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Novel nanocomposite technologies for dynamic monitoring of structures: a comparison between cement-based embeddable and soft elastomeric surface sensors

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Disciplines
Civil Engineering | Construction Engineering and Management | Controls and Control Theory | Electrical and Electronics | Environmental Engineering

Comments
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Novel Nanocomposite Technologies for Dynamic Monitoring of Structures: a Comparison between Cement-Based Embeddable and Soft Elastomeric Surface Sensors

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Abstract. The authors have recently developed two novel solutions for strain sensing using nanocomposite materials. While they both aim at providing cost-effective solutions at monitoring local information on large-scale structures, both technologies are different in their applications and physical principles. One sensor is made of a cementitious material, which could make it suitable for embedding within the core of concrete structures prior to casting, and is a resistor, consisting of a carbon nanotube-cement based transducer. The other sensor can be used to create an external sensing skin and is a capacitor, consisting of a flexible conducting elastomer fabricated from a nanocomposite mix, and deployable in a network setup to cover large structural surfaces. In this paper, we advance the understanding of nanocomposite sensing technologies by investigating the potential of both novel sensors at dynamic monitoring of civil structures. First, an in-depth dynamic characterization of the sensors using a uniaxial test machine is conducted. Second, their performance at dynamic monitoring of a full-scale concrete beam is assessed, and compared against off-the-shelf accelerometers. Experimental results show that both novel technologies compare well against mature sensors at vibration-based structural health monitoring, showing the promise of nanocomposite technologies at monitoring large-scale structural systems.

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1. INTRODUCTION

Structural health monitoring (SHM) of civil structures has the potential of enabling timely inspection and maintenance, resulting in enhanced structural safety and longer life span [1, 2]. However, the SHM task is complicated by the inherent size of the structures to be monitored. Most of existing sensing solutions are hardly scalable without necessitating substantial costs and complex signal processing algorithms. It results that monitoring and diagnostic solutions may rapidly become financially unattractive because of their low return on investment.

Recent advances in nanomaterials and synthetic metals have led to new possibilities in sensor developments [3, 4], including high conductive materials and flexible electronics that enable substantial improvements in the cost-effectiveness of SHM solutions for geometrically large systems. Building on these technological advances, the authors have developed two novel strain gauges, with the common objective to provide local information over global surfaces, analogous to biologic skin.

The first sensor consists of a Carbon NanoTube Cement based Sensor (CNTCS) [5]. The CNTCS is a self-sensing cement paste that can be applied over large linear segments to enable monitoring of concrete structures. The similarity between the sensor’s material and structural concrete also suggests that CNTCS could be embedded in concrete structures prior to casting. Embedded, the CNTCS would have the advantage to easily bind with the monitored structure, with the potential to transform the structures into infinite sets of potential sensors. This would enlarge the sensitive volume to its maximum extent. Cementitious materials, such as the one used for CNTCS, also have the same durability as the monitored structure, which allows long-term applications with limited maintenance issues. With the CNTCS, local strain is transduced in a change in electrical resistance.

The second sensor proposed by the authors consists of a Soft Elastomeric Capacitor (SEC) that can be deployed over large surfaces, at low cost, to enable meso-sensing [6, 7]. Arranged in a network configuration, the sensing strategy could provide discrete measurements at numerous locations. The SEC is fabricated from a poly-styrene-co-ethylene-butadiene-co-styrene (SEBS) matrix mixed with titanium dioxide (TiO₂) sandwiched between electrode plates composed of SEBS mixed with carbon black (CB). Local strain is transduced in a change in capacitance. As it will be derived in Sect. 2.2 and validated in Sect. 4.2, a particular advantage of the sensor is its bi-directional measurement capability, which provides a mean to measure dynamic responses along two major axes.

These two technologies are similar by being novel strain gauges fabricated from nanocomposite mixes, but different in their installations: the CNTCS has been designed as an embeddable cement-based sensor, and the SEC as a surface sensor.

