Strain Measurement in a Reinforced Concrete Beam Using Embedded Smart Concrete Sensors

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Abstract. The paper is aimed at investigating the use of embedded smart concrete sensors for monitoring the strain in full-scale reinforced concrete beams. The new sensors are made of the same matrix material of the concrete elements to be monitored and can be easily embedded into structural components before casting, thus achieving a durable and distributed sensing solution for structural health monitoring purposes. The self-monitoring ability is obtained through the dispersion of nano-metric conductive carbon-based fillers which induce new piezoresistive properties. In this study, a set of smart concrete sensors was embedded on top of a simply supported reinforced concrete beam and the dynamic performance of the element was evaluated, by measuring the variation in electrical resistance of the smart concrete sensors and benchmarked against measurements carried out with traditional strain gauges. The results of such comparisons demonstrate that the new sensors are apt for strain monitoring in RC structural components.

Keywords: Reinforced concrete beams · Smart concrete ·
Structural health monitoring · Strain measurement · Modal identification

1 Introduction

Novel nano- and micro-cementitious materials appear promising in the literature scenario of innovative research programs due to their interesting properties suitable for several applications (Modal et al. 2008; Pisello et al. 2017). In the field of civil engineering several studies concern the enhanced mechanical capabilities they exhibit (Li et al. 2003; Metaxa et al. 2009). Further innovative researches investigate multi-functional applications. Among them, the self-sensing ability appears promising. Such a property allows the development of a self-monitoring system for concrete structures. Indeed, the concrete elements could become strain sensors if doped with piezoresistive particles or instruments with smart cementitious embedded sensors. Such sensors are made with the same matrix material of the structures they are embedded in, thus achieving a durable and distributed sensing solution for structural health monitoring purposes (Coppola et al. 2011; Han et al. 2007). The self-monitoring capability is achieved through the introduction of conductive piezoresistive micro- or nanoparticles into the structural material. The variation of the strain is detected through the

observation of electrical resistance variation between two embedded electrodes subjected to a stabilized constant tension. The dielectric nature of the matrix material determines a drift of the electrical signal in unloaded conditions, called polarization effect, which can however be reduced through a preliminary application of a constant tension (Cao and Chung 2004). A growing interest in smart cementitious materials has been reported throughout scientific literature (Rainieri et al. 2013; Han et al. 2011; Azhari and Banthia 2012; Camacho-Ballesta et al. 2016) above all about the characterization of their peculiar properties. However few works concerning structural elements made by using these materials are available. The Authors started a research about cementitious materials doped with carbon-based nanometric fillers investigating, in the first step of the work, the self-sensing capabilities of the materials and analyzing the issues related to the fabrication of sensors with suitable characteristics of homogeneity, repeatability and scalability (Materazzi et al. 2013; Ubertini et al. 2016; Downey et al. 2017). After the analysis of the results of the first tests, the Authors investigated the application of the smart sensors with better performances to structural concrete elements (D'Alessandro et al. 2017). The present paper describes the setup and the results of a experimental campaign carried out on a reinforced concrete beam with seven embedded cementitious smart sensors doped with carbon nanotubes (CNTs). With respect to their previous works, the Authors extended the investigation to all the manufactured sensors and to all the embedded sensors, comparing the vibration results to those obtained from different identification approaches. Section 2 reports the characteristics of the materials used for the fabrication of the self-sensing materials, and the description of the experimental setups of the tests. Section 3 describes the electrical and electromechanical tests, while Sect. 4 reports the results. Section 5 comments the experimental campaign and concludes the paper.

