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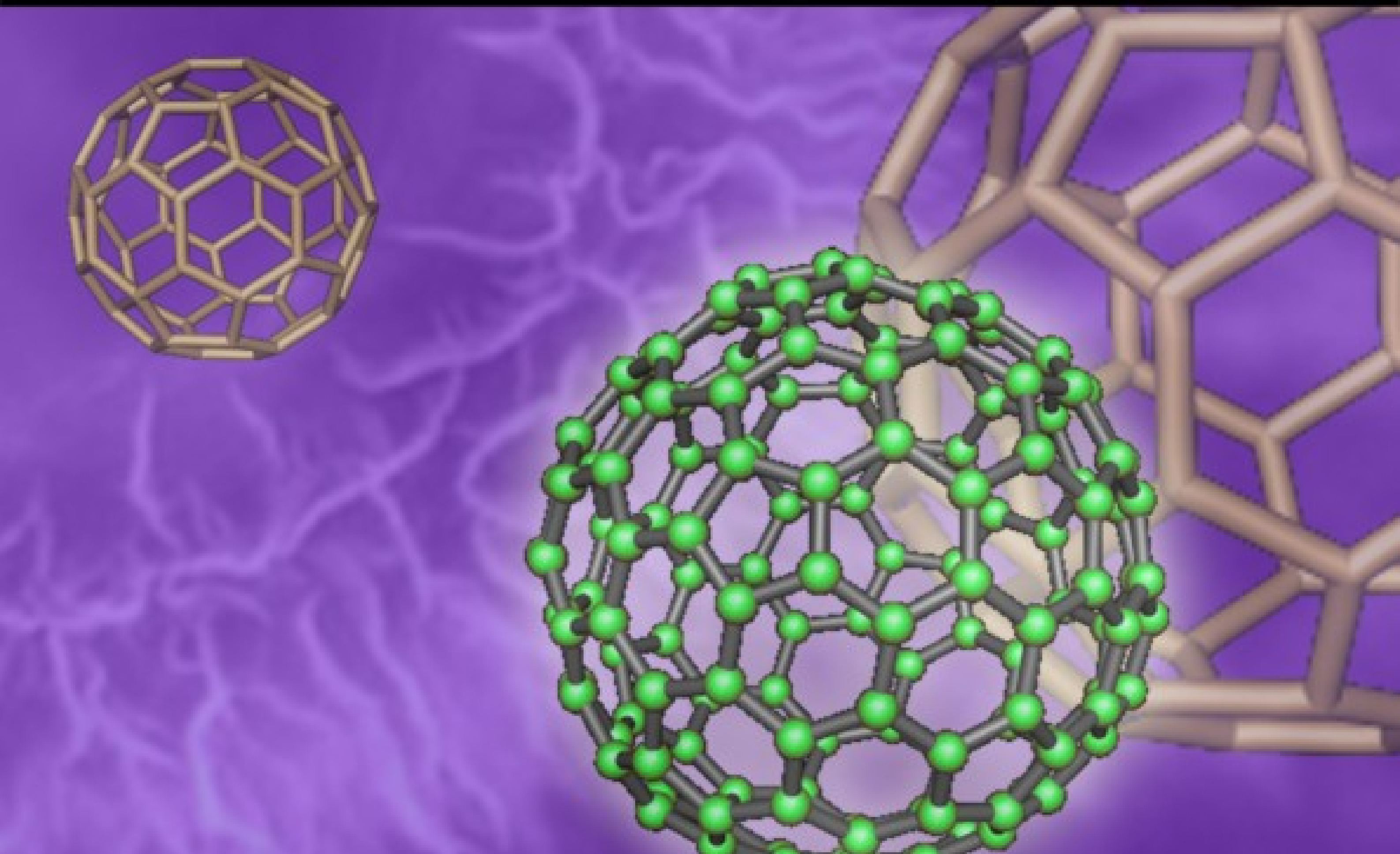

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Contents

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Low-Cost Wireless Nanotube Composite Sensor for Damage Detection of Civil Infrastructure

