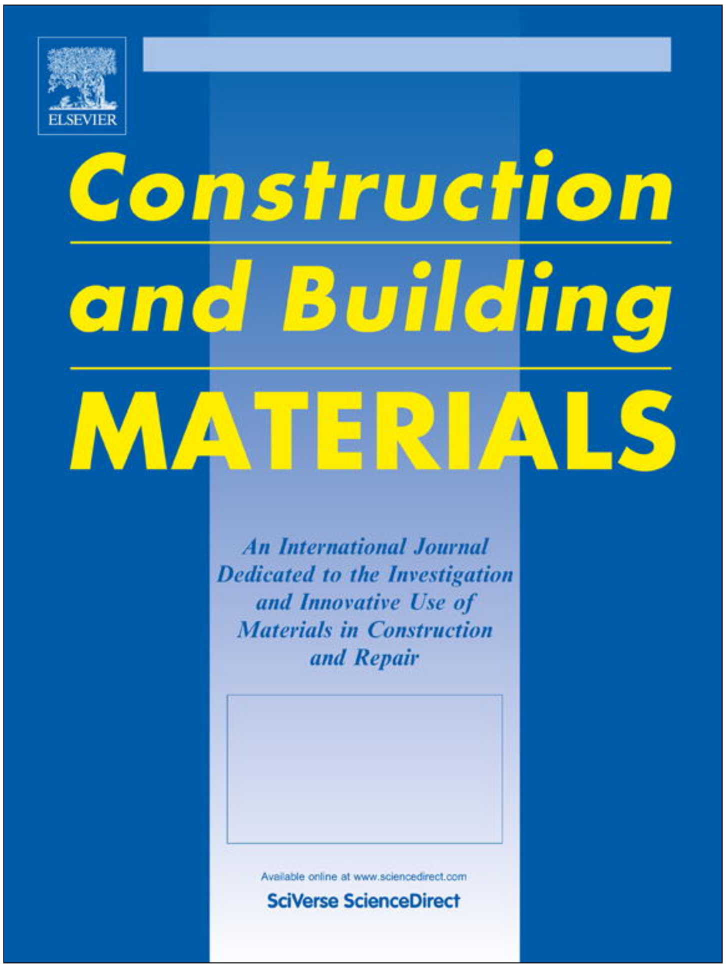
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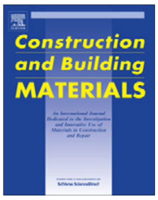

Nano-carbon black and carbon fiber as conductive materials for the diagnosing of the damage of concrete beam

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HIGHLIGHTS

- ▶ The concrete beam with carbon black and fiber for damage diagnosis under bending was studied.
- ▶ The effect of conductive materials on the fractional change in resistance (FCR) of beam was studied.
- ▶ The relationship between FCR and strain of neutral axis of beam was suggested.
- ▶ The model of damage degree vs. FCR of concrete beam was established.
- ▶ We can evaluate the damage of concrete beam by measuring of the FCR.

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ABSTRACT

The nano-carbon black (NCB) and carbon fiber (CF) as electric conductive materials were added into the concrete. The effect of the NCB and CF on the mechanical properties and on the fractional change in resistance (FCR) of concrete was investigated. The relationships among the FCR, the strain of initial geometrical neutral axis (IGNA) and the beam damage degree were developed. The results showed that the relationship between the FCR and IGNA strain can be described by the First Order Exponential Decay function, and the internal damage of concrete beam was reflected by the relationship between damage degree and resistance.

1. Introduction

Cumulative damage and the degradation of structure or material resistance are the common reasons for the failure of conventional concrete structures like bridges, power station and other structures under different load, fatigue or erosion effect or material aging. The study of cumulative damage has been concentrated on the strain behavior and fatigue process of specimens, to prevent possible sudden failure effectively and to prolong the service life of concrete structures [1,2]. Electrically conductive concrete allows to perform resistivity measurements, which could be used to analyze the strain or stress variations in the structure member [1–8]. Due to the strain sensing of damage of electric conductive concrete with NCB or CF, the evaluation of early damage of concrete members in the practice without embedding sensors tend to be more convenient. The conduction concrete also provides wide application prospect in terms of electromagnetic shielding of vital equipment, and de-icing of airfield and highway [3–9].

The addition of NCB may improve the electrical conductivity, the toughness of the aggregate interface in the concrete matrix and lower cost, NCB shows also the fine filler effect which can enhance the density of the concrete matrix [10,11]. The addition of short CF as an admixture can form a continuous conduction net and reduce the electric resistance, decrease the shrinkage cracking, improve the durability and freezing resistance and does not induce large amount of water demand. The combined use of NCB and short CF into concrete can both show the advantage of the conductive network of CF and make use of electric characteristics of NCB [10–21], and also provides the conductive concrete with well mechanical property.

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The damage of the cement-based material may change the electric resistance, as observed for damage in the elastic tension regime, in the plastic deformation region and after cracking of concrete [9,18,19,22]. The strain and damage of carbon fiber reinforced cement specimens under compression, tension or flexural loading have been discussed in previous studies [10,18–21]. The investigation on the combined use of NCB and short CF in cement or concrete could be found [10,11]. For structure concrete in the practice, the concrete members with coarse aggregate are often subjected to different loading, such as under compression, tension and bending, and the member may also undergo various stages regarding the load-deformation relation, including pre-cracking behavior and post-cracking behavior. The study on strain sensing of carbon fiber reinforced geopolymer concrete under bending and compression has been reported [23].

However, the study on the conventional concrete beam with diphasic electrical conduction admixtures for diagnosis of damage under bending is still very rare. There are some problems to overcome in studying of conductive concrete beam. The electric characteristics of the concrete must be made suitable for the application without clear degrading of the workability of fresh concrete and mechanical behaviors of hardened concrete.

In this paper, based on the investigation of the NCB and CF on the workability, compression strength and flexural strength of concrete, a series monophasic and diphasic conductive material reinforced concrete beams were experimentally studied, in order to analyze the strain and the FCR of beam under various loading levels. The purpose of this work is to evaluate the influence of the combined use of NCB and short CF as diphasic conductive materials on the FCR of concrete beam under four point bending, especially to study the relationships among FCR, the strain and the damage degree of concrete beam under bending in the pre-cracking region.