2 Materials and Experimental Methods

2.1 Fillers

The fillers used as doping for the cementitious matrix of the sensors were Arkema carbon nanotubes (CNTs). Their carbon content is more than 90% and their apparent density is between 50 and 150 kg/m^3. They are multi-walled with a mean diameter of 5–10 nm and length of 200–500 μm. Their peculiar aspect ratio makes them particularly suitable for electrical applications. Figure 1(a) shows that they appear as a black powder, while Fig. 1(b) is a micrograph of an aqueous suspension of CNTs obtained using a Scanning Electron Microscope (SEM) with a magnification of 100 kX. In the SEM picture the dimensional characteristics of the CNTs are clearly visible. The nanometric dimensions of the fillers and the Van der Waals forces which exist among the nanotubes determine the agglomeration of the particles in normal conditions: an optimized dispersion procedure was developed to achieve a material more homogeneous and isotropic.
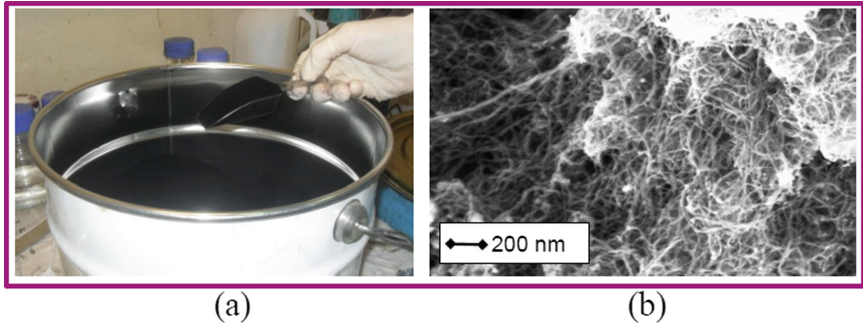
Fig. 1. (a) Appearance of carbon nanotubes; (b) Microscope enlargement of a sample of carbon nanotubes.

2.2   Cement-Matrix Sensors with CNTs

Table 1 shows the components of the cement-based materials doped with CNTs used to prepare the smart sensors. The water/cement ratio was 0.45. The cement was 42.5 pozzolanic. The amount of the CNTs was the 1% of the weight of the cement. The same quantity of a Lignosulfonic acid sodium salt was introduced in the mix design to improve the filler dispersion. Also a 0.5% of plasticizer based on polycarboxylate ether polymers was added to the dough in order to obtain a satisfactory workability.

Table 1. Mix design of cementitious material with carbon nanotubes.

Components (kg/m^3)	Cement-based sensors
Cement	1277
Water	575
CNTs	12.8
Dispersant	12.8
Plasticizer	6.3
w/c ratio	0.45

Figure 2 shows the preparation process of the sensors and of the RC beam. First, the sensors were formed and cured and then they were embedded on the top surface of a RC beam during its molding.

The CNTs were dispersed into the water through the addition of a dispersant and the sonication of the suspension for 30 min (Fig. 2(a)–(b)).

Then the dispersed aqueous suspension, the cement and the plasticized were manually mixed (Fig. 2(c)).

Successively, the dough was poured into oiled molds and four stainless steel nets were embedded symmetrically on the top surface of the samples. The inner nets were placed at a distance of 2 cm, while the outer ones at a mutual distance of 4 cm. The nets consisted of wires with a nominal diameter of 1 mm and placed at a mutual distance of 0.6 mm. Twelve cubes with sides of 51 mm were fabricated.
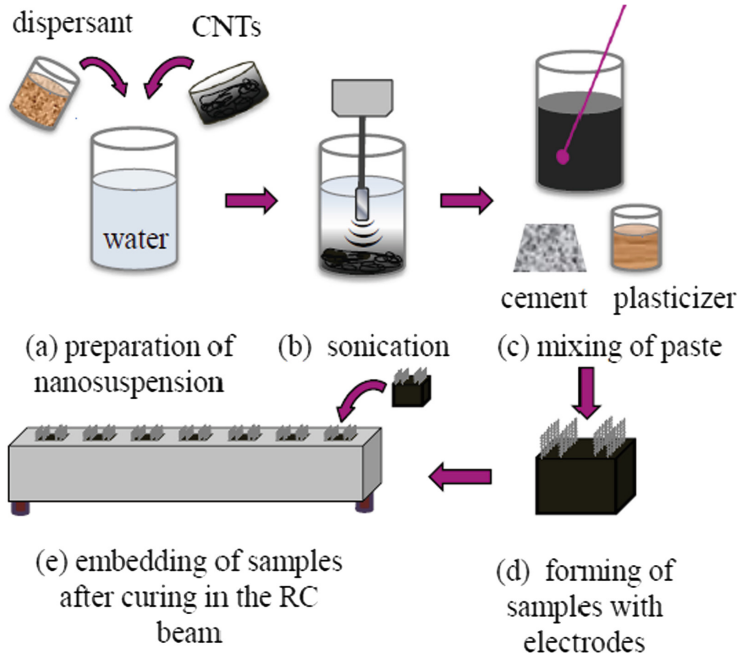
Fig. 2. Preparation process of a reinforced concrete beam with embedded cementitious sensors