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Abstract: This paper presents a new low-cost wireless nanotube composite sensor for structural damage detection. A cement matrix with networked carbon nanotubes was used to develop an in situ, wireless and embedded sensor for crack detection in concrete structures. By wirelessly measuring the change in the electrical resistance of the carbon nanotube networks, the progress of damage can be detected and monitored wirelessly. As a proof of concept, the wireless cement-carbon nanotube sensors were embedded into concrete beams and subjected to monotonic loading to evaluate the effect of damage on their response. Results indicated that the wireless response of the embedded nanotube sensors were able to detect the initiation of damage at an early stage of loading. *Copyright © 2009 IFSA.*

Keywords: Nanotube sensor, Wireless monitoring, Damage detection, Civil infrastructure

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1. Introduction

Concrete structures undergo uncontrollable damage process manifesting in the form of cracks due to the coupling of fatigue loading and environmental effects. In order to achieve long-term durability and performance, continuous health monitoring systems are needed to make critical decisions regarding operation, maintenance and repairs. Recent advances in nanostructured materials such as carbon nanotubes (CNTs) have opened the door for new smart and advanced sensing materials that could effectively be used in health monitoring of structures. In the area of structural health monitoring, CNTs were mainly used to monitor the level of mechanical strains in composite materials where CNTs were integrated into polymers to act as strain sensors. For example, Frogley et al [2] developed a strain sensor by embedding CNTs into a polymer matrix and measured the Raman spectrum shift as a function of mechanical strain. Dharap et al [3] proposed a carbon nanotube film sensor made up of randomly oriented carbon nanotubes to measure mechanical strain at a macro level, then Kang et al [1] developed a carbon nanotube polymer material and used it to form a piezoresistive strain sensor for structural health monitoring applications. Other efforts in utilizing carbon nanotubes as strain sensors for health monitoring are described in detail in [1-8]. To monitor the health of civil structures, Loh et al [9] developed surface mounted single walled carbon nanotube- polyelectrolyte (SWNT-PE) composite sensors to measure strain in concrete structures, the sensors were then coupled with RFID tags to wirelessly measure their electrical resistance [10]. CNTs were also used to detect damage initiation in composite materials such as matrix microcracking and delamination. This was accomplished by embedding CNTs into the host structure to form conductive percolating network-based sensors. Thostenson and Chou [11] processed glass-fiber-epoxy composites with embedded CNTs to evaluate the onset and evaluation of damage. They showed that the measured electrical resistance is sensitive to the initial stage of the matrix microcracking and could be used to identify the nature and the progress of damage. They also demonstrated that by combining load and strain measurements in real-time with the direct current electrical resistance measurement of the CNT network, insight could be gained in the evolution and accumulation of damage in composite structures [12]. These researchers also used CNTs for health monitoring of mechanically fastened composite joints [13], where CNTs were integrated into the joints to detect local damage such as delamination, cracking and fastener loosening. Gao et al [14] coupled CNTs and acoustic emission (AE) monitoring for sensing damage development in composites. They used the relationship between the resistance change and the AE signal cumulative counts to sense the damage initiation in the laminated composite specimens.

Current CNT sensors suffer from some serious drawbacks when applied to concrete structures including susceptibility to damage by concrete alkaline environment, high cost and incompatibility with concrete. The research presented in this paper discusses the concept of using wireless and embedded nanotube sensors in concrete structures for structural integrity monitoring. Carbon nanotube networks were embedded into a cement matrix and used to develop an in situ, wireless and embedded sensor for damage detection in concrete structures. By wirelessly measuring the change in the electrical resistance of the carbon nanotube networks, the progress of damage can be detected and monitored.

2. Fabrication of the Sensor

For structural integrity monitoring, the change in the electrical resistance of the cement-CNT sensor will be used to detect crack propagation in the concrete material. Cement matrix with randomly dispersed and networked carbon nanotubes was used to fabricate the long-gauge cement-CNT sensors. The cement matrix is used to improve the compatibility with the host concrete material, while the long-gauge will allow for crack detection in large civil structures such as bridges and buildings.