Numerous SHM applications rely on dynamic identification from vibration measurements [8] in operational conditions with excitation typically provided by wind [9] and traffic.
Continuous applications of dynamic monitoring are becoming popular, as they enable real-time monitoring of differential structural changes and further knowledge on structural behavior [10]. Given the potential of dynamic monitoring techniques, the authors propose to advance the understanding of both novel sensing methods by comparing their performance at dynamic monitoring of civil structures. By conducting this comparison, the authors aim at demonstrating the promise of novel nanocomposite sensing technologies to address the large-scale monitoring challenge.

The paper is organized as follows. Sect. 2 presents the background theory on both sensors, including the state-of-the-art summary, fabrication process, and sensing principle. Sect. 3 describes the methodology used for the dynamic characterization of the sensors and for their performance assessment on a full-scale concrete beam. Sect. 4 shows and discusses the experimental results. Sect. 5 concludes the paper.

2. Background

2.1. Carbon Nanotube Cement-Based Sensor

The idea of fabricating self-sensing cementitious materials through the addition of suitable particles into traditional admixtures dates back to the early 90's [11]. Since then, literature comprised several studies devoted to cement-based materials mix with carbon fibers [12], nano-carbon black [13] and, more recently, carbon nanotubes [14, 15]. It was recognized that the particles modify the electrical resistivity of cementitious materials and define the strain sensing functional property due to piezoresistivity caused by the slight pull-out of fibers passing through microcracks [12]. Among the various types of nanoparticles, Carbon NanoTubes (CNTs) are especially promising because they possess excellent electrical and mechanical properties. For this reason, they are currently employed in the realization of many strain sensing composite materials (e.g. [16, 17]). However, the dispersion of CNTs into a cementitious matrix is a very delicate task because of their low solubility in water solutions [18].

Compared to other existing cement-based sensing composites, the novel CNTCS sensor has been designed and manufactured with a procedure specifically tailored for dynamic sensing of strain. This field of research is almost unexplored, as most literature works have been focused so far on the response of nanotechnology-modified cement-based materials to slowly varying strain, while their response to dynamically varying strain was rarely investigated. The CNTCS is calibrated to achieve a good sensitivity, using physical and chemical methods for dispersion of nanotubes in order to obtain a homogeneous and effective composite material. Compared with traditional strain gauges, the CNTCS is fabricated with a material similar to structural concrete, which could allow embedding within an external cover. This could transform a new or existing structure into a self-sensing system and cost-effectively enlarge the sensing surface. Also, the use of a cement paste provides a significant
enhancement in the hardware durability, providing the sensor with a life expectancy similar to the one of the monitored structure.

The fabrication process of a CNTCS is shown in Fig. 1. First, an ammonium polyacrylate-based dispersing additive (BYK 154) is added to deionized water in the amount of 1% by weight of CNTs (Fig. 1(a)). Then, Multi-Wall Carbon Nanotubes (MWCNTs) (type Arkema Graphistrength C100) are added to the solvent in the proper amount (2% by weight content of cement) (Fig. 1(b)). Dispersion of nanoparticles is the crucial step that mostly affects the final result, as the suitable electrical properties of nanomodified cement matrix are achieved only if a homogeneous CNTs network is formed in the composite material. In particular, CNTs network should be three-dimensional, free of CNTs bundles, with contacts between nanotubes. Here, dispersion is achieved by sequentially applying 10 minutes of magnetic stirring (Fig. 1(c)), 60 minutes of sonication (Fig. 1(d)) and 15 minutes of mechanical mixing (Fig. 1(e)). The power of the ultrasound of the sonicator (ultrasound probe series Vibra Cell Bioblock Scientific mod. 75043) is adjusted to 225 W and the speed of rotation of the agitator set equal to 1500 rev/min. After well dispersed, the water suspension is mixed with a plasticizer (BASF SKY 521) and with the cement powder (Fig. 1(f)). It is then poured in an oiled mold (Fig. 1(g)), and net electrodes are embedded (Fig. 1(h)). Finally, after unmoulding, curing of the sample is carried out.