The samples were unmolded after 48 h and cured in laboratory conditions for 28 days (Fig. 2(d)). After curing, the samples were instrumented with two strain gauges 2 cm long with a Gauge Factor of 2.1, placed on opposite lateral sides. Then the single sensors were investigated through electrical and electromechanical tests.

2.3 Reinforced Concrete Beam Preparation with Embedded Cementitious Sensors

After the analysis of the electrical characteristics of the samples, seven of them were embedded (instrumented with the strain gauges) on the top surface of a RC beam, during the concrete casting, at a mutual distance of 25 cm. Figure 3 shows the dimensions of the RC beam and the deployment of the cementitious sensors. The beam was manufactured using ordinary concrete with Portland cement and a characteristic strength of 30 MPa. The beam had a square section with sides of 25 cm and length of 220 cm. It was simply supported through two steel plates embedded on the bottom part of the beam, at a distance of 200 cm. The longitudinal reinforcement consisted of 6 steel rebars with a diameter of 8 mm (2 upper and 4 lower) and steel stirrups with diameter of 8 mm placed - in the central part of the beam - at a mutual distance of 160 mm, reduced to 100 mm near the supports. Figure 4 describes the geometry of the cementitious sensors (Fig. 4(a)), their application on the upper surface of the RC beam (Fig. 4(b)) and the appearance of the RC beam with embedded cementitious sensors after curing.
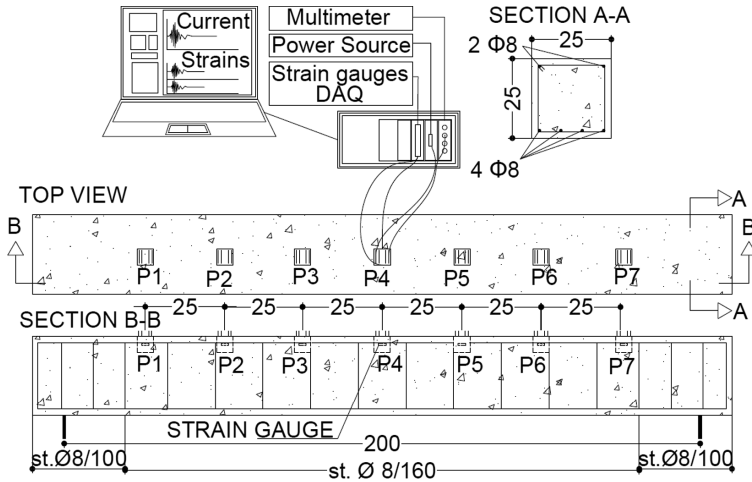
Fig. 3. Experimental setup of the reinforced beam instrumented with embedded sensors (measures in cm).

