DIPHASIC CONDUCTIVE CONCRETE WITH NANO MATERIALS AND CARBON FIBER FOR SELF-SENSING OF STRAIN

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Abstract
In this work, both carbon fiber and nano carbon black were used as conductive phases to produce the diphasic electric conductive concrete. Electric conductive concrete beams subjected to flexural load were investigated to study the relationship between the strain of geometrical neutral axis and the fractional change in resistance of conductive concrete, and the results show that this relationship can be well fitted by the exponential decay first order curve before cracking. The slope of the fitted curve can reflect the sensitivity of the conductive concrete. This self-sensing of strain of conductive concrete can be applied as a new way for assessing the strain and stress state of the bending members.

1 Introduction
For the purpose of hazard mitigation, health monitoring is valuable for structure safety. The application of conductive cementitious composite materials was reported to use the electric resistance measurement to monitor strain and damage [1-11]. Over the last decade, the nano materials have been used as smart fine fillers for a broad range of multifunctional composites as well as strain or damage sensors [5, 13-16]. In this research, both carbon fiber (CF) and nano carbon black (NCB) were added into concrete as conductive phases to enhance the electrical conductivity to produce the diphasic electric conductive concrete, which allows to perform resistivity measurements to detect strain and stress state.

Dispersing CF into concrete can form some continuous conductive pathways which carry current and play a fundamental role in the electrical transport process, consequently enhance electrical conductivity of concrete [3, 6]. In addition, due to the extremely small size of NCB relative to that of traditional carbon fibers, it is possible for nano carbon black to penetrate the matrix regions in carbon fiber reinforced composites and connect the conductive pathways into conductive networks, thus further improve the electrical conductivity [2, 5]. The strain initiation and evolution in the concrete can cause damage and subsequently induce the break of conductive pathways or networks, which results in the electric resistance change.

This paper presents a study on the relationship between the damage degree and the fractional change in resistance (FCR) of electric conductive concrete beams subjected to bending, and this relationship is established using the regression analysis. The results show that the relationship between the strain and FCR can be well fitted by the exponential decay first order function before the concrete cracks. The slope of the fitted curve can reflect the sensitivity of the electric conductive concrete.

2 Materials and testing methods

2.1 Materials and specimen preparation

The CF as conductive phase was asphalt base short carbon fiber, with diameter of 12-15 μm and length of 6 mm. Its density was 1.55 – 1.60 g/cm^3. The carbon black used was super conductive nano carbon black in the form of porous agglomerates of carbon particles of average size 17 nm, and a density of 0.3–0.5 g/cm^3. Plain concrete as reference concrete without CF and NCB was prepared, in order to assess the effect of the different conductive phases on the concrete, mix design of plain concrete is presented in Table 1. The type of cement was CEM I 42.5. The W/B was 0.45, and a water reducing agent (WR) was used in the amount of 1.0% by mass of binder. The 28d compressive strength was 43.6 MPa. The carbon fiber and nano carbon black content used ranged from 0.4% to 1.0% (0.4%, 0.8% and 1.0%) and 0.1% to 0.3% (0.1%, 0.2% and 0.3%) respectively by mass of binder. The series of electric conductive concrete samples added with different types (carbon fiber only, nano carbon black only, both carbon fiber and nano carbon black) and different contents of conductive phases are listed in Table 2.

Cement (kg/m^3)	Fly ash (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	Water (kg/m^3)	WR (kg/m^3)
373.33	160	733.33	733.33	240	5.33

Table 1. Mix design of reference concrete.

Serial number	Content of CF	Content of NCB	Remarks
PC	0	0	Reference concrete
CF04	0.4%	0	Concrete containing CF
CF08	0.8%	0	
CF10	1.0%	0	
NCB01	0.1%	0	Concrete containing NCB
NCB02	0.2%	0	
NCB03	0.3%	0	
DC41	0.4%	0.1%	Diphasic conductive concrete containing NCB and CF
DC81	0.8%	0.1%	
DC42	0.4%	0.2%	
DC82	0.8%	0.2%	

Table 2. Series of electric conductive concrete samples.

In case that CF was used (whether together with NCB or not), methylcellulose was used as dispersing agent along with a defoamer to optimize the dispersion of carbon fiber to concrete [4]. Methylcellulose and the defoamer were not used in the absence of carbon fiber. A forced concrete mixer was used for mixing. Methylcellulose was dissolved in water and then the defoamer and CF (if applicable) were added and stirred by hand for about 2 min. Then, this methylcellulose mixture, fine aggregate, coarse aggregate, cement, fly ash, water, NCB (if applicable) and water reducing agent were mixed for 5 min. After pouring the mix into oiled molds, an external electric 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 = 100%) for 28 days. All the specimens prepared for testing were beams with the size of 100mm×100mm×400mm.

