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Natural frequencies identification of a reinforced concrete beam using carbon nanotube cement-based sensors

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ABSTRACT

Cementitious materials doped with carbon nanoparticles are robust materials capable of transducing strain into changes in electrical resistance. These properties encourage the development of spatially distributed sensors for structural health monitoring of concrete structures. Yet, very few applications of transducers made of cement-based nanocomposites to structural elements have been documented. The majority of applications are limited to measurement of static responses.

The authors have recently proposed the novel application of cement-based nanocomposite technologies for vibration-based structural health monitoring of concrete structures. To this aim, prismatic sensors made of cement paste doped with carbon nanotubes have been proposed as embedded sensors for concrete structures. Prior results have shown the promise of these sensors at vibration measurements. In this paper, the authors further the understanding of the dynamic behavior of cement-based carbon nanotube sensors by conducting experiments on a full-scale reinforced concrete beam for output-only identification of natural frequencies. The performance of the novel sensor is benchmarked against off-the-shelf strain gauges and accelerometers. Results show that the proposed sensor compares well against existing technologies at vibration monitoring. Also, the nanocomposite sensor is capable of detecting high frequencies, which is made possible by a very low level of noise and an excellent signal-to-noise ratio obtained from shielded wire connections and proper tailoring of the fabrication process.

1. Introduction

Continuous assessment of structural health through vibration measurements has become one of the key issues of structural health monitoring (SHM). This online monitoring is typically conducted through an automated investigation of modal parameters estimates and of their temporal variations [1,2], using multivariate statistical analysis tools [3]. Recent field applications of continuous vibration-based monitoring include long-span bridges [4], footbridges [5] and historic structures [6].

It is recognized that SHM of civil structures has the potential to enable timely inspection and maintenance, consequently enhancing structural safety and structural life expectancy [7,8]. However, practical SHM applications are still limited. One factor impeding the wide applicability of SHM solutions is associated with the inherent size of the structures to be monitored. Most existing sensing solutions are hardly scalable without necessitating substantial costs and complex signal processing algorithms, making SHM financially unattractive to infrastructure owners due to their apparent low return on investment.

The rapid growth of nanotechnologies has opened new possibilities in sensor developments [9,10], including new multifunctional materials that enable substantial improvements in the cost-effectiveness of SHM solutions for geometrically large systems [11,12]. Building on these technological advances, the authors have recently developed a strain sensor fabricated from a multifunctional cement-based composite material, with the objective to provide an innovative solution to the large scale monitoring challenge of concrete structures.

The material consists of a self-sensing cement paste doped with carbon nanotubes [13]. The resulting sensor, termed carbon nanotube cement-based sensor (CNTCS), transduces local strain into a change in electrical resistance. CNTCSs can be applied over large linear segments or embedded prior to casting to enable monitoring of concrete structures. When embedded, CNTCS forms a mechanically strong bond with the monitored structure, and creates a continuously distributed set of strain sensors within the structure. CNTCS also have a durability similar to the structure, which allows long-term applications with limited maintenance.

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In a prior work [13], the authors investigated the electrical response of CNTCS when subjected to sinusoidal compression loads at various frequencies. Although only a limited frequency range was investigated (up to 5 Hz), results suggested that CNTCSs were promising at dynamic measurements, and encouraged more extensive investigations devoted to assessing their performances at vibration-based SHM.

In this paper, the authors further the understanding of CNTCS by examining its capability to perform output-only modal identification. This verification is conducted through laboratory vibration tests on a reinforced concrete (RC) beam, where a significantly larger range of frequencies is investigated in comparison to prior work. For the first time, the performance of the CNTCS is benchmarked against mature, off-the-shelf sensors. Also, efforts are made to enhance the CNTCS signal-to-noise ratio to improve the resolution in dynamic identification. These include modifications to the fabrication process and to the data acquisition procedures.

The paper is organized as follows. Section 2 presents the background theory on CNTCS, including the state-of-the-art summary, fabrication process, and sensing principle. The sensor's improvements in comparison to prior work are discussed. Section 3 describes the methodology used for dynamic identification of a full-scale concrete beam through CNTCS. A discussion on the improvements in the data acquisition procedure is provided. Section 4 shows and discusses the experimental results. Section 5 concludes the paper.

2. Description of nanotube cement-based sensors

2.1. State-of-the-art summary

Earliest studies on self-sensing cementitious materials appeared in the 90s [14]. The physical principle of strain sensing in these materials is based on a change in their electrical resistivity. A strain in the materials provokes a change in piezoresistivity caused by the slight pull-out of the fibers passing through microcracks [15]. This occurs if the nanoparticles are properly dispersed in the matrix and their amount reaches a critical fraction termed *percolation threshold*.