The raw materials used to manufacture the cement-CNT sensors include Portland cement (ASTM type I), untreated single walled nanotubes (SWNT) (purchased from NanoAmor, Inc.) and thin copper electrodes. Three volumes of CNTs 0.5, 1 and 1.5% were used in this investigation. The properties of the nanotubes as provided by the manufacturer are given in Table 1. First, water containing 5% of polycarboxylate-based superplasticizer and CNTs were first mixed and sonicated to produce a homogenous dispersed suspension. The polycarboxylate-based superplasticizer was used as a surfactant to improve the wettability of cement and CNTs. The CNT-water admixture then was mixed with cement using a rotary mixer with a flat beater for a period of 5 min, and then the mixture was poured into aluminum molds as shown in Fig. 1.

Table 1. Properties of SWNT (NanoAmor, Inc.).

Constituent	Young's Modulus (GPa)	Tensile Strength (GPa)	Poisson's Ratio	Diameter (nm)	Length (με)	Electrical Conductivity (S/cm)
Carbon Nanotube	810	32	0.2	1.5	10	10^2-10^{-4}

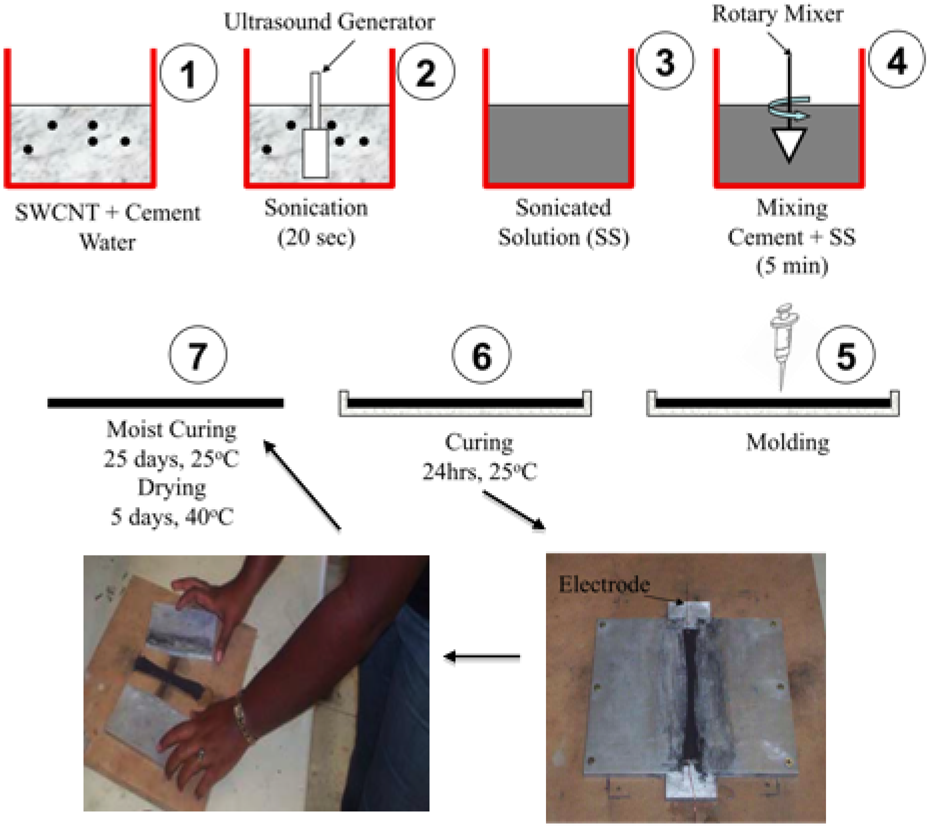

Fig. 1. Fabrication process of cement-CNT sensors.

During the fabrication process, electrodes (one electrode at each end) were inserted into the fresh mixture. After 24 hrs of curing, the sensors were removed from molds and moist cured at a temperature of 25 °C for 25 days, and then dried at 40 °C for 5 days. The typical dimensions of the cement-CNT sensor are shown in Fig. 2.

