASCE 15 (2003) 476–483.