Carbon black enhanced cementitious composites for self-sensing micro strain

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Abstract. As one of the non-destructive test methods, self-sensing cementitious composites have been developed for concrete structures to monitor the health condition. In this study, the focus was put on the self-sensing capacity for low amplitude strain which was often overlooked in the previous research. Carbon black nanoparticles were added as conductive filler in cementitious composites and their piezo-resistivities were recorded in low-amplitude cyclic loadings. Besides, hammer induced stress wave was utilized to activate the self-sensing mechanism in composites. Because the tunnelling effect occurs at several nanometres and is extremely sensitive to the micro strains, these signals were collected as the electrical resistance variance between two closely contacted electrodes and compared with the signals from lead zirconate titanate (PZT) sensors. The developed materials provides the potential of high-resolution strain measurement and stress wave detection without any external instruments.

Introduction

Concrete is the major construction material for a variety of structures including building, bridges and dams. In recent years, the serious consequence led from failure of concrete structures has brought attention to the health monitoring of these concrete components and technologies such as optical fiber and strain gauge are now widely applied. However, these monitoring approaches still face some inevitable issues in installation, measurement and maintenance. Therefore, self-sensing cementitious materials, which have the advantage of high sensitivity and compatibility to the host material, has drawn more interest in this area. With the addition of electrically conductive fillers like carbon fibers, the composite materials have been proved excellent ability to capture the external stress by measuring the electrical properties [1-3]. This property has been successfully applied in pavement for traffic monitoring purpose [4, 5]. Apart from its stress sensing properties in elastic range, it has demonstrated potential for damage identification and quantification in tensile, compression, flexural and impact scenarios [6-9]. Dong et al. [6] have investigated the behaviour of self-sensing composite under a combination of cyclic and impact test. It not only displayed endured sensing ability after damage but also quantitively reflected the accumulation of damage. In addition, the response of electrical information under dynamic compression was also found to be consistent with results from the accelerometer and strain gauge by Ding et al [10]. However, these experiments are all limited in a relatively high stress scenario within a low frequency range. The responses of self-sensing composites to lower stresses have not been explored and their feasibility at higher frequencies is not studied. In this research, the self-sensing ability for carbon black nanoparticle reinforced cementitious composites has been investigated in both static and dynamic cases through low-amplitude cyclic loadings and impact waves, respectively.

Experiment set up

Material preparation. The self-sensing cementitious composites in this work are composed of 2%wt of carbon black nanoparticles which are acting as conductive fillers and form a stable network in the cementitious cube. The production of the composites follows the standard procedure in ASTM C1738 with a ratio of 0.9:0.45:0.1:0.02:0.01 between cement, water, silica fume, carbon black and superplasticizer. The carbon black nanoparticles are first mixed with water and superplasticizer and then sonicated in water bath prior to the mixing with binder to avoid agglomeration as possible.

Cyclic loading set up. In the cyclic loading test, cube specimen of 50 mm×50 mm×50 mm is made with electrodes mesh embedded inside in Figure 1. Strain gauges are attached on different surfaces and average values are taken to evaluate the overall strain of the specimen. During the experiment, the surface of electrodes is perpendicular to the loading direction. At first, three cycles of loadings in 0.5, 1 and 1.5 kN, respectively were applied on the sample for verifying its piezoresistivity. Then the loadings were lowered to 5 N and increased to 80 N with a factor of 2 times. The electrical resistance, strains and loadings were recorded throughout the test.