3. Wireless Sensing Node for the CNT Sensor

The CNT sensor was interfaced with an off-the-shelf wireless communication system shown in Fig. 3. The system was used to wirelessly measure the response of the embedded cement-CNT sensor. The wireless and embeddable sensing system consists of a rectifier, 16-bit A/D converter with a sampling rate of 80 Hz, 110 dB CMRR amplifier, 16 bits ID-memory and coil antennas. The interrogator consists of oscillator, demodulator/level shifter, data logger and antennas. The wireless monitoring system uses inductive links for sensor powering and data collection. Through the transmitter antenna, the interrogator emits an electromagnetic wave in the range of 916.5 MHz, the latter is picked up by the receiver antenna of the sensor system and uses it to power its data acquisition system attached to the cement-CNT sensor. The sensor node uses its transmitter antenna to send the rectified sensor signal to the interrogator, which will be transferred to a data logger for processing to obtain the sensor information such as ID number and the electrical resistance.

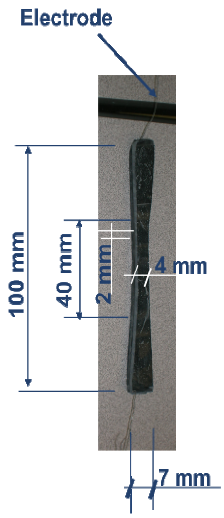

Fig. 2. Typical cement-CNT sensor.

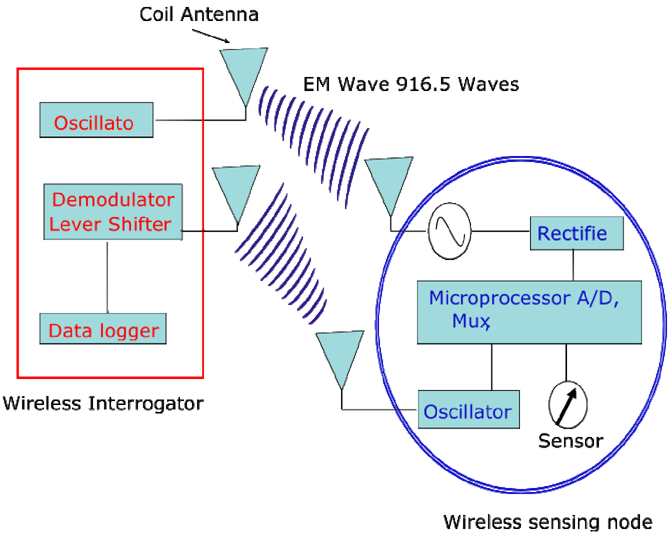

Fig. 3. Wireless communication system for the cement-CNT sensors.

4. Nanotube Percolation Threshold

To determine the percolation threshold of the SWNT, the sensors were interfaced to the wireless communication systems and their electrical resistance was measured. The electrical resistance was recorded using the wireless communication system through a two-point measurement scheme. The resistance of contacts and wires are negligible relative to the resistance of the sensors and therefore were not counted for. The experiments were conducted at room temperature. Three samples were used for each volume of SWNT as shown in Fig. 4. As can be seen, there was a sudden decrease in the electrical resistance as the volume of CNTs increased from 0 to 0.5 % and a percolation threshold of 0.5% was assumed for the sensors. The electrical resistance further decreased when the volume of SWNT increased from 0.5 to 1%. However, it appeared that the increase of the SWNT volume beyond 1% yielded a slight decrease in the electrical resistance indicating that continuous conductive networks has been formed in the cement matrix at 1% and there is no need to exceed this volume. Therefore, based on this finding, only cement-CNT sensors with a volume of 1 % of SWNT were evaluated.