The relationship between the FCR and the strain of initial geometrical neutral axis (IGNA) of concrete beam was established via the regression analysis. Based on the damage mechanics theory and the relationship mentioned above, the correlation between damage degree and the FCR has been set up. The results show that the relationship between the FCR and the strain of the IGNA of concrete beams can be fitted and described well by the Exponential Decay First Order curve before cracking.

2. Experimental investigations

2.1. Materials and mixture design

In this work, the base mix design of concrete without conductive admixture (NCB and CF) was as follows: CEM I 42.5 370 kg/m^3, fly ash 160 kg/m^3, fine aggregate 733 kg/m^3 (1–4 mm), coarse aggregate 733 kg/m^3 (5–10 mm), water 238.5 kg/m^3, superplasticizer (SP) 5.3 kg/m^3. The base mixture of concrete without conductive materials is illustrated in Table 1.

The NCB content with particle size ca. 30–90 nm (Fig. 1a) was between 0.1% and 0.4% by mass of binder (0.53–2.12 kg/m^3), the density of NCB was about 0.5 g/cm^3 and the volume resistivity was 2.3 Ω cm. The carbon fiber content with diameter of 12–15 μm and length of 6 mm (Fig. 1b) was between 0.4% and 1.6% by mass of binder (2.12–8.48 kg/m^3), the density of CF was about 1.6 g/cm^3 and the volume resistivity of CF was between 3 and 7 m Ω cm. The volume resistivity of dried concrete without conductive materials usually ranges between 6 and 11×10^5 Ω cm [24], and the volume resistivity of dried concrete with electric conductive materials usually ranges between 2 and 6×10^4 Ω cm. The defoamer dosage was 2.13 kg/m^3, and the content of methylcellulose used was between 2.13 and 8.52 kg/m^3. The different dosages of the conductive admixtures NCB, CF and BF (NCB + CF) by mass of binder in various concrete samples are compared and listed in Table 2.

2.2. Samples and set-up description

A forced mixer was used for mixing. For concrete specimens with conductive admixtures, NCB was mixed firstly with cement, fine and coarse aggregate before adding of water, however, the carbon fiber, methylcellulose and defoamer were dissolved or pre-mixed with 5 l water for well dispersion of fibers. Then the pre-mixture, NCB and superplasticizer, cement, fly ash and aggregate, water were mixed 5 min [11]. The specimens prepared for testing were beams with the size of 100 mm × 100 mm × 400 mm. The specimens were demolded after 1 day and then cured at room temperature in air (relative humidity = 100%) for 3 days. Then, four electrical contacts were prepared in the form of conductive adhesive tape, which was wrapped around the specimen. Based on the four probe method of electric resistance measurement, contacts A and D were for passing current while contacts B and C were for measuring of voltage [18]. Finally, the prepared specimens were cured at room temperature again for 28 days. We analyze the relationship between FCR and the strain of IGNA. The FCR measured is the fractional change in volume resistance of the beam and not the surface resistance at bottom. Compared to the tension strain at the bottom of the beam, the elongation of the IGNA could comprehensively reflect the strain state for the whole member section from the top of the compression zone to the bottom of the tension zone. The dimensions and electrical contacts details of all beams are shown in Fig. 2. The result was the average of three beams.

Table 1
Base mixture proportion.

Cement (kg/m^3)	Fly ash (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	Water/ binder ratio	SP
370	160	733	733	0.45	1% of the binder

2.3. Test methods

A hydraulic servo testing machine (MTS Model 810) was used. The close-loop test was controlled by displacement, and the deformation rate of net mid-span was 0.2 ± 0.02 mm/min until the specified end-point deflection is reached [11], which was 3 kN larger than the previous loading level. The Load–time relationship of the beam is illustrated in Fig. 3. Six strain gages were applied – three on each of the two opposite surfaces for measuring the longitudinal strain (Fig. 4). Other experimental instruments include A.C. stabilized voltage supply, IMC Intelligence Data Collecting System, fixed resistor and AC/DC converter.

3. Influence of conductive admixtures on the mechanical and electrical properties of concrete beam

3.1. Influence of conductive admixtures on the workability and the compression strength

The workability of fresh high flowable concrete with and without conductive admixture has been evaluated based on [25,26] by measuring of the slump flow. A concrete mix can be classified as high flowable if the requirements for flowability, segregation resistance and filling ability are fulfilled. The experimental results of workability are listed in Table 3. The factor *d* represents the average diameter in slump flow test.

The concrete conductivity increases with the increasing of the dosages of NCB and CF, however, for structure concrete in the practice, the workability of fresh concrete is an important precondition for selecting of the types and content of the conductive materials. The workability declines with the increasing of NCB or CF contents, and the upper limit of the dosage of conductive materials is determined mainly by the workability and not by the conductivity. This point was ignored in the previous investigations. From Table 3, it can be seen that the fresh NC (plain concrete without any conductive admixtures) corresponds well to the requirements of self compacting concrete, there is very good flowability and no segregation [25,26], however, the workability of fresh concrete declines with the increasing of NCB or CF contents. Fig. 5 demonstrates the measurement of slump flow of fresh NC and the fresh BF 28. They indicate the free deformability of the fresh NC mixture. The slump flow of BF 28 is only about 410 mm. It means that the content of diphasic conductive admixtures (0.747 kg/m^3 NCB + 2.99 kg/m^3 CF) is less than the lower limit (450 mm) of the workability of high flowable concrete. The flow behavior of NCB 03, NCB 04, and BF 28 were much less fluid than other mixtures due to the relative high content of CF and NCB.