2.4   Experimental Setup

For the electrical, electromechanical and vibration tests, a stabilized tension was applied to the internal electrodes, placed at a mutual distance of 20 mm, through a PXIe-1073 chassis device with the module 4130. The electrical measurements were carried out using another PXI module, n. 4071. The electrical output of the traditional strain gauges was recorded through PXI device, too. The electrical current of each sensor was measured after 6000 s of application of a tension of 5 V, in order to reduce the polarization effect. The electrical resistance was evaluated through the relation expressed in (1).

$$R(t)\big|_{t=tp} = \frac{V}{I(t)\big|_{t=tp}} \tag{1}$$

where V and $I(t)$ are the applied constant voltage and the measured variation of current intensity over time, respectively, and tp is the polarization time.

The electromechanical tests were carried out using a servo-controlled universal dynamic testing machine, model IPC Global UTM14P (Fig. 5). In order to investigate the sensitivity of the cementitious sensors, both cyclical and sinusoidal loads were centrally applied on the section of the samples. The first were applied with a 1 kN/s speed, up to a load of 2 kN; the second ones had increasing frequencies from 0.25 to 8.0 Hz, with loads between 0.5 and 1.5 kN.
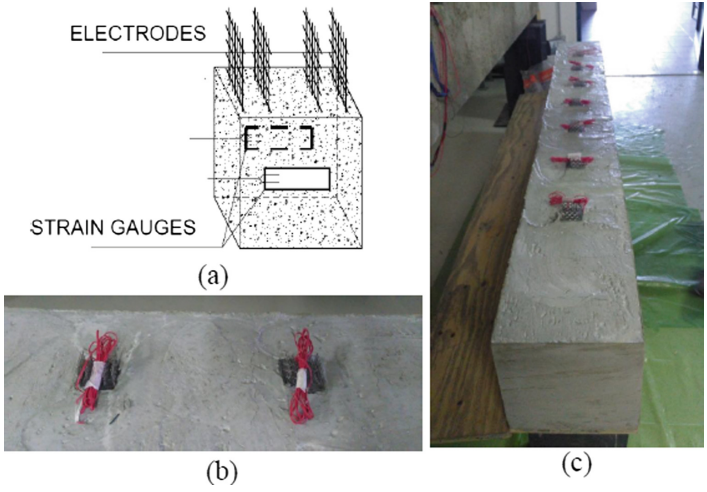
Fig. 4. (a) Sketch of an instrumented sensor; (b) Sensors embedded into the RC beam; (c) RC beam with embedded sensors, after curing.
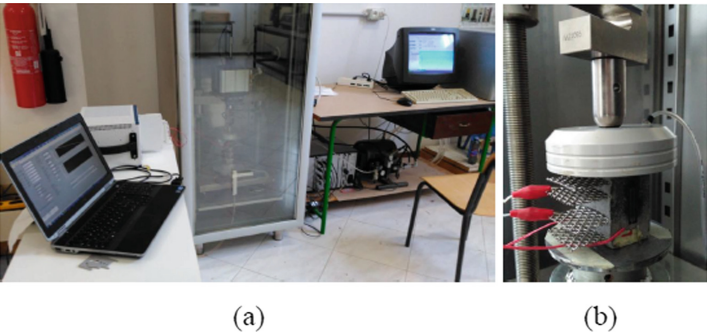

Fig. 5. (a) Experimental setup of the compressive tests on cementitious sensors; (b) detail view of a sensor.

3   Experimental Campaign

The experimental campaign consisted in electrical and electromechanical tests on single nanomodified cementitious sensors, and in vibration tests on the RC structural beam with embedded sensors.