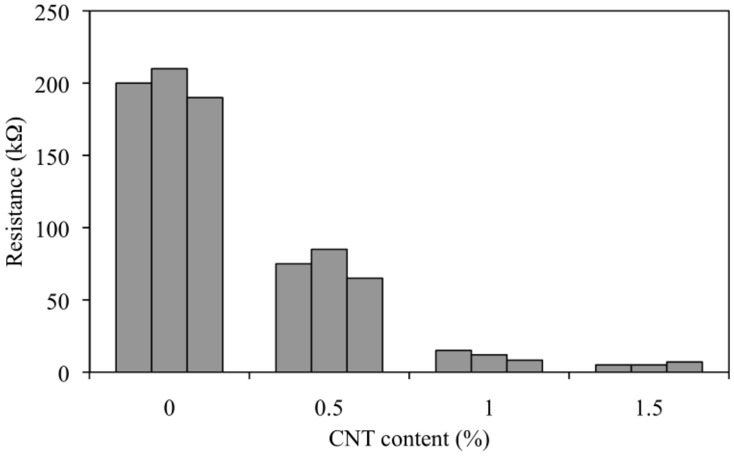

Fig. 4. Effect of SWNT concentration on the wireless electrical resistance measurements.

5. Validation of Wireless Damage Detection using the CNT Sensor

To evaluate their response, four cement-CNT sensors were interfaced to the wireless communication system and subjected to unidirectional monotonic tensile load using a universal testing machine (UTM) with a loading rate of 33 N/min. During loading, the electrical resistance was measured wirelessly using a two-point measurement scheme and the tensile strain along the longitudinal axis of the sensor was measured with conventional strain gauges attached to the middle of the sensor. Fig. 5 shows the effect of the applied monotonic load on the tensile strain and electrical resistance of the embedded cement-CNT sensors with a SWNT volume of 0.5 and 1%. As shown, for sensors with 1 % of SWNT, the electrical resistance increased linearly and monotonically up to 125 με strain, and then transitioned to a non-linear behavior up to specimen failure. Under applied tensile load, the thickness of the cement matrix between neighboring nanotubes tends to increase resulting in an increase in the effective resistance of the sensor. As the applied stress continues to increase, damage begins to develop at the nanotube-cement-nanotube interface due to high strain concentrations. This damage formation increases the length of the gap area between nanotubes where electrical tunneling takes place and thus increases the effective resistance of the cement-CNT sensor. With the progress of damage, some percolation paths were cut-off leading to a sudden change in the electrical resistance as can be seen in figure 5 where the resistance suddenly increased around 65 με, 125 με and 160 με. These changes roughly correspond to the drop points in the load-strain curve. As the damage expands, the transition from the linear to non-linear region takes place. This is mainly attributed to the fact that the number of percolation routes being cut-off by the damage is increased and the number of nanotube contact points is reduced leading to a sharp and non-linear increase in the electrical resistance as the applied load reaches its maximum. At this stage, most of the percolation paths have been cut-off and the last current carrying paths were cut-off at 180 με.

The cement-CNT sensor with a SWNT volume of 0.5 % exhibited a low sensitivity to the applied stress. The effective resistance remained dormant over a tensile strain of 75 με then increased in a non-linear manner up to failure. Although, the 0.5 % of SWNT increased the conductivity of the cement matrix, the measured effective electrical resistance however was not able to detect the early cracks that occurred at a strain of 0.3 με. The author believed that this was due to the fact that the amount of SWNT (0.5 %) did not produce a large number of conductive branches as compared to samples with 1 % of SWNT. Based on this, it was concluded that these sensors would not be able to detect crack propagation when embedded into the concrete beams and therefore were omitted from the experimental tests.