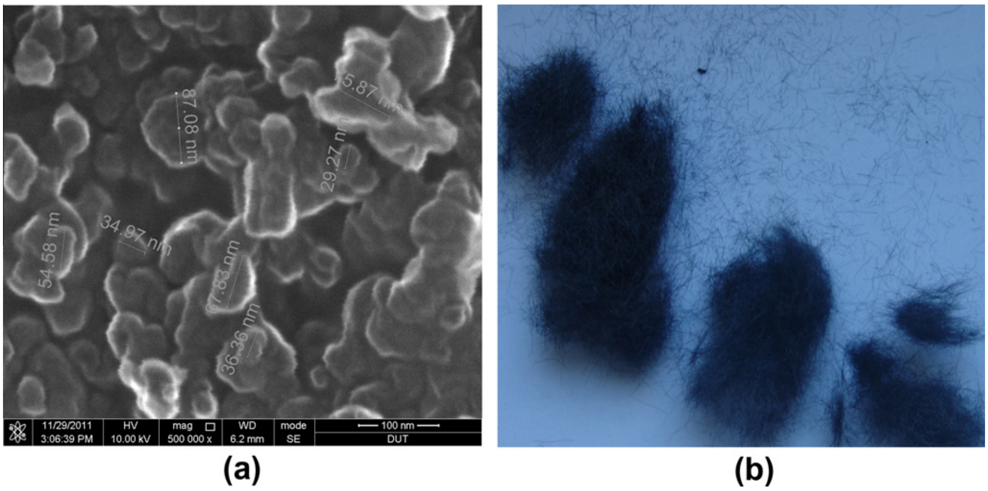

Fig. 1. (a) Particle size of nano-carbon black using high resolution field emission SEM and (b) carbon fiber.

Table 2
Comparison of the dosages of the conductive admixtures.

Serial number		NCB mass/binder%	CF mass/binder%
Plain concrete (concrete without conductive admixture)	PC	0	0
Concrete containing NCB	NCB 01	0.1%	0
	NCB 02	0.2%	0
	NCB 03	0.3%	0
	NCB 04	0.4%	0
Concrete containing CF	CF 04	0	0.4%
	CF 08	0	0.8%
	CF 10	0	1.0%
	CF 13	0	1.3%
	CF 16	0	1.6%
Concrete containing BF (NCB and CF)	BF 14	0.1%	0.4%
	BF 18	0.1%	0.8%
	BF 24	0.2%	0.4%
	BF 28	0.2%	0.8%

The average values of the compressive strength f_{cu} and flexural strength σ_u of three specimens at the age of 28d can be found in Table 3. The increment of the compression strength ranges between 2.2% and 6.2%. It means that the addition of NCB, CF and BF demonstrates some positive effect on the compressive strength of concrete, but does not show significant trend of improving compressive strength.

3.2. Investigation of the conductive admixture on the flexural strength, strain and electric resistance of beam

We consider simply supported single-span beam that is reinforced with conductive admixtures. When a beam is subjected to bending moments, bending strains are produced [15]. These strains produce stresses in the beam, compression in the top and tension in the bottom. The load is applied on the beam until the section

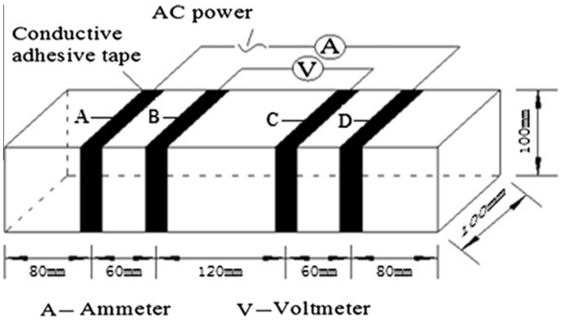

Fig. 2. Bending beam for simultaneous measurement of longitudinal resistance.

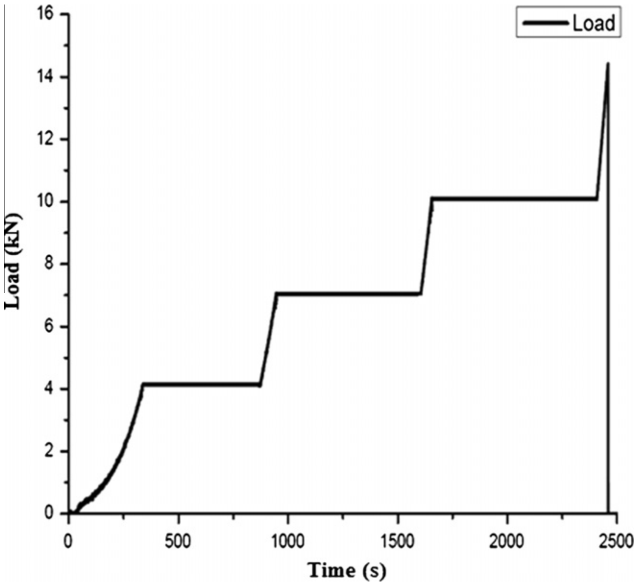

Fig. 3. Load–time relationship of the beam.

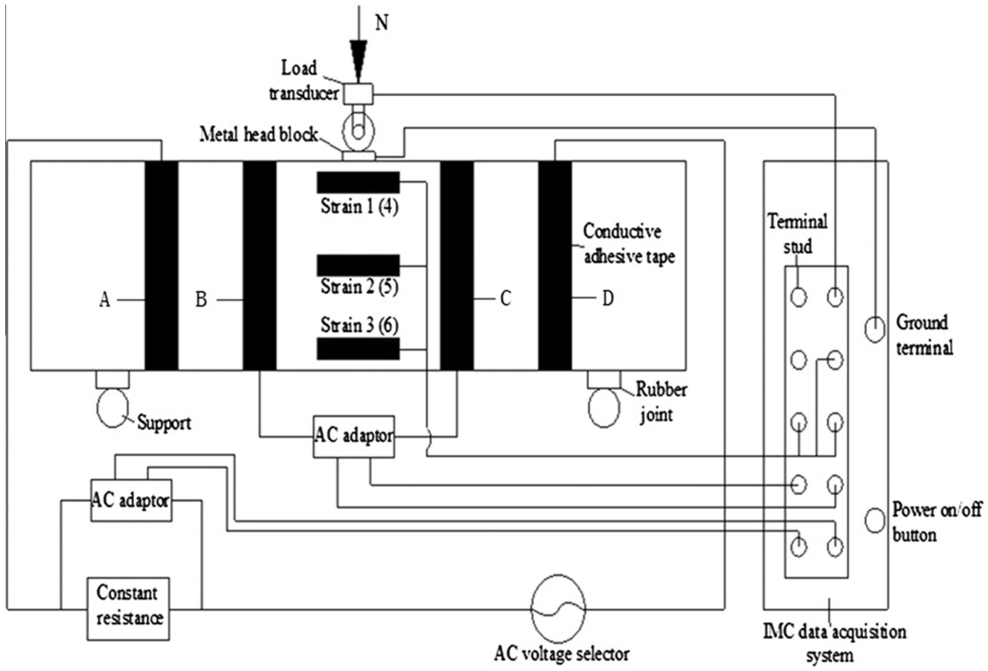

Fig. 4. Arrangement of measuring points of strain and voltage.