Fig. 1(i) shows the picture of the final specimen of dimensions $50 \times 40 \times 50$ mm$^3$. Four bidimensional stainless steel electrodes, composed by 1 mm diameter wires deployed to form $12.5 \times 12.5$ mm nets, are embedded in approximately 3/4 of the width of the sensors. Inner electrodes are placed at a mutual distance of 20 mm, while outer two electrodes are placed at a distance of 10 mm from inner ones. Fig. 2 shows the SEM picture of the CNTs in the water suspension (a) and in the nanomodified cement paste (b), demonstrating the effectiveness of the dispersion of the nanoparticles.

Table 1 summarizes the main properties of the carbon nanotubes used in CNTCS, while the composition of the cement paste is described in Table 2. MWCNTs are used because of their higher sensitivity to stress changes with respect to single-wall nanotubes [19].
Table 1: Properties of the MWCNTs used in the experiment.

<table>
<thead>
<tr>
<th>Property</th>
<th>Description/Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Appearance</td>
<td>Black powder</td>
</tr>
<tr>
<td>Apparent density</td>
<td>$50 - 150 \text{ kg/m}^3$</td>
</tr>
<tr>
<td>Mean agglomerate size</td>
<td>$200 - 500 \mu m$</td>
</tr>
<tr>
<td>Weight loss at 105°C</td>
<td>&lt; 1%</td>
</tr>
<tr>
<td>Carbon content</td>
<td>&gt; 90% in weight</td>
</tr>
<tr>
<td>Free amorphous carbon</td>
<td>Undetectable(SEM)</td>
</tr>
<tr>
<td>Mean number of walls</td>
<td>5 - 15</td>
</tr>
<tr>
<td>Outer mean diameter</td>
<td>10 - 15 nm</td>
</tr>
<tr>
<td>Length</td>
<td>0.1 - 10 \mu m</td>
</tr>
</tbody>
</table>

Table 2: Cement paste mix design.

<table>
<thead>
<tr>
<th>Components</th>
<th>Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>MWCNTs</td>
<td>324 kg/m$^3$</td>
</tr>
<tr>
<td>DisperByK154</td>
<td>3.24 kg/m$^3$</td>
</tr>
<tr>
<td>Cementtype 42.5</td>
<td>16200 kg/m$^3$</td>
</tr>
<tr>
<td>Superplasticizer</td>
<td>32.4 dm$^3$/m$^3$</td>
</tr>
<tr>
<td>Water</td>
<td>6970 kg/m$^3$</td>
</tr>
<tr>
<td><strong>w/c ratio</strong></td>
<td><strong>0.43</strong></td>
</tr>
</tbody>
</table>

When the amount of nanoparticles in the composite material reaches a critical fraction and the CNTs are properly dispersed, percolation starts and the material becomes a conductor. In such condition, a compressive strain results in closer interactions between nanoparticles and in a higher electrical conductivity. Conversely, a tension strain provokes the opposite effect with a decrease in conductivity. From these observations, it is clear that the change in axial strain $\Delta \varepsilon$ is physically correlated with the change in electrical resistance $\Delta R$ between two points in the material.

A major issue affecting the relation between $\Delta R$ and $\Delta \varepsilon$ is that cement paste possesses dielectric properties and consequently exhibits electrical polarization effects. This occurs when a dielectric is subjected to an electrical field. The applied electrical field polarizes the material by orienting the dipole moments of molecules that have random orientations under normal conditions. The result of polarization is an electrical field in the direction opposite to the applied electrical field due to the formation of the dipoles. The main consequence of the dielectric properties of the material is that the sensor does not behave as a simple resistor but rather as resistor and a capacitor in parallel, with some parasitic resistance arising from the
contact electrodes-sensor. However, this parasitic resistance can be neglected in comparison with internal resistance.

The measurement principle of CNTCS consists of computing the change in strain by measuring the change in resistance of the sensor. Here, measurements of electrical current between CNTCS electrodes under application of a stabilized voltage difference are taken and electrical resistance is measured by dividing applied voltage by electrical current.

