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Strain monitoring of concrete components using embedded carbon nanofibers/epoxy sensors

Yanlei Wang [a], Yongshuai Wang [a], Baoguo Han [a], Baolin Wan [b,*], Gaochuang Cai [c], Zhizheng Li [a]

[a] State Key Laboratory of Coastal and Offshore Engineering, School of Civil Engineering, Dalian University of Technology, Dalian, Liaoning 116024, China
[b] Department of Civil, Construction and Environmental Engineering, Marquette University, Milwaukee, WI 53201, USA
[c] Laboratory of Solid Structures, University of Luxembourg, Luxembourg L1359, Luxembourg

HIGHLIGHTS

- Embedding CNFs/epoxy sensors into concrete components is studied at first time.
- The piezoresistive performances of the CNFs/epoxy sensors are evaluated.
- A compensation circuit is proposed to eliminate the effect of temperature.
- The calibration and monitoring curves exhibited a consistent variation trend.

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ABSTRACT

In this study, embedded strain sensors based on the principle of piezoresistivity were fabricated by epoxy-based composites filled with different contents of carbon nanofibers (CNFs). The piezoresistive performances and relevant parameters including gauge factor, linearity, repeatability and hysteresis of these sensors were investigated. A compensation circuit was proposed to eliminate the influence of temperature on sensing signals of the sensors. The CNFs/epoxy sensors were embedded into concrete cylinders to monitor their compressive strains under monotonic and cyclic loadings, thereby assessing practical applications of the CNFs/epoxy sensors as strain sensors for monitoring concrete structures. The results indicate that the sensors containing 0.58 vol% of CNFs, which have a gauge factor of 37.1, a linearity of 5.5%, a repeatability of 3.8% and a hysteresis of 6.3%, exhibited better piezoresistive performance compared to those containing 0.29 vol% of CNFs. The calibration and monitoring curves exhibited a consistent variation trend when the cylinders embedded with sensors were subjected to monotonic and cyclic loadings. This demonstrates that the CNFs/epoxy sensors have considerable potential to be used as embedded strain sensors for structural health monitoring of concrete structures.

1. Introduction

Civil infrastructures often suffer deterioration, damage accumulation or even sudden collapse due to fatigue load, environmental factors and a range of natural disasters, etc. Structural health monitoring (SHM) is a method to continuously monitor and evaluate the state of civil infrastructures. SHM systems use a group of sensors to measure real-time data of strain, displacement, temperature, etc. of structures, which help engineers and owners to detect anomalies in the structure's performance in timely manner [1]. With the aid of SHM, the structural strengthening or retrofitting measures can be timely established to ensure the safety and serviceability of the structure [2].

Conventional strain sensors, such as electrical resistance strain gauges, fiber optic sensors and piezoelectric ceramics, have been widely used in SHM [3,4]. However, utilization of these sensors is often limited due to some drawbacks including low sensitivity, high cost, poor durability, and fragility. In these circumstances, using piezoresistive composites to fabricate strain sensors has attracted extensive attention [2]. The sensors prepared by piezoresistive composites have advantages of multi-functionality, high sensitivity, cost effectiveness, excellent durability, and relatively easy fabrication processes, which are distinct from the conventional SHM sensors [5,6]. The theory making these sensors work is the principle of piezoresistivity, which is defined as a change in electrical resistance in response to the mechanical strain applied

* Corresponding author.
E-mail address: baolin.wan@marquette.edu (B. Wan).

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to the composites [7]. One common technique of the piezoresistive sensors are to incorporate electrically conductive reinforcement fillers (e.g., carbon nanotubes (CNTs) [2,8,9], carbon nanofibers (CNFs) [10–13], graphene nanoplatelets [14], carbon black [9,15], and nickel powder [16]) into dielectric or semiconducting matrix (e.g., rubber [17], epoxy [10,18], and cement [19–23]).

Considerable number of researches have proved that it is feasible to prepare the sensors by piezoresistive composites for strain monitoring [18,24–28]. Monteiro et al. [27] investigated a piezoresistive carbon black cement composite for traffic monitoring. A linear and reversible piezoresistive performance was found with gauge factors ranging from 40 to 60. Nam et al. [28] investigated the piezoresistive sensing capabilities of glass and carbon fiber-reinforced plastic composites incorporating CNTs and concluded that these composites showed continuous sensing characteristics. Luo et al. [25] explored the piezoresistive properties of cement composites reinforced by functionalized CNTs. Experimental results indicated that excellent piezoresistive properties were achieved at the doping level of 0.3% by weight, wherein high strain sensitivity was recorded as 286.6 for the cases of adding small amounts of surfactant.

Most current researches [18,24–28] mainly focus on the piezoresistive performances of the sensors themselves under different conditions. However, only a few researches studied the strain sensing capability of piezoresistive sensors embedded into concrete structures have been undertaken [29–32]. Xiao et al. [30,31] investigated strain sensing properties of cement-based sensors embedded into concrete cylinders and beams, respectively. The results indicated that the embedded cement-based sensors had nice strain-sensing abilities. However, cement-based sensors are greatly affected by environmental humidity. Therefore, humidity insulation method should be used to guarantee the sensing precision of cement-based composites under various ambient conditions [30]. Additionally, the polarization effect of cement matrix adversely affects the accuracy of the monitoring [33]. Compared to cement, epoxy has excellent chemical resistance, wear resistance, electric insulation, waterproof function and large deformation range. If it was used as the matrix for the compressive strain sensors, it could not only eliminate the effects of humidity and polarization, but also enable the whole process monitoring of steel or fiber reinforced polymer (FRP) confined concrete structures with a large ultimate failure strain subjected to compressive loadings, which cannot be achieved by the cement-based sensors with a relative small strain monitoring capacity. Therefore, it is worth to study the performance of embedded epoxy-based sensors for strain monitoring of concrete components subjected to compression.