crack is impending. During the loading process, the strain near the top of concrete beam in the compression zone, the strain of initial geometrical neutral axis (IGNA) and tensile strain near the bottom of the concrete beam (Fig. 4) have been measured by strain gages and the resistance of concrete beam has been measured simultaneously. Then the strains of IGNA can be obtained by strain gages (2) and (5), and the FCR at each loading stage can be measured also. In order to isolate the concrete beam from the loading frame, two rubber joints under the supporting points were used during the experiment (see Fig. 4).

3.2.1. Flexural strength

If the beam section does not crack, then the ordinary elastic beam theory applies. The effects of conductive admixtures on flexural strength $\sigma_u = M_u/W$ (where M_u is ultimate bending moment, W is the section modulus) are illustrated in Table 3. It can be seen that the flexural strength of concrete beams increases with the addition of the conductive admixtures. Among them, the samples with only NCB show a fewer increment of the flexural strength with the increasing of the NCB dosages (between 1.8% and 8.8%). However, the flexural strength of concrete beams increases clearly with the increasing of CF and BF dosages. Compared to the NC beam without any conductive admixture, the increment of the flexural strength of beams with CF and BF ranges between 10% and 19%.

3.2.2. Influence of conductive admixture on the relationship between strain and FCR

The influences of various conductive admixtures on the relationships between the fractional change in resistance (FCR) and the strain of initial geometrical neutral axis (IGNA) of concrete beams are illustrated in Fig. 6. From the curves above it can be seen that the relationship between the FCR and the strain of IGNA corresponds well with the First Order Exponential Decay Function, which can be expressed in following equation:

$$Y = m\exp(-X/n) + p \tag{1}$$

where m, n and p are constant parameters corresponding to the type and the amount of electric conductive phase, the variable X is the strain of initial geometrical neutral axis (IGNA), respectively; the unit of X is in $\mu\varepsilon$, and the FCR is the percentage of Y.

Table 3
Content of conductive admixture, slump flow, compressive strength and flexural strength.

Mixture/samples		Content of NCB (kg/m^3)	Content of CF (kg/m^3)	Slump flow d (mm)	Compressive strength (f_{cu}) (Mpa)	Flexural strength (σ_u) (Mpa)	Standard deviation of f_{cu}	Standard deviation of σ_u
Plain concrete	NC	0	0	620	42.55	4.44	2.56	0.11
Concrete with NCB only	NCB01	0.3733	0	600	43.53	4.52	3.10	0.12
	NCB02	0.7467	0	540	43.67	4.71	2.59	0.34
	NCB03	1.1200	0	390	44.17	4.79	3.73	0.25
	NCB04	1.4933	0	Slump 60	45.45	4.83	2.81	0.16
Concrete with CF only	CF04	0	1.4933	590	43.49	5.1	3.55	0.36
	CF08	0	2.9866	570	44.37	5.19	4.23	0.47
	CF10	0	3.7333	550	45.1	5.22	2.25	0.51
	CF13	0	4.8533	520	44.6	5.3	4.27	0.44
	CF16	0	5.9733	500	44.76	5.31	3.98	0.33
Concrete with BF (NCB + CF)	BF14	0.3733	1.4933	590	43.78	4.9	2.06	0.44
	BF18	0.3733	2.9866	540	44.01	4.94	3.22	0.29
	BF24	0.7467	1.4933	480	43.54	5.02	3.72	0.31
	BF28	0.7467	2.9866	410	43.98	5.13	3.68	0.48

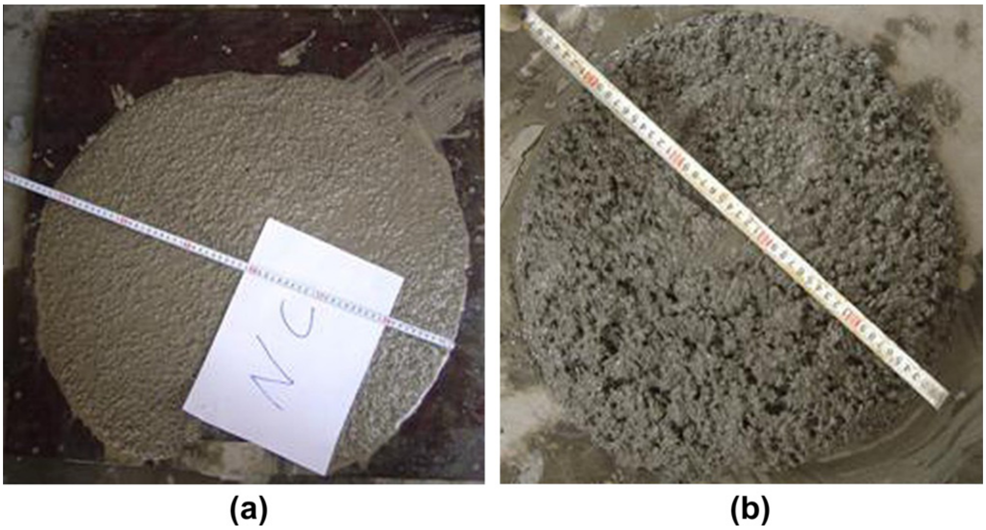

Fig. 5. Slump flows of (a) NC and (b) BF 28.