Measured electrical current of CNTCS and, consequently, measured electrical resistance vary with strain and polarization. In particular, in unstrained conditions, the measured electrical resistance asymptotically reaches over time the internal electrical resistance. This slow variation of electrical resistance due to polarization is superimposed to faster variations when strain occurs. At a first level of approximation, the former effect can be eliminated through a high-pass filter and the correlation between measured resistance and strain can be modeled by means of the same formula used for conventional strain gauges:

$$\frac{\Delta R}{R_0} = \lambda_{\text{CNTCS}} \Delta \varepsilon$$  \hspace{1cm} (1)

where $\lambda_{\text{CNTCS}}$ is the gauge factor of the CNTCS and $R_0$ is the value of the unstrained internal electrical resistance of the sensor. Because of the peculiar electromechanical behavior of the sensors, $\lambda_{\text{CNTCS}}$ is rate dependent and also varies with $\varepsilon$, resulting in a nonlinear relationship of strain-to-signal. In this paper the variational strain is obtained by assuming linearity of Eq. (1).
Figure 1: Fabrication process of a CNTCS.

Figure 2: SEM pictures of the CNTCS: (a) water suspension with CNTs; and (b) hardened composite cement paste.

2.2. Soft Elastomeric Capacitor

Flexible sensors have been previously proposed for SHM applications [20, 21, 22, 23, 24, 25]. Popular applications include the addition of CNTs within the polymer matrix to create resistance-based strain sensors [26, 27, 28]. Capacitance-based strain sensors have also been proposed, with applications to strain [29, 30], pressure [31], tri-axial force [32],

7
and humidity [33, 34] measurements. The SEC developed by the authors differs from literature by combining both a large physical size and relatively high initial capacitance, resulting in a larger surface coverage and higher sensitivity. A network of SECs offers the combined advantages of being cost-effective, operable at low frequencies, mechanically and environmentally robust, low-powered, easy to install onto surfaces, and customizable in shapes and sizes. The proof-of-concept of the SEC technology has been demonstrated by the authors with an off-the-shelf flexible capacitor [35], and with the nanoparticle mix used in this paper [6].

The fabrication process of an SEC is shown in Fig. 3. First, the SEBS (Mediprene Dryflex) matrix is dissolved in toluene (Fig. 3(a)). The solution is doped with TiO$_2$ rutile (Sachtleben R 320 D) by dispersing a 15% vol. concentration using an ultrasonic tip (Fisher Scientific D100 Sonic Dismembrator) (Fig. 3(b)). The addition of these inorganic particles into the SEBS matrix increases the permittivity and durability of the polymer [36]. The SEBS-TiO$_2$ mix is drop casted on an 80 $\times$ 80 mm$^2$ glass slides and dries for 48 hours to let the toluene evaporate (Fig. 3(c)). During this drying phase, a 10% vol. concentration of CB (Printex XE 2-B) is added to another SEBS-toluene mix. The CB particles are dispersed in a sonic bath for 24 hours (Fig. 3(d)). The conductive mix is painted onto the top and bottom surfaces of the dried dielectric (SEBS-TiO$_2$) to create the electrodes, and let drying for 48 hours to let the toluene evaporate. Two conductive copper tapes are embedded in the electrode mix to allow a mechanical connection to the sensor. Fig. 3(f) is a picture of the resulting SEC. Fig. 4 is a SEM picture of the resulting SEC showing a good dispersion of the TiO$_2$ particles.

Figure 3: Fabrication process of an SEC.
The capacitance $C$ of an SEC can be approximated by

$$C = \varepsilon_0 \varepsilon_r \frac{A}{h} \quad (2)$$

where $\varepsilon_0 = 8.854 \, \text{pF/m}$ is the vacuum permittivity, $\varepsilon_r$ the dimensionless polymer relative permittivity, $A = w \cdot l$ the sensor area with width $w$ and length $l$, and $h$ the height of the dielectric. The relative permittivity is assumed to be constant at low frequencies ($< 100$ Hz). A small change in $C$ can be obtained from Eq. (2) by expressing the differential $\Delta C$ as

$$\Delta C = \left( \frac{\Delta l}{l} + \frac{\Delta w}{w} - \frac{\Delta h}{h} \right) C \quad (3)$$