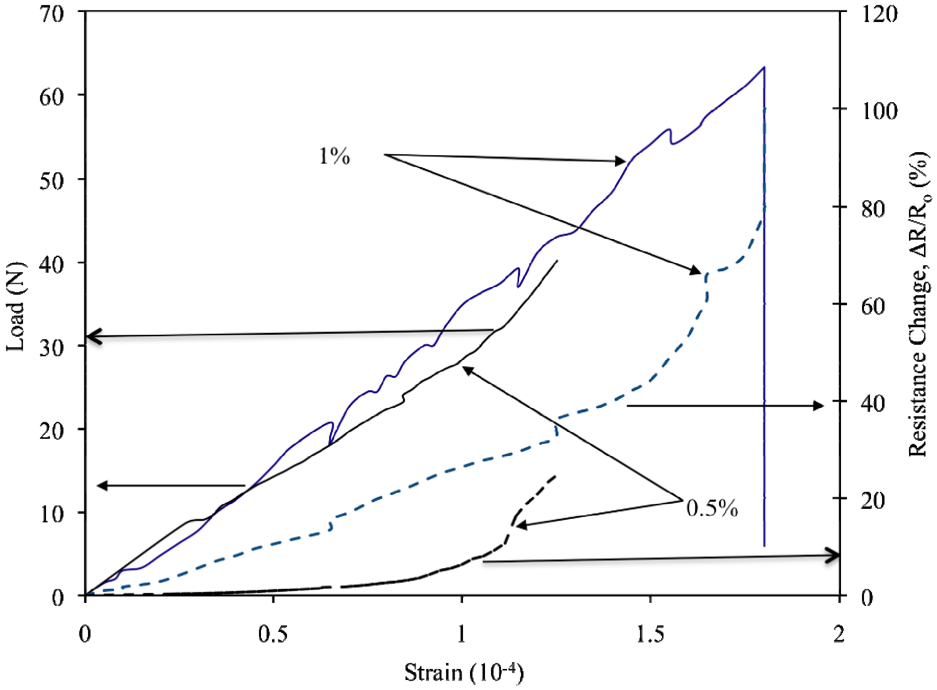

Fig. 5. Typical cement-CNT sensors wireless response under monotonic direct tensile loading.

The cement-CNT sensors were also interfaced with the wireless monitoring system and embedded into concrete beams to wirelessly detect crack propagation in the concrete specimens. As shown in Fig 6, the nanotube sensors were embedded into concrete beams 100 mm × 100 mm × 600 mm and placed just below the steel wire reinforcement (2×4 mm) and above the artificial concrete notch. The concrete notch is used to initiate crack propagation through the cement-CNT sensor. The four concrete beams (see Fig. 6) were subjected to three-point bending test using a universal testing machine (UTM) and monotonically loaded up to failure.

During loading, the sensor response was recorded with the wireless interrogator and the beams middle deflection was recorded with an LVDT attached to a wired data acquisition system. The experimental setup is shown in Fig. 7.

The typical wireless response of the embedded cement-CNT sensor in terms of electrical resistance is depicted in Fig. 8. As can be seen, for monotonically loaded beams, the electrical resistance of the sensor increased linearly with the applied load then suddenly increased at a deflection of 0.2 mm. This sudden increase is attributed to the concrete beam cracking as indicated in the load-deflection response of the beams. At this stage, the nanotube ends moved away from each other due to the applied strain, causing high strain concentrations in the cement matrix leading to microcracks at the nanotube/matrix interface which in return cut-off one or more conduction branches. As the applied load increases, microdamage in the sensor expands and the effective resistance of the sensor increases. With the concrete crack widening, multiple percolation paths were cut-off resulting in a sudden increase in the effective resistance at 2.3 mm deflection as demonstrated by the rapid decrease in the applied load. The effective resistance is then increased rapidly in a non-linear manner. The final abrupt increase in the effective resistance takes place when the applied load reaches its ultimate where all percolation branches were cut-off.