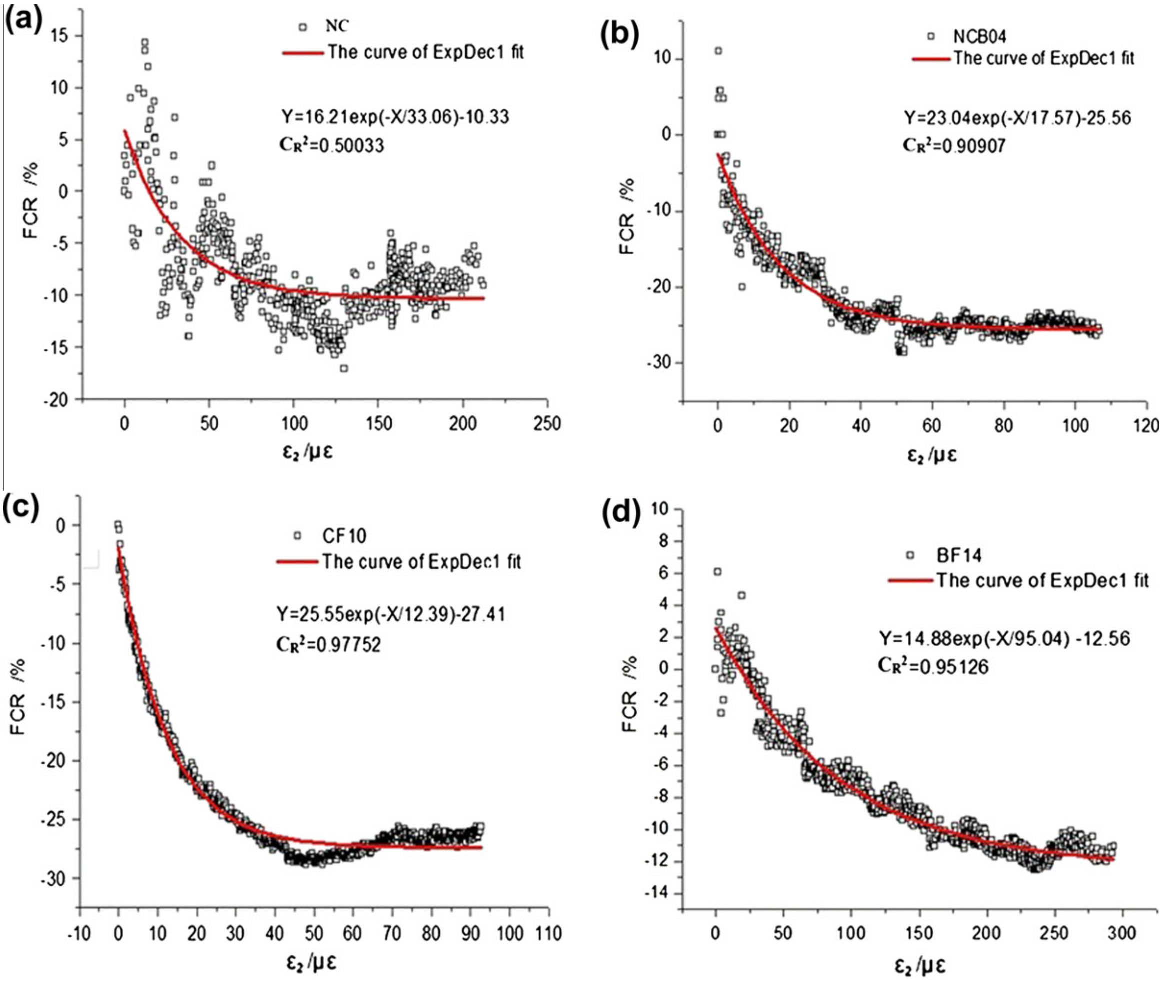

Fig. 6. Relationships between FCR and ε_2 of (a) NC, (b) NCB 04, (c) CF 10 and (d) BF 14.

The parameters fitted and the correlation coefficient C_R^2 are illustrated in Table 4.

The correlation coefficients of all beams in Table 4 range from 0.5 to 0.978. From Fig. 6 and Table 4, it can be seen that:

- The correlation coefficient C_R^2 of plain concrete beam is only 0.50. It means that for the NC beam without conductive admixtures the tested value is not strong related to the predicted Eq. (1).

Table 4
Fitted parameters of regression equation.

Serial number	Constant m	Constant n	Constant p	Correlation coefficient C_R^2
NC (NCB0% + CF0%)	16.21	33.06	−10.33	0.50033
NCB01 (NCB0.1% + CF0%)	32.31	47.48	−21.05	0.82466
NCB02 (NCB0.2% + CF0%)	34.57	5.21	−39.11	0.76742
NCB03 (NCB0.3% + CF0%)	56.89	85.79	−44.85	0.92748
NCB04 (NCB0.4% + CF0%)	23.04	17.57	−25.56	0.90907
CF04 (NCB0% + CF0.4%)	27.87	13.00	−29.74	0.79566
CF08 (NCB0% + CF0.8%)	20.83	19.26	−21.25	0.83359
CF10 (NCB0% + CF1.0%)	25.55	12.39	−27.41	0.97752
CF13 (NCB0% + CF1.3%)	12.39	14.84	−11.00	0.9471
CF16 (NCB0% + CF1.6%)	42.96	15.75	−52.68	0.82598
BF14 (NCB0.1% + CF0.4%)	14.88	95.04	−12.56	0.95126
BF18 (NCB0.1% + CF0.8%)	106.63	83.70	−82.74	0.77459
BF24 (NCB0.2% + CF0.4%)	12.98	34.94	−15.24	0.90456
BF28 (NCB0.2% + CF0.8%)	13.45	68.90	−16.11	0.8813

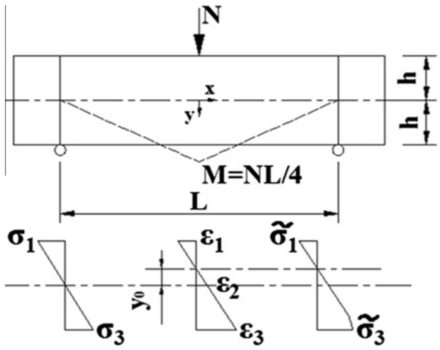

Fig. 7. Flexural damage of rectangular concrete beam.