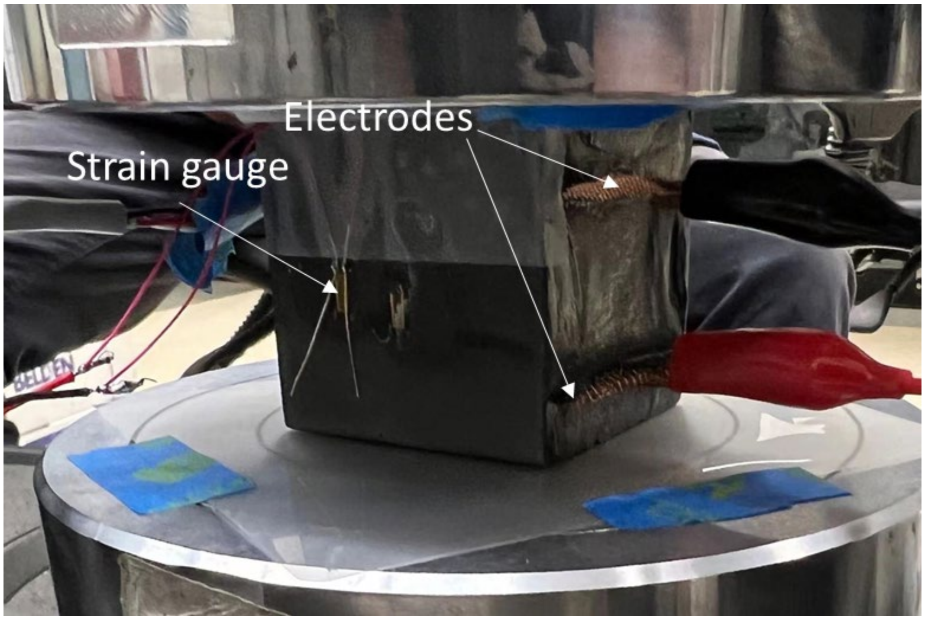

Figure 1. Cyclic test set up

Hammer-induced impact wave. The carbon black reinforced cementitious composites are embedded inside a concrete slab of 300 mm×300 mm×45 mm. PZT sensors and needle shape electrodes are surface-bonded and embedded in both plain concrete and self-sensing composites respectively as shown in Figure 2(a). The electrical resistance between the electrodes will be collected by an ad-hoc designed signal amplifier by which the resistance will be converted into voltage signals and collected by the oscilloscope.

In the experiments, hammer will introduce an impact wave at the right bottom corner of the slab indicated in Figure 2(b). The PZT sensor and two pairs of electrodes on the self-sensing composite is labelled as P2, S1 and S2, separately, while the PZT on the concrete slab is label as P1.

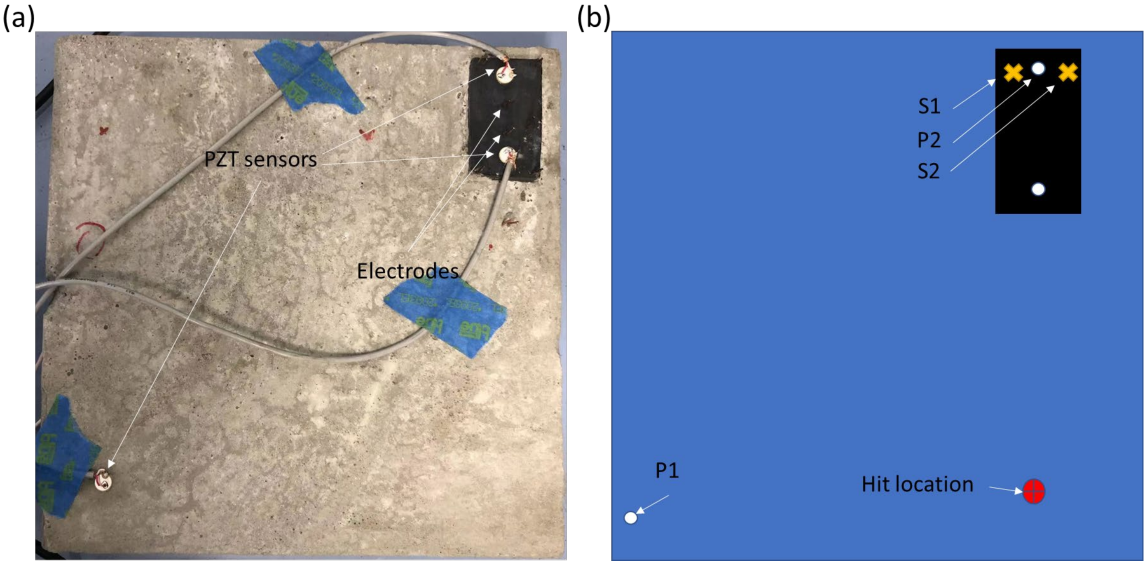

Figure 2. Impact test components (a) location (b) labels

Results

In the first experiment, relatively high loadings are applied on the cube specimen first. The electrical resistance data is converted to fractional resistance change (FRC):

$$FRC = \frac{R_t - R_0}{R_0} \tag{1}$$

Piezoresistivity: In Figure 3, strains from strain gauge and FRC are plotted against the loadings. It can be seen that the pattern of both matches well with the loadings. When the loadings drop back to zero in each cycle, the electrical resistivity also returns to the initial value, indicating that 2% carbon black nanoparticle-reinforced cementitious materials have a good repeatability for the sensing purpose and piezoresistivity for capturing the external stress variation.