3.1   Electrical and Electromechanical Tests on the Cementitious Sensors

Electrical tests were aimed at investigating the conductive properties of the material and the issues related to the electrical measurements. As mentioned before, DC current produced a drift of the signal. Electromechanical tests, with application of both cyclical

and dynamic loads, permitted to evaluate the sensitivity of each sensor through the achieving of their gauge factors *GF*:

$$GF = -\frac{\Delta R/R_0}{\varepsilon} \tag{2}$$

where ΔR was the incremental variation in electrical resistance, R_0 the unstrained electrical resistance, and ε the measured axial strain, (positive in compression). Figure 6 shows the two different load histories for electromechanical tests on single cementitious sensors.
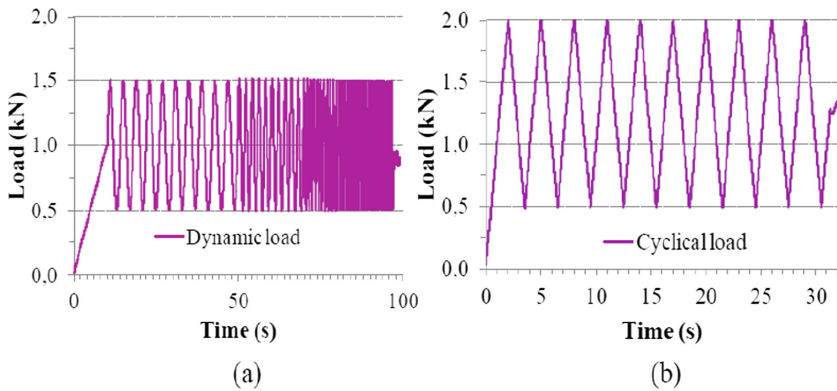

Fig. 6. (a) Cyclical and (b) dynamic loads applied on the single sensors.

3.2   Vibration Tests on the RC Beam with Embedded Cementitious Sensors

Vibration tests were performed after a polarization of thirty minutes, applying random hits in time and space with an instrumented hammer. During the tests, a voltage of 2.5 V was provided to each sensor. The current was recorded with a sampling rate of 1000 Hz. The tests investigated the performance of all the seven sensors embedded into the RC beam, of the strain gauges placed on the sensors and of the piezoelectric accelerometers applied on the extrados of the beam. The data obtained from such tests permitted to evaluate the principal modal frequencies of the structural element. The results of the smart cementitious sensors were compared to the ones obtained through traditional strain gauges, piezoelectric accelerometers and analytical calculation.

4   Results

4.1   Electrical and Electromechanical Tests on the Cementitious Sensors

Figure 7 shows the values of electrical resistance obtained through the electrical tests on the 12 samples. The mean value of such feature was 614.3 Ω while the standard
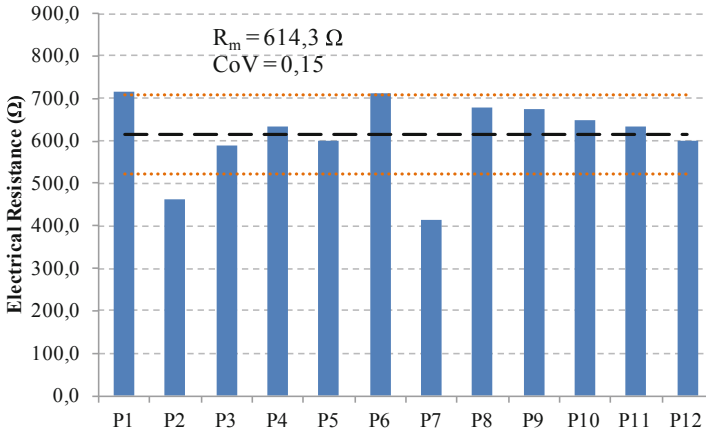
Fig. 7. (a) Variation of electrical resistance of the different cementitious samples with average value and standard deviation.

deviation was 92.7 Ω. The resulting Coefficient of Variation CoV was 0.15. The series of new cementitious sensors demonstrated a reasonable repeatability, whereby the CoV of variation was very similar to that one of concrete-like materials. Table 2 shows the values of GF of all the cementitious samples, obtained with both cyclical and dynamic tests. Their mean value, standard deviation and coefficient of variation are 18.47, 25.22, 1.37 and 25.36, 43.65, 1.72, respectively.

The results demonstrate a higher scatterin of the values of GF with respect to those of the unstrained resistance, thus demonstrating the importance of a specific calibration of the sensors before their embedding into the structural element.