In this study, the sensors were prepared by CNFs/epoxy composites containing two different contents of CNFs. The piezoresistive performances of the strain sensors themselves were investigated firstly, followed by the exploration of relevant parameters including gauge factor, linearity, repeatability and hysteresis. Secondly, a compensation circuit was proposed to eliminate the influence of temperature on sensing signals of the sensor. Finally, concrete cylinders embedded with CNFs/epoxy sensors were subjected to monotonic and cyclic loadings to explore the strain sensing capability of the sensors, thereby assessing practical applications of the CNFs/epoxy sensors as compressive strain sensors for concrete structures.

2. Experimental program

2.1. Materials

Pyrograf-III PR-24-XT-HHT (manufactured by Prograf Products, Inc., USA), which are heat treated CNFs with diameters of 70–200 nm and lengths of 50–200 μm, were employed as the nanofillers. The properties of the CNFs provided by the manufacturer are shown in Table 1. The epoxy used as the matrix of the nanocomposite was produced by Tianjin Swancor Wind Power Materials Co., Ltd., China. The epoxy is mixed by two parts: SWANCOR 2511-1A (main agent) and SWANCOR 2511-1BS (curing agent) with a ratio of 10:3 in weight, or 30:11 in volume. It has low viscosity, moderate gel time, nice mechanical properties, high heat deflection temperature (HDT), and good wettability to carbon fibers. The CNFs in the amount of 0.29% and 0.58% by volume of composite were added to the composites, and the corresponding sensors are called $S_{0.29}$ and $S_{0.58}$, respectively, in this paper. Acetone was used as diluting agent in the amount of 2% by volume of composite. Copper wire mesh with the size of 20 mm × 30 mm was used as the electrodes of the sensors. Commercial ready mixed concrete was used for the construction of the concrete cylinders. The mean 28-day compressive strength of the concrete cylinders was 33.5 MPa.

2.2. Specimens

2.2.1. CNFs/epoxy sensors

It is well established that the homogeneity of nanofibers dispersion into the epoxy matrix is one of the most important factors affecting the composite's electrical and piezoresistive performance. Two methods, including mechanical stirring and ultrasonic treatment, were used to disperse CNFs into epoxy matrix in this research. The CNFs/epoxy sensors were prepared by following procedure as shown in Fig. 1: (1) Different amounts of CNFs (0.29 vol% and 0.58 vol%) were dispersed into acetone by a mechanical stirrer (Model SFJ-400, Shanghai Modern Environmental Engineering Technology Co., Ltd., China) at high speed (1500 r/min) for 10 min, and then sonicated by Branson 2800 Ultrasonic Cleaner (Model 2510 E-DTH, 100 W 40 kHz, Branson Ultrasonic Co., Ltd., USA) for 8 h at 20 °C to get CNFs-acetone mixture. (2) Heated (at 60 °C for 2 min) SWANCOR 2511-1A was dissolved in the CNFs-acetone mixture via stirring at high speed (1500 r/min) for 20 min and ultrasonically dispersing at 60 °C for 8 h to get a slurry-like mixture. (3) The mixture was placed in a vacuum oven (Model DZ-2BC, Tianjin Taisite Instrument Co., Ltd., China) to remove acetone and air bubbles. (4) After the mixture was cooled, the curing agent (SWANCOR 2511-1BS) was added and mixed by mechanical stirring at low speed (500 r/min) for 5 min. (5) The CNFs/epoxy mixture was poured into a silicone mold, which was brushed a layer of oil for easily removing the specimen after curing, and two copper wire mesh electrodes were embedded in the mixture. On one hand, the size of the sensor needs to be as small as possible in order to prevent the sensor from damaging the concrete structure. On the other hand, it is difficult to place the sensor in concrete cylinder if it is too small. According to the research of Han et al. [16], the size of the sensor was set to 20 mm × 20 mm × 40 mm. (6) The sensors were pre-cured at room temperature for 24 h followed by a post-cure for additional 8 h at 80 °C.

2.2.2. Concrete cylinders

The concrete cylinders with 150 mm in diameter and 300 mm in height were prepared by following procedure: (1) The calibrated sensor was placed at the center of a polyvinyl chloride (PVC) mold. The sensor was tied to a thin steel wire that had been fixed to the PVC mold. (2) Concrete was slowly poured into the PVC mold. (3) An external vibrator was used to compact concrete after pouring. (4) The cylinders were demolded after 24 h and then cured in a curing room maintaining temperature of 20 ± 3 °C and relative humidity of 95% for 28 days.

2.3. Measurements

2.3.1. Piezoresistive test for sensors

The piezoresistive experiments were performed by applying monotonic and cyclic uniaxial loadings, and simultaneously measuring the strain and the electrical resistance of the CNFs/epoxy sensors. The load was applied by an electronic universal testing machine (Model WDE-200E, Jinan Gold Testing Machines Inc., China) under displacement control. Two cyclic loading paths were applied in this research. Loading type 1 (shown in Fig. 2a) consisted of eight load-unload cycles with constant amplitudes of 25 MPa. Loading type 2 (shown in Fig. 2b) consisted of five cycles with incremental amplitudes of 10, 15, 20, 25 and 35 MPa, and repeated three times for each amplitude. In this study, six specimens of $S_{0.29}$ and $S_{0.58}$

Table 1
Properties of the CNFs.

Diameter (nm)	Length (μm)	Aspect ratio	Surface area (m^2/gm)	Moisture (wt%)
70–200	50–200	250–2800	41	<5