- The correlation coefficient C_R^2 of other beams with conductive materials like NCB, CF or diphasic electric conductive materials (NCB + CF) is higher than 0.76. Hence, the relationship between FCR and strain of IGNA is quite strong correlated with Eq. (1).
- The correlation coefficient C_R^2 of NCB03, NCB04, CF10, CF13, BF14 and B24 is higher than 0.9. It means that the relationship between FCR and strain of IGNA is very strong correlated with the Eq. (1), and the self- diagnosing of the damage could be more suitable especially for concrete member with above suggested contents of conductive admixtures.
- The curves in Fig. 6 demonstrate a monotone decreasing relationship between FCR and the strain of IGNA.

3.3. Stress–strain state and the damage degree of concrete beam

Based on the theory of damage mechanics [16], the beam damage before the concrete cracking is discussed in this section. The problem could be simplified as uni-dimensional damage, and only the damage in the tension area is analyzed. The effective tensile stress $\tilde{\sigma}_t$ in the tension area can be expressed in following equation:

$$\tilde{\sigma}_t = \frac{\sigma_t}{1-D} = E\varepsilon_t, (\sigma_t \geqslant 0, D \geqslant 0) \tag{2}$$

where D and E are damage degree and elastic modulus, respectively; ε_t and σ_t are the strain and stress of the extreme tension fiber at the bottom of the concrete beam, respectively.

The effective compressive stress $\tilde{\sigma}_c$ in the compressive area is given in following equation:

$$\tilde{\sigma}_c = \sigma_c = E\varepsilon_c, (\sigma_c \leqslant 0, D = 0) \tag{3}$$

where ε_c and σ_c are the strain and stress of the extreme compression fibre at the top of the concrete beam, respectively.

When the effective stress $\tilde{\sigma} > 0$ (tension stress), we have that $D = \frac{\tilde{\sigma}}{k}$, where k is damage modulus. At the peak value of stress, the critical cracking stress is σ_{cr} and the damage degree D is equal to D_{cr}.

From damage mechanics, $D_{\text{cr}} = 0.5$. Therefore, the effective critical cracking stress $\tilde{\sigma}_{\text{cr}}$ can be expressed in following equation:

$$\tilde{\sigma}_{\text{cr}} = D_{\text{cr}} k = \frac{k}{2} \tag{4}$$

The IGNA of beam section may move up to the compression area as the tension area of concrete beam is damaged under tension and behaves approximately plastic. The depth of the beam section ($2h$) and the displacement of IGNA (the distance between the actual geometrical neutral axis and the initial geometrical neutral axis y_0) are illustrated in Fig. 7. The width of beam section is b. During the loading process, the stress pattern in the compression zone changes continuously.

The effective stress $\tilde{\sigma}_1$, $\tilde{\sigma}_3$ of the extreme fibre at the top or bottom of the beam section and damage degree D of the extreme tension fibre at the bottom can be expressed in equations as follows:

$$\tilde{\sigma}_1 = \frac{6hy_0(h+y_0)}{(h-y_0)^3} k \tag{5}$$

$$\tilde{\sigma}_3 = \frac{-6hy_0}{(h-y_0)^2} k \tag{6}$$

$$D = \frac{\tilde{\sigma}_3}{k} = \frac{-6hy_0}{(h-y_0)^2} \tag{7}$$

As crack forms in the tensile zone of concrete beam, the failure occurs, and the load bearing capacity of the beam depends on the effective tensile stress $\tilde{\sigma}_3$. When the effective tension stress of concrete $\tilde{\sigma}_3$ reaches the critical cracking stress $\tilde{\sigma}_{\text{cr}}$ ($\tilde{\sigma}_3 = \tilde{\sigma}_{\text{cr}} = \frac{k}{2}$), then the beam without reinforcement will fail. The displacement of IGNA $(y_0)_{\text{cr}}$ and N_{cr} can be also described as follows in Eqs. (8) and (9):

$$(y_0)_{\text{cr}} = -0.102h \tag{8}$$

$$N_{\text{cr}} = \frac{0.944kbh^2}{L} \tag{9}$$

From the equations above, the factors of strain (ε_1, ε_3) can be given in equations as follows:

$$\varepsilon_1 = \frac{6N_{\text{cr}}Ly_0(h+y_0)}{0.944Ebh(h-y_0)^3} \tag{10}$$

$$\varepsilon_3 = \frac{-6N_{\text{cr}}Ly_0}{0.944Ebh(h-y_0)^2} \tag{11}$$

where ε_1, ε_2 and ε_3 are the concrete strain at the top of the beam (outer fiber of the compression zone), the strain of the IGNA and the strain of the extreme tension fibre at the bottom, respectively.

The relationship between the strain of IGNA (ε_2) and the damage degree D can be written in (12) and illustrated in Fig. 8a:

$$\varepsilon_2 = \frac{N_{cr}L}{0.944Ebh^2} \cdot D^{\frac{1-\sqrt{1-\frac{2}{3}D}}{2}} \quad [0 \leqslant D \leqslant 0.5] \tag{12}$$

It can be seen that the damage degree D increases monotonously with the increasing of the strain of IGNA ε_2.

Let R_0 denote the initial electric resistance of concrete beam before loading, and R denote the electric resistance of beam subjected to external loading at different time t. In the Function of First Order Exponential Decay $Y = m\exp(-X/n) + p$, we replace Y by

Table 5
Results of measured resistance, calculated damage degree, the effective stress and strain of BF 24.