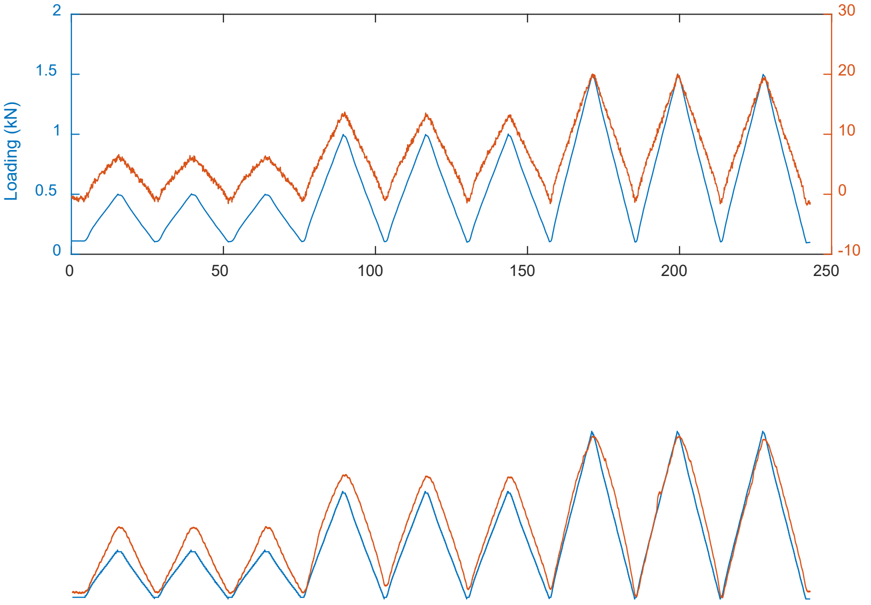

Figure 3. (a) Strain and (b) FRC response in high loading cyclic test

Low-amplitude cyclic loading: At the loading of 5 N, data from strain gauge fluctuates around 0 but shows rough trend with the applied stress while the FRC barely has any response in Figure 4. However, starting from 10 N till 80 N, FRC presents a clear pattern with the stress and the increasements at each loading stage are linearly proportional to the increasement of the loading which is double of the previous step. In terms of the strain gauges, more noise is observed especially in the range of 10-40 N where the strain change does not correspond to the amplitude of applied loadings. This is because the effective measurement range of strain gauges is quite local and the non-uniform deformation on the surface limits the ability of strain gauge to accurately evaluate the overall deformation of the composites. In contrast, since the FRC is acquired by the measurement from surface to surface resistance, the coverage area is larger and it can more reliably reflect the overall applied stress.