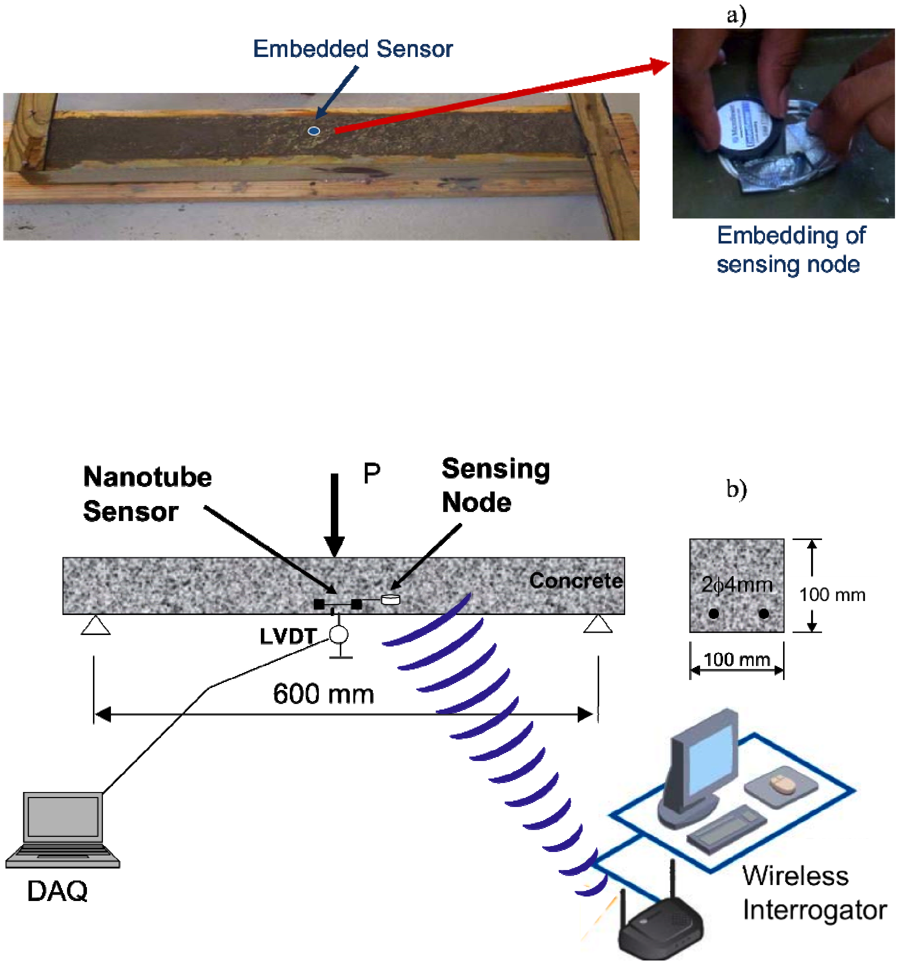

Fig. 6. Experimental test (a) embedding of sensing node (b) wireless monitoring process.

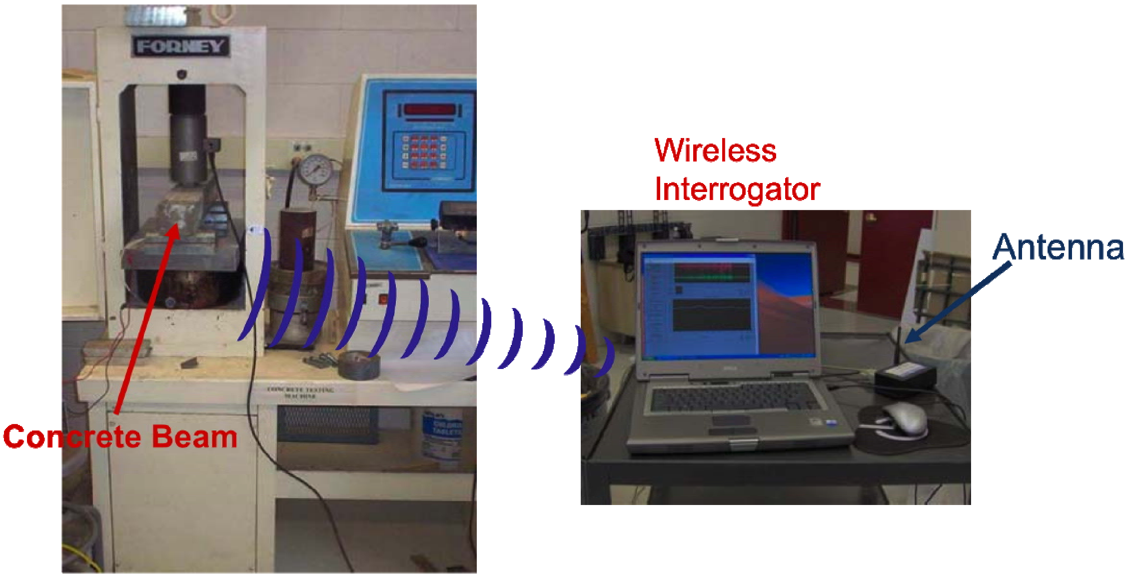

Fig. 7. Typical setup for the wireless damage detection system in the concrete beams with embedded cement-CNT sensors.