Time t(s)	Calculation results			
Variable factors	293	504	923	1655
R (Ω, measured)	1163	1138	1114	1098
|FCR| (%)	4	6	8	9.3
D (%)	21.8	33.14	42.99	48.64
ε_2 (10^{-6})	5.03	11.87	20.4	26.40
y_0 (mm)	−1.96	−3.12	−4.21	−4.88
$\tilde{\sigma}_1$ (N/mm^2)	−3.69	−5.36	−6.65	−7.91
$\tilde{\sigma}_3$ (N/mm^2)	3.99	6.08	7.88	8.90
ε_1 (10^{-6})	−123.00	−178.82	−221.75	−243.78
ε_3 (10^{-6})	133.04	202.62	262.53	296.51

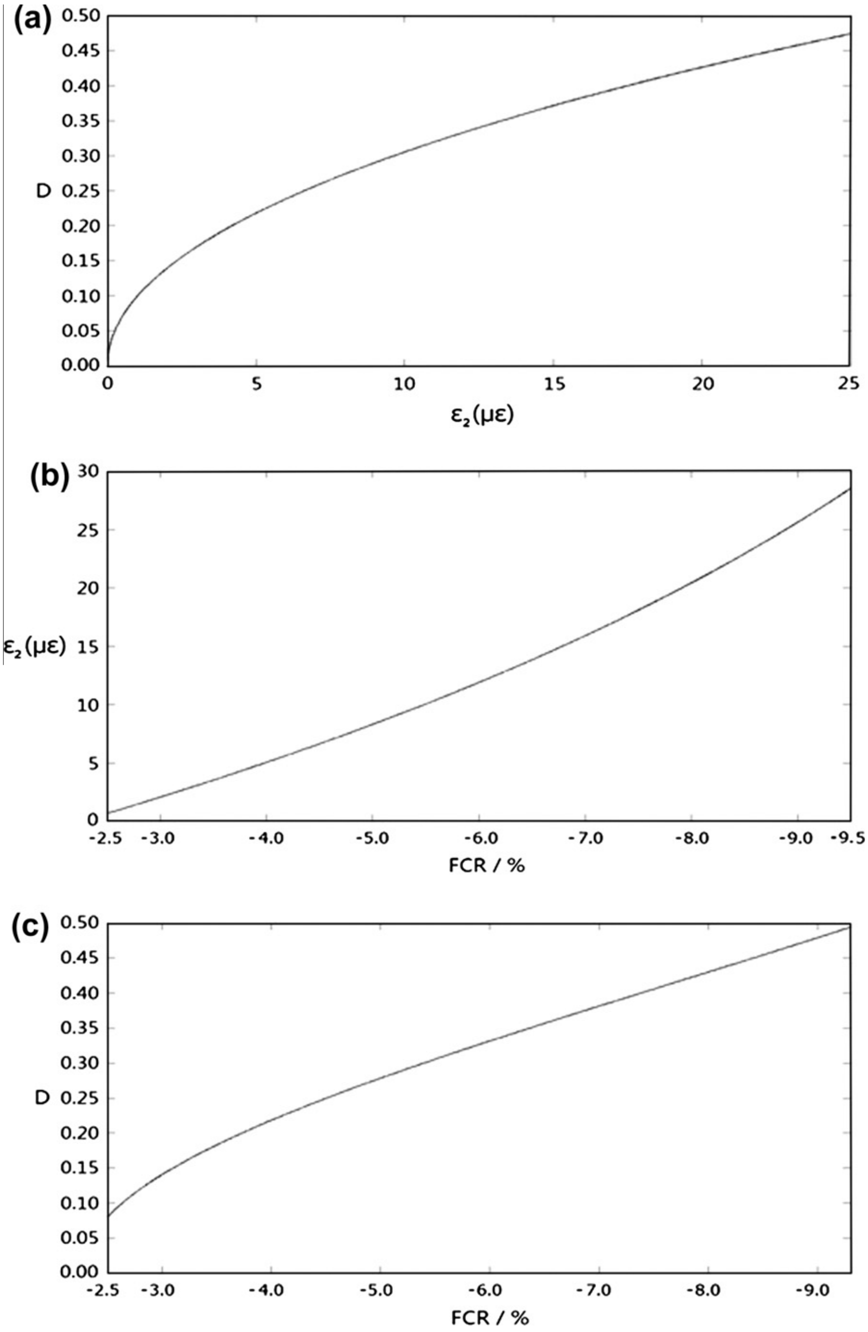

Fig. 8. Relationships between (a) the damage degree and the strain of IGNA, (b) the strain of IGNA and FCR and (c) the damage degree D and FCR.

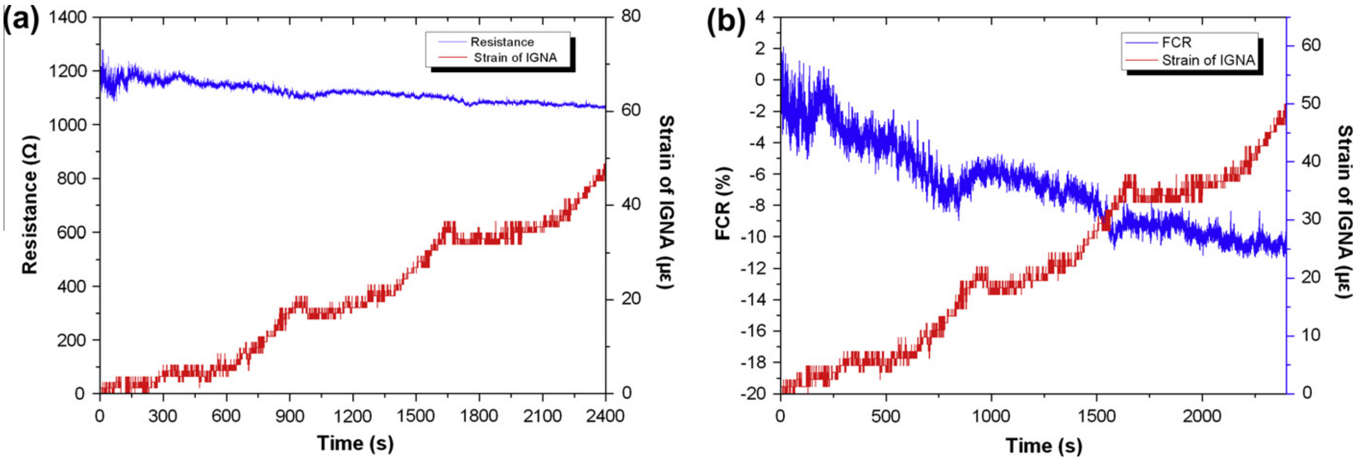

Fig. 9. Relationship among the resistance (a) or FCR (b), the strain of IGNA and Time.

