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Damage detection, localization and quantification in conductive smart concrete structures using a resistor mesh model

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ABSTRACT

Interest in self-sensing structural materials has grown in recent years due to their potential to enable continuous low-cost monitoring of next-generation smart-structures. The development of cement-based smart sensors appears particularly well suited for structural health monitoring due to their numerous possible field applications, ease of use, and long-term stability. Additionally, cement-based sensors offer a unique opportunity for monitoring of civil concrete structures because of their compatibility with new and existing infrastructure. In this paper, we propose the use of a computationally efficient resistor mesh model to detect, localize and quantify damage in structures constructed from conductive cement composites. The proposed approach is experimentally validated on non-reinforced and reinforced specimens made of nanocomposite cement paste doped with multi-walled carbon nanotubes under a variety of static loads and damage conditions. Results show that the proposed approach is capable of leveraging the strain-sensing and damage-sensitive properties of conductive cement composites for real-time distributed structural health monitoring of smart concrete structures, using simple and inexpensive electrical hardware and with very limited computational effort.

1. Introduction

Real-time condition assessment and structural health monitoring (SHM) of civil infrastructure can provide enhanced structural safety and increased maintenance service intervals through condition-based maintenance [1]. However, SHM is often complicated by the inherent size of the civil structures under monitoring and the inability of traditional sensors to distinguish between global (i.e. loss in stiffness) and local (e.g. a crack in grouted joint) properties [2]. For example, global vibration characteristics (e.g. modal frequencies and mode shapes) can be easily estimated from acceleration time histories through output-only operational modal analysis methods. However, correlating changes in modal parameters to localized damage cases has been shown more challenging [3,4].

For the deployment of real-time condition assessment strategies in civil infrastructure, the monitoring scheme must be capable of damage detection and localization [1]. A possible solution to the local-global damage localization challenge is the deployment of highly scalable sensing solutions to form dense sensor networks, deployed onto the structure's surface, that are capable of discretely monitoring local changes in a structure over its global area [5]. Various researchers have proposed dense sensor networks, often termed sensing skins, as a solution to the local-global challenge. Yao et al. [6] proposed large sensing sheets of resistive strain gauges (RSG) with embedded processors on a 50 µm thick polyimide sheet for crack detection and localization on civil infrastructure. Loh et al. [7] introduced a layer-by-layer assembled carbon nanotube nanocomposite sensing skin that, when combined with the electrical impedance tomography mapping technique, enabled two-dimensional damage detection. Hallaji et al. [8] developed a large-area sensing skin for damage detection in concrete structures, consisting of electrically conductive copper paint that is

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applied to the surface of the concrete. Cracks in the underlying concrete resulted in a dislocation of the sensing skin, and, therefore, in a change in skin conductivity. Electrical impedance tomography was then used to detect and localize damage in the substrate. Downey et al. [9] proposed the use of a hybrid dense sensor network consisting of large-area strain-sensing capacitive-based sensors and RSGs for the low-cost monitoring of large structures. The various dense sensor networks presented here, while promising, lack the capability to directly detect a structure's internal damage. The problem of detecting internal damage is of great importance as, for instance, load bearing walls are often made of thick slabs of steel reinforced concrete composites and internal damage may not be evident on the surface. Other notable examples demonstrating the importance of detecting internal damage include the reinforced concrete beam-column joints that can undergo shear failure under seismic loading and grout failure in mechanically spliced column-footing connections [10].

A solution to the challenge of internal monitoring of civil structures is to embed self-sensing structural materials into the segments of interest to enable smart monitoring [11,12]. Self-sensing cement-based structural materials offer the benefit of easily binding with the monitored structure as they possess similar material properties as the structure being monitored [13]. Fabrication of self-sensing cementitious materials through the doping of carbon-based particles into traditional admixtures of cement has been achieved [14]. Various carbon-based materials have been mixed with cementitious materials, including carbon fibers [15,16], nano-carbon black [17] and, more recently, multi-walled carbon nanotubes (MWCNT) [4,18,19]. MWCNTs offer great potential due to their excellent electrical and mechanical properties [20,21]. For this reason, they have been employed in the fabrication of many strain sensing composite materials. It has been demonstrated that the cementitious material's strain sensing property is due to piezoresistivity caused by the slight pull-out of fibers passing through micro-cracks [16].