4.2 Vibration Tests on the RC Beam with Embedded Cementitious Sensors

Figure 8 shows examples of time histories of strain and normalized variation of electrical resistance obtained from sensors embedded in different position of the RC beam during vibration tests. Signals have been filtered in order to eliminate the residual drift after the polarization phase. Despite signal noise due to the high sampling frequency used to acquire the data, hammer hits are clearly visible in all the considered outputs. In order to demonstrate the strain sensing capability of the embedded sensors, Fig. 9 reports the comparison between the average strain, acquired by two strain gauges placed on the lateral sides of the sample P4 and the strain computed from the filtered electrical output provided by the sensor, using Eq. (2). By overlapping the signals, a good agreement between acquired and estimated strain can be noted. The spectral analysis carried out on the outputs of the vibration tests allowed to identify the modal frequencies of the beam. Figure 10 reports the PDS of the sensors P3, P4 and P6 and of the corresponding strain gauges. The modal frequencies were compared to the results obtained through the analytical approach and from the traditional strain gauges and accelerometers. Table 3 demonstrates the good agreement of the results.

Table 2. GF of the samples obtained from the measurements during cyclical and dynamic loads.

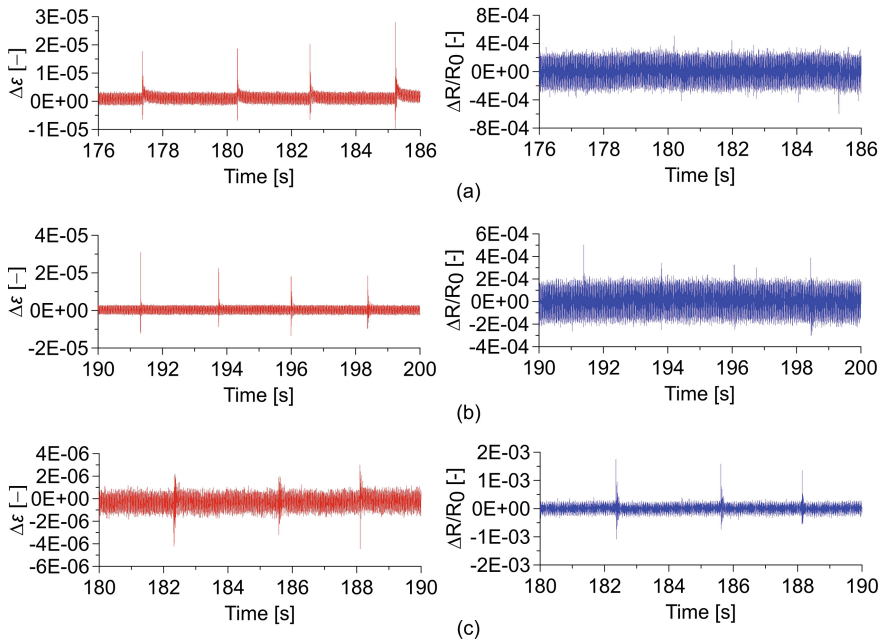| Type of sample	GF	
Cyclical test	Dynamic test	
P1	25.95	39.94
P2	1.99	3.63
P3	5.43	8.26
P4	22.56	10.73
P5	8.79	13.23
P6	28.38	32.95
P7	1.17	1.10
P8	1.78	1.54
P9	26.40	23.32
P10	1.47	2.24
P11	90.77	158.06
P12	6.94	9.31
Mean value	18.47	25.36
Standard Deviation	25.22	43.65
CoV	1.37	1.72