2.2 Testing

Before flexural testing, the initial resistance (R_0) of beams was measured. For the elimination of the error which is caused by the contact resistance of electrodes, the 4-pole method was adopted for the measurements of resistance [12]. Conductive adhesive tapes tightly wound around the specimens were symmetric with respect to the mid-point of longitudinal axis at four locations, formed the electrodes. The specimen configuration for measurements of resistance is illustrated in Fig. 1. The outer two electrodes (240 mm apart) were for passing current, the inner two electrodes (120 mm apart) were for measuring the voltage. A hydraulic servo testing machine was used. Testing was conducted under repeated three-point bending at progressively increasing flexural stress amplitudes until failure occurred. Load–time curve of this flexural test is shown in Fig.2. Six strain gages were applied for measuring the longitudinal strain, two of which were used on each of the two opposite surfaces to measure changes in strain of geometrical neutral axis under the externally applied load. The resistance of beams was continuously measured simultaneously during loading by using 4-pole method mentioned above. Schematic view of beam under loading with current electrodes, voltage electrodes is illustrated in Fig. 3. Rubber joints were used under the supporting points during the experiment (see Fig.3), in order to isolate the concrete beam from the loading frame.

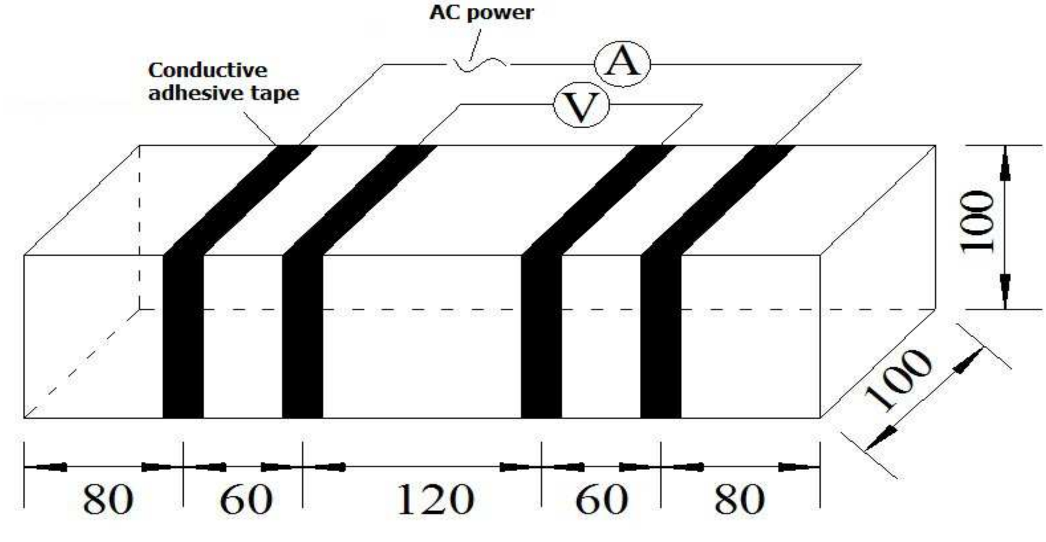

Figure 1. Specimen configuration for measurements of resistance.

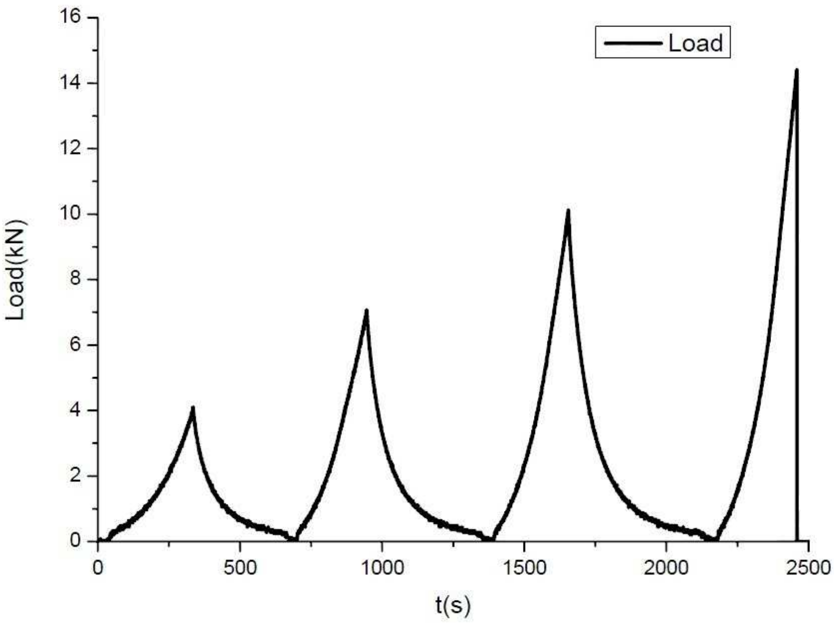

Figure 2. Load-time curve of beam under the three-point bending test.