Specializing Eq. (3) for unidirectional strain ($\Delta w = 0$), and assuming that the polymer is incompressible (the Poisson ratio of pure SEBS materials $\approx 0.49$ [37], resulting in a change in volume $\Delta V \approx 0$), the following geometric property can be derived between $\Delta l$ and $\Delta h$:

$$V_0 = V_0 + \Delta V$$
$$w \cdot l \cdot h = (l + \Delta l)(h + \Delta h)w$$
$$\frac{\Delta l}{l} \approx -\frac{\Delta h}{h} \quad (4)$$

where $V_0 = w \cdot l \cdot h$ represents the nominal volume. It follows from Eqs. (2) to (4) that

$$\frac{\Delta C}{\Delta \varepsilon} = 2C \quad (5)$$

Eq. (5) represents the sensitivity of the sensor, from which a gauge factor of $\lambda_{\text{SEC}} = 2$ can be obtained. While the gauge factor is not in function of the level of dopant, the addition
of TiO₂ can result in a significant change in sensitivity. Also, the sensor sensitivity can be customized by altering the sensor geometry. For the SEC shown in Fig. 3(f) (\( C \approx 700 \text{ pf}, \ w = b = 70 \text{ mm}, \ h = 0.45 \text{ mm} \)), the resulting sensitivity is \( \Delta C/\Delta l \approx 20 \text{ pF/mm} \), but may vary by \( \pm 20\% \) due to the manual fabrication process.

The measurement principle of an SEC is shown in Fig. 5. The sensor is adhered onto the monitored surface with an epoxy. A strain in the monitored surface \( \Delta l/l \) is transduced as a change in the SEC geometry, which can be read as a change in capacitance \( \Delta C/C \) by the Data Acquisition (DAQ) system.

3. Methodology used for the comparison

3.1. Dynamic Characterization

Prior to conducting the experimental tests on the large-scale concrete beam specimen, the dynamic response of both sensors is studied in a controlled laboratory setup. To provide an accurate comparison, an SEC of dimensions \( 40 \times 40 \times 0.45 \text{ mm}^3 \) is adhered directly onto the surface of the CNCTS of dimensions \( 50 \times 40 \times 50 \text{ mm}^3 \). Fig. 6(b) is a picture of the CNCTS specimen and Fig. 6(c) shows the SEC adhered onto the surface of the same CNCTS specimen. The testing equipment consists of a servo-controlled pneumatic universal testing machine (IPC Global UTM-14P) with 14 kN load capacity, equipped with an environmental chamber to control for a constant temperature. The sensing specimen is precompressed at 1 kN, and subjected to a harmonic load with frequency increasing in discrete steps from 0.25 to 15 Hz. The upper bound of this investigated frequency range is dictated by the technical characteristics of the testing machine capabilities. Nevertheless, the experiment covers a range in which natural frequencies of civil structures typically lie. Considering the values of the applied axial load, during the experiment the CNCTS-SEC specimen remains in the linear elastic range of deformation.

The output from the CNCTS is measured using a high speed digital multimeter, model National Instruments (NI) PXI-1071, installed into a NI PXIe-1073 (Fig. 6(e)). This last also
Figure 6: Test setup for the dynamic validation: (a) uniaxial test machine with CNTCS-SEC specimen; (b) detail view of tested CNTCS; (c) detail view of SEC adhered onto the surface of the CNTCS; (d) detail view of the DAQ system for SEC; and (e) detail view of DAQ system for CNTCS.

hosts a source measure unit, model NI PXI-1130, providing stabilized potential difference to the CNTCS in a single isolated channel. The measurement is done by providing a voltage input of 2 V and measuring current intensity outputted by the CNTCS through the multimeter at a sampling rate of 1000 Hz. The capacitance from the SEC is measured at 390 Hz using an ACAM PCAP01 data acquisition system (Fig. 6(d)). For the dynamic characterization, data are unfiltered in frequency, time drift in the output of the CNTCS is corrected through subtraction of an interpolating polynomial of order 10 and that in SEC’s output through a linear detrend. Fig. 6(a) shows the CNTCS-SEC specimen installed in the testing machine.