Fig. 8. Examples of time histories of strain and normalized variation of electrical resistance during vibration tests for (a) P3, (b) P4 and (c) P6.
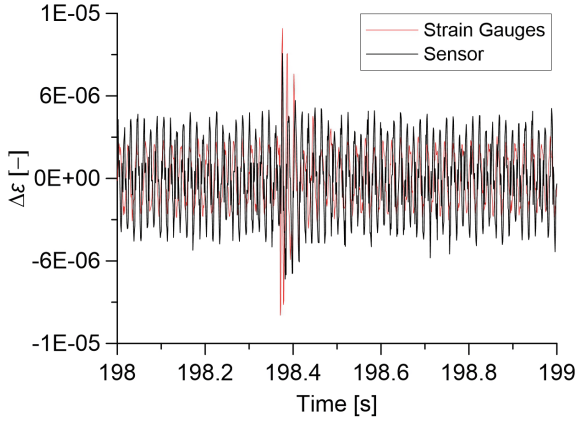
Fig. 9. Time histories of measured average strain from strain gauges and estimated strain from electrical measurements.
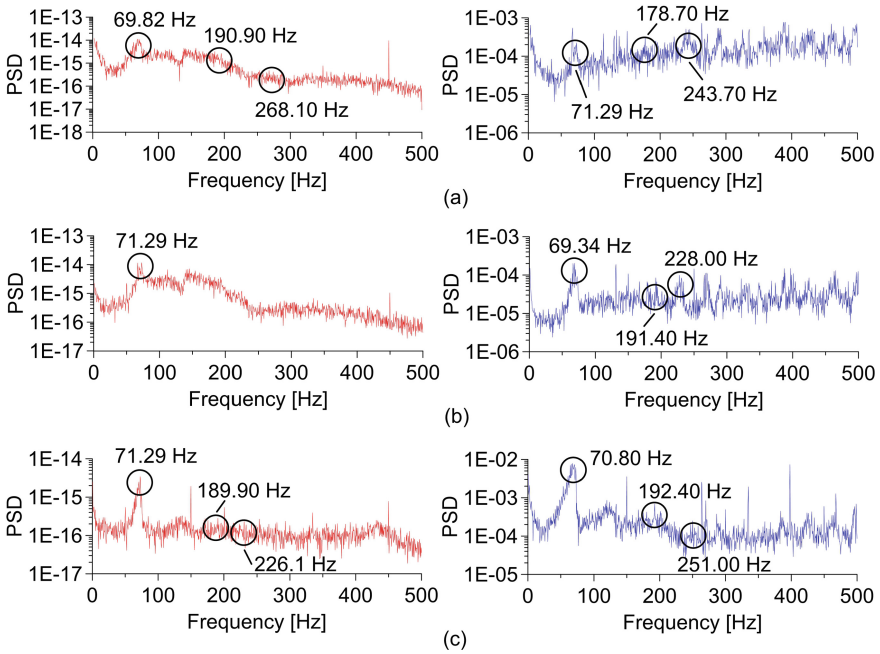

Fig. 10. PSD of strain gauges and smart sensors measurements for (a) P3, (b) P4 and (c) P6.

Table 3. Modal frequencies of the beam evaluate with different methods.

Type of modal analysis	Modal frequencies (Hz)		
	V1	V2	V3
Analytical	69.47		277.80
Smart sensors	70.80	192.40	251.00
Stain gauges	71.29	189.90	226.10
Accelerometers	80.57	186.00	265.60

5   Comments and Conclusions

This research was aimed at investigating the dynamic analysis of a RC beam through novel cement-based CNT-doped embedded sensors, in comparison to traditional ones. The electrical behavior and the sensitivity of the smart sensors were first investigated through electrical and electromechanical tests with cyclical and sinusoidal applied loads. After their characterization, the sensors were embedded at the top of a full-scale RC beam. Vibration tests on the beam showed that the novel sensors were able to identify impulsive loads and to provide dynamic strain measurements permitting the identification of the main modal frequencies of the beam. The agreement of the results with those ones obtained from traditional transducers and from the analytical approach demonstrate that the novel carbon-based cementitious sensors are promising for monitoring full-scale concrete structures through their embedding into structural elements.

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