Following these first publications on multifunctional cement-based composites, different dopants have been investigated, including carbon fibers [15,16], nanocarbon black [17] and, more recently, carbon nanotubes (CNTs) [18,19]. It has been shown that CNTs possess excellent electrical and mechanical properties, which are now exploited in different types of nanocomposites (e.g. [20]). While these properties make CNTs promising dopants, their dispersion within the cementitious matrix is significantly complicated by their low solubility in water solutions [21]. In particular, the development of appropriate physical and chemical procedures is necessary to produce bundle-free three-dimensional CNTs networks.

In sensing applications, the vast majority of literature has focused on the static response of nanotechnology-modified cement-based materials, while vibration-based SHM has been almost unexplored. The authors have developed the CNTCS, specifically tailored to dynamic measurements. For this purpose, the fabrication process of CTNCS has been refined to optimize the sensitivity. This refinement includes enhanced physical and chemical methods for dispersing the CNTs to obtain an homogeneous composite material. Unlike traditional strain gauges, CNTCS are fabricated with a cementitious material, which allows embeddement within an external cover of concrete structures and provides a strong mechanical bond. This results in a life expectancy of the sensing hardware similar to the one of the monitored structure, and opens the possibility to cost-effectively monitor large structural surfaces via a continuous distributed sensor network.

The following subsections describe the CNTCS physical properties, its fabrication process, and the sensing principle.

2.2. Physical properties of CNTCS

The specimens fabricated for the experimental campaign consist of square-base prisms made of nanomodified cementitious material with embedded electrodes.

The specimens dimensions are $40 \times 40 \times 160\ \mathrm{mm}^3$. The electrodes consist of copper wires of 1 mm diameter, disposed symmetrically with respect to the center of the specimens, equally spaced at a distance of 10 mm and embedded in approximately 3/4 of the width of the specimens. Eight electrodes are embedded with the purpose of allowing measurements in different configurations (e.g. two-probe, four-probe, etc.), with various distances between active electrodes.

The matrix of the CNTCS consists of a cement paste fabricated with Portland cement type 42.5 and a water/cement ratio of 0.40. This material provides a suitable homogeneity and enhances strain sensitivity in comparison to mortar or concrete. Conductive nanoparticles are dispersed in the matrix, consisting of multi walled carbon nanotubes (MWCNTs) type Graphistrength C100 from Arkema. The particular structure of MWCNTs, made of concentric cylinders of graphene sheets, makes them more sensitive than Single Walled CNTs. The physical properties of the particular MWCNTs selected in the fabrication process are reported in Table 1. The composite material mix design is summarized in Table 2, also reporting quantities used for a single specimen.

2.3. Fabrication process

The fabrication process of CNTCS is schematically described in Fig. 1. First, a Sky 521 plasticizer based on second-generation polycarboxylate ether polymers is added to deionized water at a concentration of 5% by volume of water (Fig. 1(a)). Second, MWCNTs are added to the mix in the amount of 2% by weight content of cement (Fig. 1(b)). Since nanotubes are not hydrophile, a specific sequence of mixing processes with different devices is adopted to disperse the MWCNTs within the mix before the addition of cement powder. This dispersion technique aims at preventing CNTs from agglomerating into bundles, which would result in a lack of homogeneity in the composite material, and is conducted as follows. The MWCNTs solution is first mixed with a magnetic stirrer for 10 min (Fig. 1(c)). It is followed by 15 min of sonication with a 225 W ultrasound device equipped with a probe series Vibra Cell Bioblock Scientific model 75043. (Fig. 1(d)). During sonication the beaker containing the nanomodified solution is soaked in a cool water bath, in order to limit evaporation. Lastly, the solution is mixed for 15 min with a mechanical agitator with a speed of rotation of 1500 rev/min (Fig. 1(e)). Sonication has been recognized as the key step in the manufacturing process, which mostly affects strain sensitivity of CNTCS. For this reason, the duration of the

Table 1
Physical properties of the MWCNTs used in the experiment.

Property	Description/Value
Appearance	Black powder
Apparent density	50–150 kg/m^3
Mean agglomerate size	200–500 μm
Weight loss at 105 °C	<1%
Carbon content	>90% in weight
Free amorphous carbon	Undetectable (SEM)
Mean number of walls	5–15
Outer mean diameter	10–15 nm
Length	0.1–10 μm