Research on damage detection and localization has been performed for various forms of conductive cement composites. Multiple examples of data-driven damage detection, where damage is inferred from a change in electrical signal [19,22,23], can be found in the literature. Chen et al. [15] demonstrated a data-driven damage detection approach in a carbon fiber-reinforced concrete beam under a three-point-bending test. The damage was clearly detected, but damage localization within the specimen was not achieved. Hou et al. [24] presented an electrical impedance tomography method for use with cementitious structures. Results demonstrated that the electrical impedance tomography method was capable of detecting and localizing damage in a polymeric fiber reinforced cementitious composite. However, repeated measurements were required along with various applied current distributions to solve the tomography mappings inverse problem. Furthermore, electrical impedance tomography requires the use of a finite element or finite difference method to obtain an approximation of the solution, because an analytical solution is generally difficult to formulate [25].

This work introduces a computationally efficient and direct model-based approach to damage detection, localization and quantification of crack type damage in self-sensing cement-based structural materials. Here, a simple resistor mesh model is created to approximate the self-sensing material. Varying strain and damage states can be introduced into the resistor mesh model through changing the resistive value of individual resistors. This capability is based on the hypothesis that the electrical resistivity of any self-sensing conductive material depends on its strain [18] and fault state (healthy/damaged) [26]. Cracks in the self-sensing material are considered to cause a reduction in conductivity since cracks are non-conducting when opened. The resistor mesh model is efficiently solved through nodal analysis, providing a voltage level for each model node, and compared to experimental data. Individual resistors within the model can then be adjusted to localize the damage within the material. This approach enables real-time detection and localization of damage in concrete structures with simple and inexpensive electrical hardware while requiring only light computations. The proposed method is validated for an MWCNT cement composite under static damage cases and a steel reinforced MWCNT cement composite under a four-point loading case. In the four-point loading case, a finite element analysis model is developed to update the resistor model with strain-induced resistance changes for each loading case.

The contributions of this paper are twofold: (1) a straightforward and easily solvable resistor mesh model is introduced and experimentally verified for damage detection, localization and quantification in multi-functional cement-based self-sensing materials; (2) experimental validation of the resistor mesh model for damage detection and localization in a steel reinforced cement-based beam is performed, successfully locating and detecting an internal damage case that is non-evident on the specimen's surface.

This paper is organized as follows. Section 2 presents background on the self-sensing cement-based material used for experimental validation, along with the biphasic DC measurement approach used for monitoring the self-sensing material. Section 3 presents the proposed resistor mesh model for damage detection and localization. Section 4 presents the three experimental validation cases and results. Section 5 concludes the paper.

2. Background

The self-sensing cement composite specimens used in this study are introduced in this section. Thereafter, the biphasic DC measurement approach used in the presented experiments is described, and its enhanced time stability in comparison to other existing methods is demonstrated along with its capability to monitor the strain sensitivity of the cement composites.

2.1. Self-sensing cementitious material

Specimens made of a self-sensing nanocomposite cement paste doped with MWCNT are used for model validation. Previously conducted axial compression tests have demonstrated that the MWCNT/cement-based matrix mix design considered here is capable of behaving as a strain-sensing structural material [18]. The fabrication process of the material and its sensing principle are described in details in Ref. [18]. Briefly, the composite is made by doping a traditional cementitious mixture with carbon nanotubes, providing the material with a piezoresistive strain sensing capability. Here, specimens were fabricated by adding 1% MWCNT (Arkema C100), with respect to the mass of cement, to deionized water and a surfactant (Lignosulfonic acid sodium salt). Nanotubes were dispersed in water by using a sonicator tip after a preliminary mechanical mixing. The obtained water-nanotube suspension was then mixed with type IV Portland cement. Four specimens were cast. The first into a $51 \times 51 \times 51$ mm^3 mold along with 4 stainless steel mesh electrodes (4×4 mesh, 1.2 mm wire diameter) for the strain sensing tests, as shown in Fig. 1. An additional 51 mm side cube, along with a $40 \times 40 \times 160$ mm^3 and a $100 \times 100 \times 500$ mm^3 beam were cast for experimental model validation. These three samples will be discussed later.

The use of any strain-sensing material requires the assumption of an electromechanical model to relate strain to a measurable electrical parameter. While various equivalent electromechanical models for cement-based materials doped with MWCNT have been