3.2. Experiment on Full-Scale Concrete Beam

The capacity of the sensors at detecting natural frequencies is studied on a reinforced concrete beam which first natural frequencies in both the vertical and lateral axes lie below 40 Hz. This test also provides an extension on the frequency range investigated in the previous
experiment. The RC beam has dimensions of $200 \times 300 \times 4000 \text{ mm}^3$, and is equipped with two steel plates partially embedded at its extremities prior to casting serving as vertical supports. The plates are inserted into steel supports to allow end rotations in the vertical plane while fixing rotations in the horizontal plane. Assuming a material density of $2500 \text{ kg/m}^3$ and a Young modulus equal to $30000 \text{ N/mm}^2$ results in analytical fundamental frequencies of $25.2 \text{ Hz}$ along the strong bending axis with simply supported boundary conditions and $38.1 \text{ Hz}$ along the weak axis with fixed boundary conditions. Vertical and horizontal vibration modes of the beam are benchmarked against results obtained using seven equally spaced seismic accelerometers that can be mounted in either vertical or in horizontal directions. The accelerometers (PCB393C - 1 V/g sensitivity with $\pm 2.5 \text{ g}$ measurement range) are attached through permanent magnets onto $40 \times 40 \times 8 \text{ mm}^3$ steel plates that are glued onto the beam. The accelerometers are wired to the central unit by means of short coaxial cables.

The beam is excited with an impulse hammer (PCB 086D20C41) equipped with force sensor (ICP quartz $0.23 \text{ mV/N}$ sensitivity and $\pm 22240 \text{ N}$ measurement range). The outputs of accelerometers and the hammer are acquired through an 8 channels data acquisition module, model PXIe-1492 (24-bit resolution with anti aliasing filters), also installed in the PXIe-1073 hosting the power and DAQ modules of the CNTCS. All data are acquired over 420 sec. Data sampling rates and sampling duration are beyond the Nyquist sampling rate and significantly larger than the first structural periods, respectively, which allows an accurate frequency identification.

The output of the CNTCS is sampled at 1000 Hz, and a high-pass filter with a cut-off frequency of 7.5 Hz is applied, to eliminate the polarization effects (see Section 2.1). The output of the SEC is sampled at 440 Hz and a similar filter is used with a cut-off frequency of 2 Hz. Given the high noise level in the DAQ system allocated to the SEC, other filtering methods could be used for better frequency localization, as shown in Ref. [38]. The authors have preferred to use the simple high-pass filter to enable a cleaner comparison.

The CNTCS is attached onto the top surface of the RC beam by means of two L-shaped steel elements, each one connected to the RC beam by means of four plugs. These connections are placed at quarter-span of the beam. A screw permits to apply an initial prestress to the CNTCS that is manually adjusted and controlled through a load cell with a digital display. This initial pressure used herein is to simulate an embedment of the CNTCS while providing a practical mean to access the sensor’s electrodes at any time for experimental purposes. Electrical isolation of the CNTCS from the RC beam connection devices is achieved using plastic sheets. A SEC of dimensions $70 \times 70 \times 0.45 \text{ mm}^3$ is glued onto the top surface of the RC beam at the same location of the CNTCS.

Fig. 7 shows the laboratory setup for the full-scale RC beam.
4. Experimental Results

4.1. Dynamic Characterization

The experimental study is initiated with the dynamic characterization of both sensors. Both specimens are subjected to a harmonic load varying between 0.25 to 15 Hz with discrete increments. Fig. 8 shows the sensors responses over the range 0.25-1 Hz. Both sensors exhibit a drift in the time domain that can be due to electrical charges in the sensor (see Section 2.1). Fig. 9 is a plot of the variation in the sensors signals in function of strain, where strain is normalized by its maximum value $\Delta e_{\text{max}}$, and the sensors outputs are normalized by their maxima $\Delta R_{\text{max}}$ and $\Delta C_{\text{max}}$ for the CNTCS and SEC, respectively. Data from Fig. 9 are taken from the range 0.25 to 0.5 Hz with a load amplitude from 0.5 to 1.5 kN. Results confirm the nonlinearity of Eq. (1), with increasing sensor’s sensitivity in compression, and the linearity of the SEC strain-signal model (Eq. (5)).
Figure 8: Sensors responses: (a) applied load; (b) CNTCS; and (c) SEC.