$100\Delta R/R_0$ and X by ε_2, hence, we get the relationship between the strain of IGNA (ε_2) and the FCR, which can be demonstrated in following equation and Fig. 8b:

$$\varepsilon_2 = -n\ln\left[\frac{100(R-R_0)}{mR_0}-\frac{p}{m}\right]\Big/10^6 \quad [R\leqslant R_0] \tag{13}$$

It can be seen that ε_2 increases with the increasing of the absolute value of FCR.

The relationship between the damage degree (D) and the FCR can be written in Eq. (14) and illustrated in Fig. 8c. It can be seen that the damage degree D increases monotonously with the increasing of the absolute value of FCR.

$$-n\ln\left[\frac{100(R-R_0)}{mR_0}-\frac{p}{m}\right]\Big/10^6 = \frac{N_{cr}L}{0.944Ebh^2}\cdot D\,\frac{1-\sqrt{1-\frac{2}{3}D}}{2} \tag{14}$$

When the elastic modulus E, beam dimensions (b, $2h$, L) and the cracking load (N_{cr}) are given, the electrical resistance (both the initial R_0 before loading and R under loading) can be measured, so the stress–strain state subjected to the cracking load can be calculated according to Eqs. (10)–(12). The displacement of IGNA $(y_0)_{cr}$ under the cracking load can be obtained from Eq. (8), and the damage degree D of the concrete beam under the cracking load can be evaluated according to Eq. (14).

3.4. An example

We take specimen BF24 as an example for the diphasic electric conductive materials using BF 24 (the combination of NCB0.2% and CF0.4%). The beam dimension is given as follows: section width (b) = 100 mm, section depth ($2h$) = 100 mm, the beam length (L) = 300 mm. The loading history of the beam with BF24 is illustrated in Fig. 3.

The elastic modulus (E) is 3.0×10^4 N/mm^2; the cracking load (N_{cr}) is 14.4 kN; the parameters m (=12.98), n (=34.94) and p (=−15.24) can be obtained from Table 4; before the beam is subjected to loading N (at the beginning (t = 0)), R_0 = 1211 Ω; and $\varepsilon_2 = 0$, $y_0 = 0$, $D = 0$. When the beam is subjected to load N, the concrete damage occurs, the resistance of the conduction concrete at any time t (R(t)) can be measured. The values of damage degree D, the stresses and strains as well as the displacement of IGNA y_0 of diphasic electric conductive concrete beam BF 24 at different load time are calculated by Eqs. (10)–(14) and summarized in Table 5.

The Relationship among the resistance (the blue curve[1]), the strain of IGNA (the red curve) and Time is illustrated in Fig. 9a, and b demonstrates the Relationship among FCR (the blue curve), the strain of IGNA (the red curve) and Time.

From Table 5, Figs. 3, 9a and b, the following points can be observed:

- For flexural beam, the electrical resistance (R) usually declines with the increasing of the loading magnitude and duration.
- For flexural beam, the absolute value of the FCR increases with the increasing of the loading magnitude and duration.
- Both the damage degree (D) and the strain of IGNA (ε_2) increase with the increasing of the absolute value of FCR. At the time of 1655 s after the loading, D = 0.486, which is close to D_{cr} = 0.5, it means that the cracking load N_{cr} is almost achieved.
- As the strain of IGNA (ε_2) increases with the loading magnitude, the FCR increases gradually with the increasing of D. This provides convincing evidence that suggested formula $Y = m\exp(-X/n) + p$ can fit the relationship between ε_2 and FCR very well.
- The absolute value of the displacement of IGNA (y_0) goes up gradually accompanied by increased absolute value of FCR and D.
- Other factors like $\tilde{\sigma}_1$ and $\tilde{\sigma}_3$, ε_1 and ε_3 increase with the increasing of FCR and D.

4. Conclusion

The purpose of this study was to explore the application of the nano-carbon black and carbon fiber as diphasic electric conductive materials for self-diagnosis of the damage of concrete beam. A series of experiments and analysis on the electric properties like the resistance and fractional change in resistance, and the mechanical properties like the loading, the strain and stress of concrete beam with electric conductive materials have been performed, and the effects of NCB, CF and diphasic BF on the relationships among the fractional change in resistance, the strain and damage degree of concrete beam before cracking have been evaluated. The relationship between the FCR and the strain of IGNA (ε_2) has been developed. The experimental and analytical results have led to the following conclusions:

(i) The compressive strength of concrete increases with the increasing of contents of NCB, CF and BF slightly.
(ii) The flexural strength of beam usually increases with the increasing of CF and BF content, however, the addition of NCB shows small influence on the flexural strength.
(iii) The FCR increases with the increasing of the loading magnitude and duration.

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[1] For interpretation of color in Fig. 9, the reader is referred to the web version of this article.

(iv) The strain of IGNA (ε_2) is a function of FCR. Before the cracking of concrete occurs, the function of First Order Exponential Decay agrees well with the relationship between ε_2 and |FCR| during the loading process of CFRC beams.
(v) Both the damage degree (D) and the strain of IGNA (ε_2) increase with the increasing of |FCR|.
(vi) As expected, all the mechanical factors of the concrete beam with conductive admixtures increase with the increasing of FCR and *D*.
(vii) An example has been validated to evaluate the effect of diphasic electric conductive materials on the ability of the self-diagnosis of the possible strain and damage. The results are satisfied.

The self-diagnosis or monitoring of the electric resistance change of conductive concrete beam could provide information of the strain and damage degree for the serviceability (i.e. impending of cracking) of bending members. The investigation reported herein is based on the foundation for the new cementitious composite materials, NCB and CF reinforced concrete with improved mechanical behaviors and increased conductivity, which could be used in the smart structure and sustainable infrastructure bending members.

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