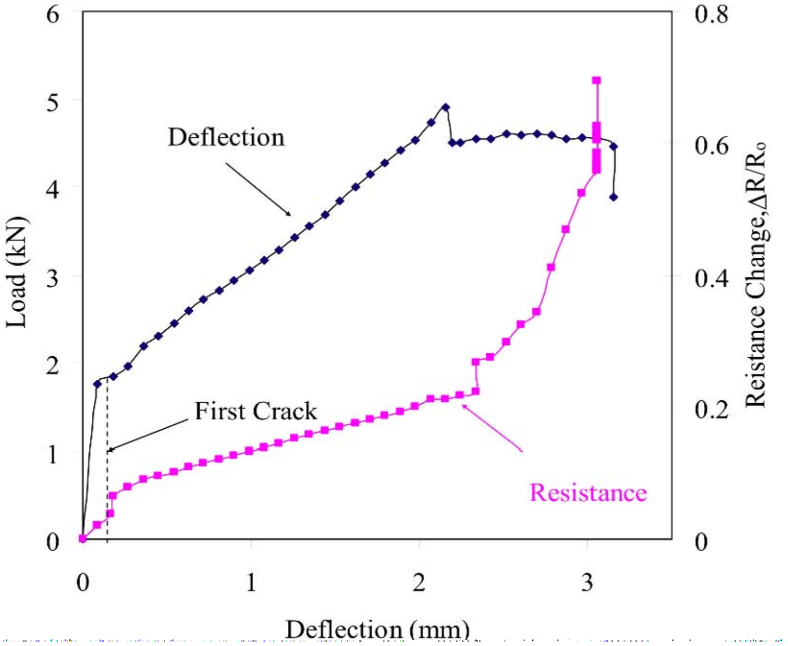

Fig. 8. Typical wireless response of cement-CNT sensors embedded into concrete beams and subjected to monotonic loading.

6. Conclusions

In this paper, wireless and embedded nanotechnology-based sensors for structural integrity of concrete members are presented. Cement-CNT sensors for crack detection in concrete structures were designed, fabricated and evaluated through a demonstration research program. Before embedment, the signal of the sensors was evaluated then similar sensors were embedded into concrete specimens to analyze the effect of cracking on their wireless response. The proposed cement-CNT sensors were interfaced to a low-cost and small wireless communication system. The wireless system uses inductive links to power and interrogate the sensors. Electrical resistance measurements showed that a percolation threshold of 0.5 % could be attributed to the sensors. The electrical resistance decreased as the volume of SNWT increased from 0 to 1 %. Slight decrease was observed when the volume of SNWT is increased beyond 1 %. Based on the direct tensile test results, the response of cement-CNT sensors is composed of a linear and non-linear region. This behavior is due to the current tunneling process in the cement matrix. Sudden increases were observed in the effective resistance of the sensors due to microcracks in the matrix, which caused the percolation branches to cut-off. In addition, the experimental results showed that the cement-CNT sensors exhibited good sensitivity, excellent repeatability and low hysteresis. The sudden change in the effective resistance is indicative of crack initiation in the host structure. Cement-CNT sensors with a SWNT volume of 0.5 % exhibited a low sensitivity to the applied stress as compared to those with a SWNT volume of 1 %. The sensors were not able to detect crack propagation. The cement-CNT sensors were successfully embedded into concrete beams and their wireless response described well the behavior of the concrete beams in terms of crack propagation where the latter greatly affected the effective resistance. Crack initiation resulted in a sudden increase in the effective resistance. Therefore, by monitoring the sudden change in the effective resistance, crack initiation can be detected. The research findings presented in this paper proved the concept of using wireless and embedded nanotechnology based sensors for integrity monitoring of concrete structures. However, more research is needed to fully understand the behavior of the cement-CNT sensors. It is important to determine the maximum thickness of the cement matrix connecting carbon nanotubes through which the current flow takes place. Moreover, the effect of light, temperature and moisture on the cement-CNT sensor response needs to be investigated. The author is currently addressing these issues through an extensive research program.

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