Figure 9: Normalized sensors’ signal variations versus normalized strain: (a) CNTCS; and (b) SEC.
Fig. 10 compares the frequency response function (FRF) of both sensors over the full range 0.25-15 Hz. The FRF plots were obtained by taking the ratio of the response over the excitation input in the frequency domain. FRF are normalized to the values obtained at the higher frequency of investigation, equal to 15 Hz. The monotonically increasing frequency response of the CNTCS shows that the sensor tends to an ideally linear behavior at higher frequencies. This is explained by the strain-rate dependency of the fractional change in resistance observed in cement-based nanocomposites [15]. The monotonically decreasing frequency response of the SEC is explained by the strain-rate dependency of the SEBS [39], as well as an adiabatic heating effect that causes a softening of the bonds [40]. This frequency dependence for both sensors represents a limitation in the sensing solutions, which can be overcome by the incorporation of a strain-rate dependent model in the electromechanical models. Nevertheless, this limitation is inconsequential in modal identification applications.

Figure 10: Normalized frequency response functions: (a) CNTCS; and (b) SEC.

Figs. 11 and 12 show the wavelet transforms for each of the sensors. The wavelet transform uses morlet wavelets on three sections of the original signal extracted using a Tukey windowing function to reduce frequency leakage. The wavelet coefficients are normalized over each time bin. The black dotted line in Figs. 11 and 12 represents the frequency input, ramping from 0.25 to 15 Hz.

Results from the wavelet transform show that both sensors can track the excitation frequency of the 0.25-15 Hz range. However, the SEC has significantly more noise than the CNTCS. This additional noise is due to limitations in the DAQ system. While the CNTCS uses a mature technology to measure resistance, the off-the-shelf DAQ system used to measure capacitance is yet to reach a similar level of precision. An electronic circuitry
Figure 11: Wavelet transform for the CNTCS signal: (a) 0.25-1 Hz; (b) 5-11 Hz; and (c) 12-15 Hz. The black dotted line is the frequency excitation.

Figure 12: Wavelet transform for the SEC signal: (a) 0.25-4 Hz; (b) 5-11 Hz; and (c) 12-15 Hz. The black dotted line is the frequency excitation.

dedicated at measuring very small changes in capacitance is currently being developed by the authors.

4.2. Experiment on Full-Scale Concrete Beam

Both sensing methods are compared for dynamic monitoring of a full-scale RC beam. Modal information is extracted by means of the classic Frequency Domain Decomposition (FDD) method. FDD is based on the evaluation of the matrix of cross-spectral densities of the output data $G(f)$, where $f$ denotes the frequency. The diagonal terms in $G(f)$ are the (real valued) auto-spectral densities, while the other terms are the (complex) cross-spectral densities. The matrix is computed by using the modified periodogram method that consists of averaging the spectra by subdividing the recorded signals into windows and overlapping frames containing $2^n$ points. The frequency resolution is thus equal to $f_s/2^n+1$, $f_s$ being the sampling frequency. To extract modal parameters estimates, the matrix $G(f)$ is decomposed through singular value decomposition at discrete frequencies. Under the hypothesis that the
input is a white noise and that damping is low, natural frequencies are identified as those that correspond to the peaks of the curves representing the singular values of $G(f)$. Mode shapes are approximated by taking the corresponding singular vectors.