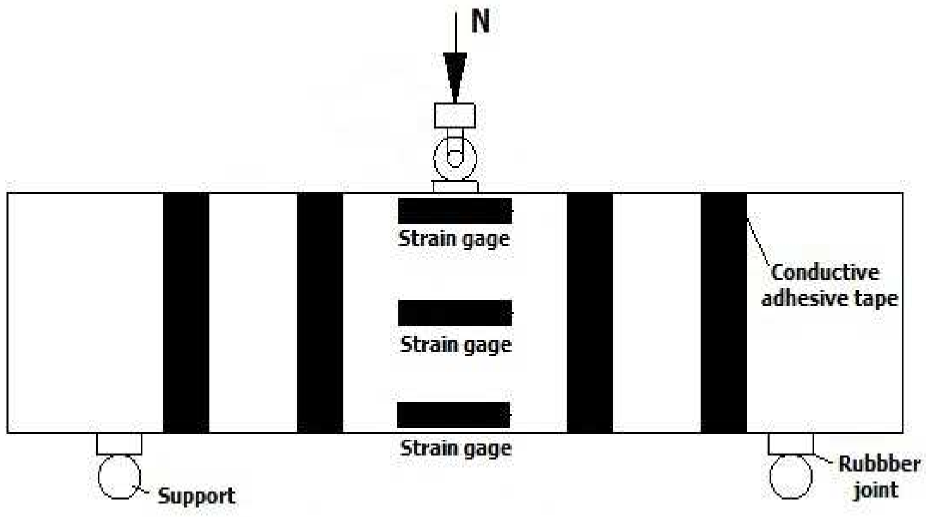

Figure 3. Schematic view of beam under loading with current electrodes, voltage electrodes.

3 Results and discussion

3.1 Results of initial resistance (R_0)

The influence of the conductive admixtures (CF, NCB and DC) on the initial resistance (R_0) of concrete beams before flexural testing are listed in Table 3. It can be seen that the R_0 decreases with the increasing of the dosages of CF, NCB and DC.

Serial number	PC	CF04	CF08	NCB01	NCB02	DC41	DC42
R_0 (Ω)	3213.8	1480.8	1381	2904.3	2875.0	1308.8	1206.8

Table 3. Results of initial resistance (R_0) of conductive concrete beams before flexural testing.

3.2 The relationship between FCR and the strain of geometrical neutral axis

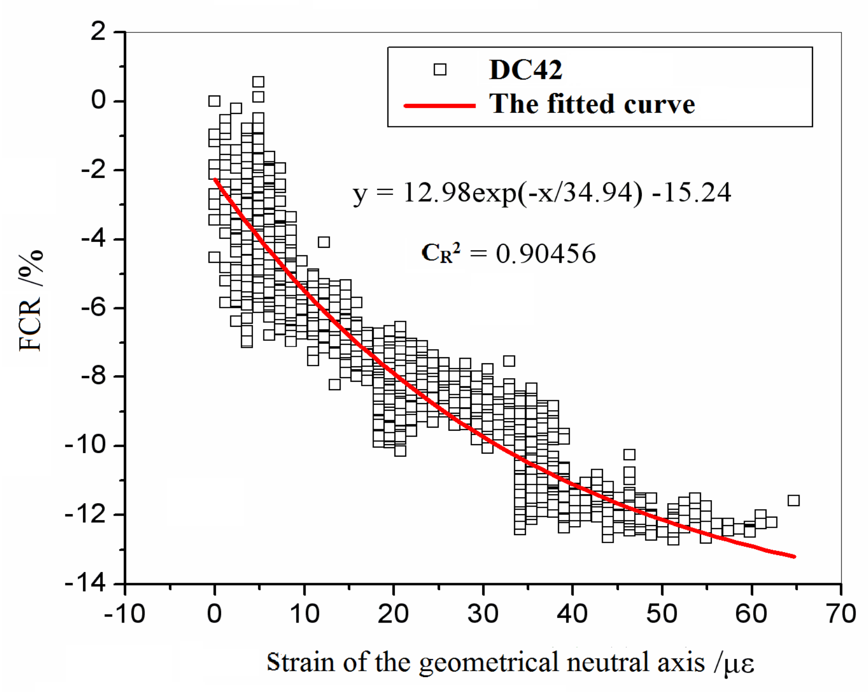

Figure 4. Relationship between FCR and the strain of geometrical neutral axis of DC42 beam.