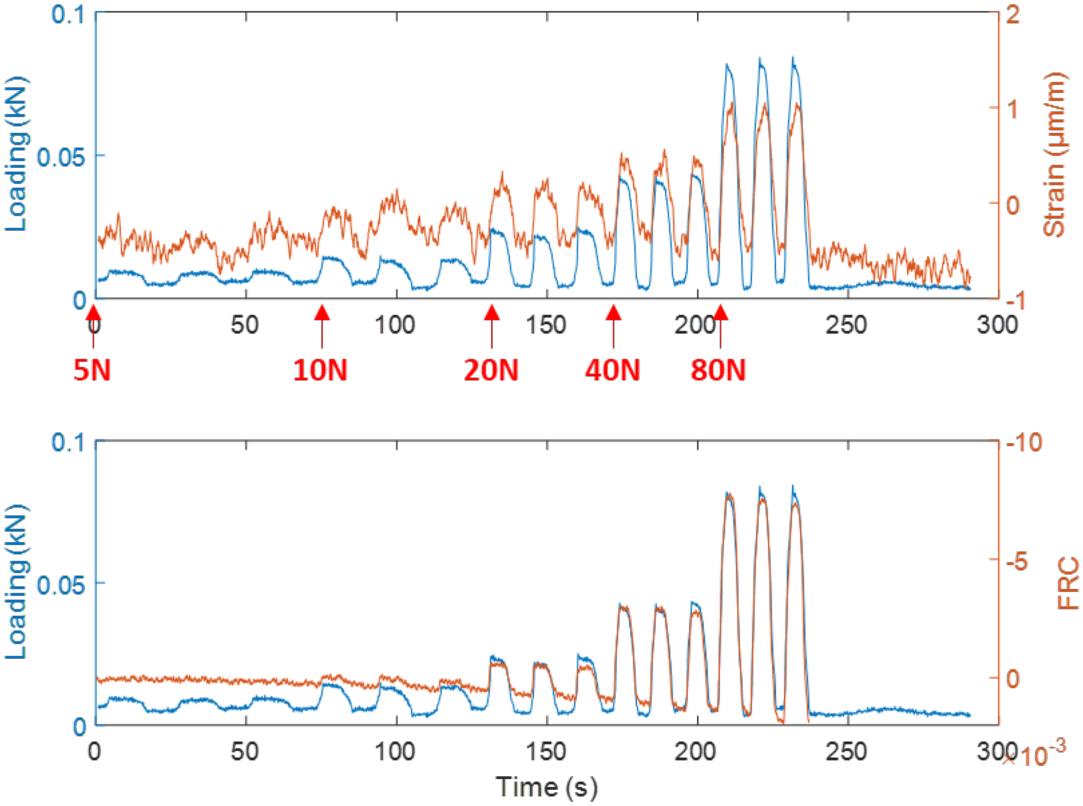

Figure 4. (a) Strain and (b) FRC response in low amplitude loadings

Hammer-induced impact wave: In Figure 5, signals received on each sensing location are shown in the time domain after wavelet-based denoise. Both PZTs and sensors have demonstrated excellent ability to capture the propagation of impact wave. Besides, the arrival time of P1, P2 and S2 is almost the same as the input wave. Thus, it is hard to determine the velocity of wave in this case unless higher frequency wave is actuated. In addition, the orientation of each pair of electrodes as well as their gap can significantly influence the way they capture the waves and it is nearly impossible for carbon black particles to uniformly distributed in cement matrix perfectly. Consequently, the wave form collected from S1 is noticeably different from other channels and a bit delay is found in the time of arrival. In the future work, the orientation and the gap of electrodes would be considered and ultrasonic wave will be activated to testify its piezoresistivity in higher frequency.

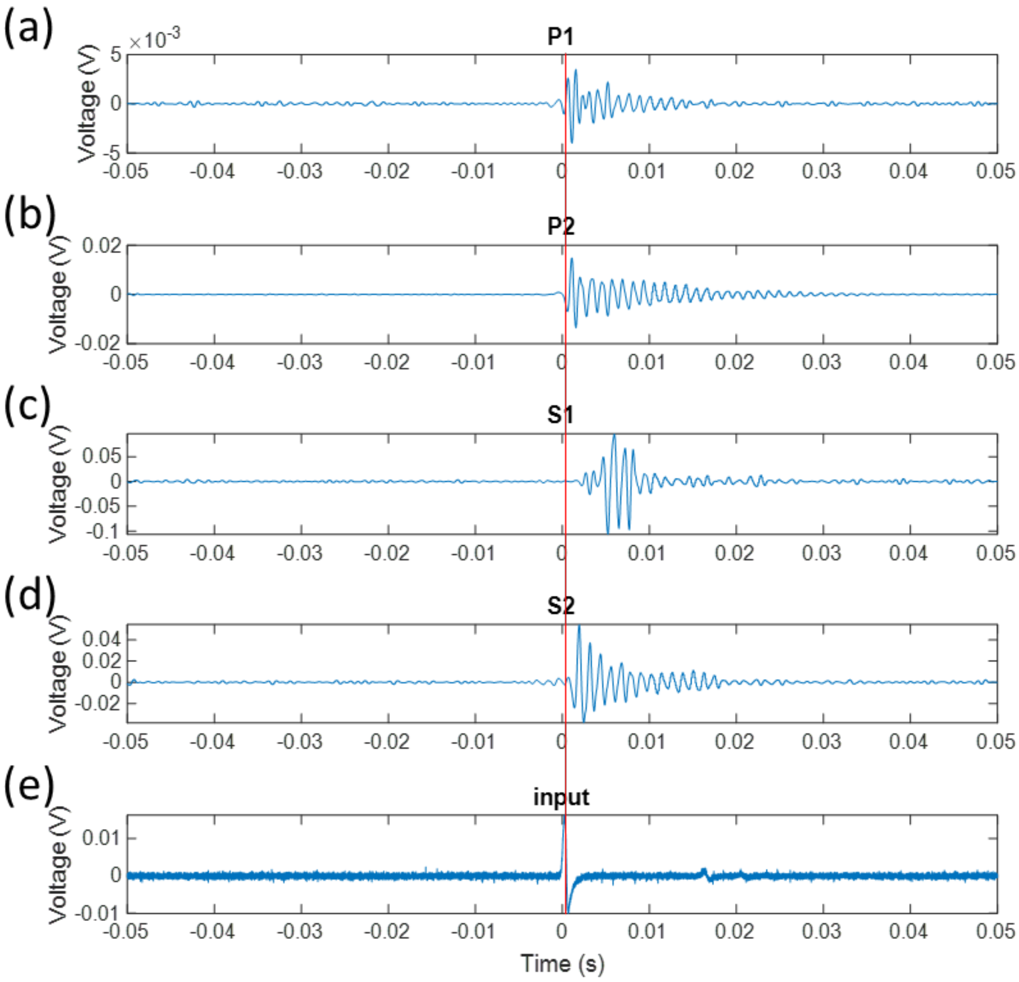

Figure 5. Signals from (a) P1 (b) P2 (c) S1 (d) S2 (e) input in time domain

Conclusions

The work presents the piezoresistivity capacity of carbon black reinforced cementitious composites in both cyclic and impact test. The results indicate an excellent piezoresistivity of the self-sensing material even at low strains, achieving a comparable sensing ability as to the traditional sensors. These findings extend the understanding of the conductive mechanism in self-sensing cementitious materials and establish a solid foundation for its further application in acoustic and ultrasonic based defect inspection.

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