Simultaneous testing of the SEC and accelerometers, as well as simultaneous testing of CNTCS and accelerometers were carried out at the beginning of June and at the beginning of July 2013, respectively. Results from the FDD applied to acceleration signals (first singular value lines of the spectral matrices of the measurements) are shown in Fig. 13. Four natural modes of vibration are identified in the range between 0 and 40 Hz. These modes include the fundamental vertical mode, denoted as mode V1 at 26.0 Hz, and the fundamental lateral mode, denoted as mode L1, at 32.7 Hz. Variation of the frequency of mode V1 from 27.1 Hz to 25.6 was observed over one month, which can be explained by an increase in temperature in the laboratory. The identified natural frequencies of modes V1 and L1 well agree with analytical predictions. Also, their estimated mode shapes, plotted in Fig. 13, resemble the analytical modes for simply supported (V1) and fixed-fixed (L1) elastic beams. In addition to these two expected modes, two more lateral modes are identified at 5.1 Hz and 19.8 Hz and are denoted as mode LS1 and LS2, respectively. By comparing their shapes, it can be concluded that these modes are originated by the rolling motions of the supports over the base. In mode LS1, the supports move in phase. In mode LS2, the supports move out of phase. These motions could be also visually observable during testing on site.

In Fig. 13, the Power Spectral Densities (PSDs) of the data recorded from CNTCS and SEC are shown and compared against the results obtained from acceleration data acquired simultaneously. These results show that the leading peak, corresponding to mode V1, is quite evident and precisely identified in both output spectra of CNTCS and SEC. Some peaks related to lateral modes are also visible in both of the sensors output spectra, which is explained by their multi-directional sensing capabilities. The peak of mode LS1 is quite evident in the case of SEC, and mode LS2 appears to be identified, but with a shift in the frequency. In the case of CNTCS, while the peak of mode LS1 is not visible, probably because it is hidden by the energy of the signal at low frequencies associated with electrical polarization of the sensor, a second peak is visible which seems to be associated with mode L1, but also with a shift in the frequency. The PSD of the SEC shows additional peaks around 10 Hz and 16 Hz, which can be associated to a local damage, as smaller peaks are observable in the accelerometers data.

5. Conclusion

Two novel solutions for strain sensing using nanocomposite materials recently proposed by the authors have been further studied by investigating their potential at dynamic monitoring of civil structures. Both technologies are aimed at providing affordable solutions for monitoring local strain in large-scale structures, but are different in terms of applications and
Figure 13: FDD results: (a) PSD of CNTCS’s output; (b) first SV line of vertical acceleration data acquired simultaneously to CNTCS’s output; (c) first SV line of lateral acceleration data acquired simultaneously to CNTCS’s output; (d) PSD of SEC’s output; (e) first SV line of vertical acceleration data acquired simultaneously to SEC’s output; (f) first SV line of lateral acceleration data acquired simultaneously to SEC’s output; and (g) mode shapes identified from acceleration data.

physical principles. The CNTCS is embeddable in concrete structures because it is fabricated from a cement-based material and can transduce variations in axial strain in variations of electrical resistance. The SEC has been developed to be a surface sensor, and can be used in a matrix form to create an external sensing skin. It can transduce variations in axial strain in variations in electrical capacitance. The main conclusions of this study are as follow:

- Dynamic characterization of CNTCS and SEC using a uniaxial test machine has shown that both sensors are capable of closely tracking excitation frequencies in the range of 0.25 to 15 Hz.
- The normalized calibration curves of both sensors have been obtained in the uniaxial test. While the CNTCS behaves as a slightly nonlinear transducer, with a sensitivity that increases in compression, the SEC exhibits a linear signal-strain relationship that agrees well with its theoretical electromechanical model.
• Frequency response curves of CNTCS and SEC have been obtained with dynamic compression tests. The curves show that the outputs of both sensors are rate dependent. In particular, the frequency response curves of CNTCS is monotonically increasing with the frequency while that of SEC is monotonically decreasing with the frequency. Both sensors seem to tend to an ideally linear dynamic behavior, with constant frequency response curves, at large frequencies.

• The pioneering application of the two novel sensing technologies in vibration monitoring of a RC beam has demonstrated their ability to clearly detect the frequency of the fundamental vibration mode at about 26 Hz, independently identified using data recorded from off-the-shelf accelerometers. Lower lateral modes have been identified by the SEC, while a higher lateral mode has been identified by the CNTCS.

Results presented in this paper show a promise toward the use of the nanocomposite technologies in vibration-based structural health monitoring systems, providing a solution to the meso-scale challenge in SHM of civil structures, such as tall buildings, bridges, road pavements and more.

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