Fig. 4 illustrates the relationship between FCR and the strain of geometrical neutral axis of DC42 beam. It can be seen that the relationship between the FCR and the strain of geometrical neutral axis corresponds well with the first order exponential decay function expressed in Eqn. (1):

$$FCR = ae^{-\varepsilon/b} + c \tag{1}$$

where a, b and c are constant parameters corresponding to the types and the contents of electric conductive phases, the variable ε is the strain of geometrical neutral axis, the unit of ε is με. The parameters fitted and the correlation coefficient (C_R^2) of all electric conductive concrete beams with different types and contents of conductive phases are listed in Table 4. The correlation coefficients of all conductive concrete beams vary from 0.796 to 0.97752 except that of PC which is only 0.5.

Serial number	a	b	c	C_R^2
PC	16.21	33.06	-10.33	0.50033
CF04	27.87	13.00	-29.74	0.79566
CF08	20.83	19.26	-21.25	0.83359
CF10	25.55	12.39	-27.41	0.97752
NCB01	32.31	47.48	-21.05	0.82466
NCB02	34.57	5.21	-39.11	0.76742
NCB03	56.89	85.79	-44.85	0.92748
DC41	14.88	95.04	-12.56	0.95126
DC81	106.63	83.70	-82.74	0.77459
DC42	12.98	34.94	-15.24	0.90456
DC82	13.45	68.90	-16.11	0.8813

Table 4. Fitted parameters of regression equation.

From Fig. 4 and Table 4, it can be seen that:
(1) The curve in Fig. 4 shows a monotone decreasing function. The absolute value of FCR of conductive concrete beams increases with the increasing of the strain of geometrical neutral axis.
(2) The correlation coefficient C_R^2 of plain concrete beam is only 0.5. It means that the predicted Eqn. (1) of PC beam without any conductive phases is not strong enough related to the tested values.
(3) The C_R^2 of other beams with conductive phases is higher than 0.76. Hence, the relationship between FCR and the strain of geometrical neutral axis is quite strong correlated with Eqn. (1).
(4) The C_R^2 of NCB03, CF10, DC41 and DC42 is higher than 0.9. It means that the relationship between FCR and the strain of geometrical neutral axis is very strong correlated with the Eqn. (1), and the self- sensing of the strain could be more suitable especially for concrete members with above suggested types and contents of conductive admixture.

3.3 The sensitivity of the electric conductive concrete

The ability of a structure material to sense its own strain (i.e. sensitivity) is attractive for smart structures [12], this sensitivity of conductive concrete can be characterized by the gage factor (λ) which is defined as the fractional change in resistance per unit strain [12, 13], hence λ is equal to the slope of Eqn. (1) and can be expressed in Eqn. (2):

$$\lambda = \left| \mathrm{FCR}' \right| = \frac{a}{b} e^{-\varepsilon / b} \tag{2}$$

where a and b are both constant parameters, the variable ε is the strain of geometrical neutral axis as Eqn. (1).

Eqn. (2) illustrates the relationship between ε and λ. It can be observed that the value of λ decreases in terms of exponential decay function as the strain of geometrical neutral axis increases. In other words, the development of strain leads to degradation of sensitivity of electric conductive concrete.

4 Conclusions

In this study, a method was proposed for self-sensing of strain by electric resistance change of conductive concrete. The CF, NCB and DC were added into concrete as conductive admixtures to produce the electric conductive concrete. The experimental and analytical results led to the following conclusions:

(1) The absolute value of FCR of conductive concrete beams increases monotonously with the increasing of the strain of geometrical neutral axis.
(2) The relationship between the strain of geometrical neutral axis and FCR can be well fitted by the exponential decay first order function before cracking.
(3) The correlation coefficient of conductive concrete beams is obviously higher than that of PC beams. The relationship of conductive concrete beams between FCR and strain of geometrical neutral axis is quite strong fitted with Eqn. (1).
(4) The gage factor (λ) of conductive concrete decreases in terms of exponential decay function as the strain of geometrical neutral axis increases.

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