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A new sensing skin for qualitative damage detection in concrete elements: Rapid difference imaging with electrical resistance tomography

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ABSTRACT

In this paper we investigate whether a thin layer of electrically conductive materials that is painted to the surface of concrete elements can be used as sensing skin to detect and locate cracking and damage in the concrete substrate. Cracking of the concrete results in the rupture of the sensing skin, thus locally increasing its electrical resistivity. We monitor the local change in the electrical resistivity of the sensing skin using electrical resistance tomography. In this work, we utilize difference imaging scheme. Experiments on polymeric substrates as well as on concrete substrates are performed. The results indicate that the developed sensing skin can be successfully used to detect and locate cracking and damage on concrete and potentially other nonconductive substrates.

1. Introduction

Cracking of concrete is a major concern for owners and operators of reinforced concrete (RC) structures since cracking is an early indicator of larger structural deformation or collapse. Cracking is also a major factor contributing to the premature deterioration of RC structures since cracks accelerate ingress of water and aggressive agent [1]. Therefore, information about the location of the cracks and the extent of cracking is useful for assessing the structural safety as well as to more accurately predict the service life of RC structures [1]. Different non-destructive techniques are used for detecting cracking such as acoustic emission, ultrasonic methods, image-based methods, x-ray tomography, and electrically-based methods. Electrical methods are generally attractive since they can be performed rapidly and are relatively inexpensive.

Electrical measurements on cement-based materials using direct current (DC) e.g., [2] or alternating current (AC) e.g., [3,4] have been utilized to detect and quantify cracking and damage. In general performing electrical measurements directly on cement-based materials is limited to small geometries due to the large impedance of concrete materials. The large impedance of concrete often would require the use of large electrodes and/or large electrical power to perform measurements on large structural members. Furthermore, the electrical resistivity of concrete changes orders of magnitude with moisture content in concrete making interoperation of electrical measurement rather difficult in field applications.

Conductive surface sensors provide an alternative electrically-based approach for crack detection on cement-based elements. These sensors are made of electrically conductive materials (such as colloidal copper and silver paints) that are applied to the surface of concrete and their electrical resistance is monitored [1]. When the concrete substrate is strained, the conductive material at the surface is stretched and its electrical resistance increases slightly. When the concrete substrate cracks the conductive material at the surface ruptures and therefore the electrical resistance of the conductive materials increase orders of magnitude. By monitoring the electrical resistance of the conductive materials applied to the surface, cracking of the substrate can therefore be detected [1]. Conductive surface sensors can be extended to large geometries. These sensors are not generally sensitive to the moisture content of concrete substrate since their electrical conductivity is orders of magnitude higher than the electrical conductivity of concrete and therefore the leakage of current to the substrate is minimal. Pour-Ghaz and Weiss [5–7] developed and used sliver-based and copper-based conductive surface sensors to monitor cracking and to locate the cracks. These studies showed that the time of visible cracking is captured accurately by conductive surface sensors. Later, more advanced methods such as frequency selective circuits (FSC) [8] and radio frequency identification [9] were used in conjunction with these conductive surface sensors for damage detection in

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concrete materials and RC elements. Conductive surface sensors were successfully used in full-scale experiments to monitor damage formation and to understand the modes of failure of segmental concrete pipelines [10].

In the studies mentioned above, one-dimensional (1D) conductive surface sensors have been used where the conductive surface sensor consists of a strip of conductive materials and the electrical resistance is measured at both ends of the sensor. In such a case, utilizing a simple resistance measurement device is sufficient and interpretation of the results is rather straightforward. However, if two-dimensional (2D) conductive surface sensors (referred to as sensing skins) are used, the use of more advanced measurement techniques and data interpretation to detect and locate the damage becomes necessary. Electrical impedance tomography (EIT) can potentially be used to detect and locate cracks in two- and three-dimensional geometries and can provide a method to monitor cracking of sensing skins.

Electrical Impedance tomography (EIT) is an imaging modality in which the admittivity distribution within the material is reconstructed from the electrode potential measurements at the boundaries under the influence of an applied current. Electrical resistance tomography (ERT) is a special case of EIT where the capacitance effects are neglected (i.e., the phase-shift between the applied current and the potential measurements are not used in ERT computations). Generally, ERT is performed using AC current but in the absence of polarization effects, DC current may also be used. ERT and EIT are emerging imaging modalities in medical applications (e.g., [11–13]). ERT has been previously used by researchers to detect and quantify damage within cement-based materials [14–16,17–19]. Hou and Lynch [14–16] performed ERT on a carbon nanotube-based film attached to the surface of cement-based materials and monitored the conductivity of this carbon nanotube film during loading and cracking of the substrate.

In this paper, we investigate whether conductive materials painted on the surface of concrete can be used as a “sensing skin” for detecting damage. We use ERT to monitor the change in the electrical resistivity of this sensing skin applied to the surface of concrete and polymeric substrates. We use difference imaging scheme in this paper and we intend to illustrate that the developed sensing skin can be successfully used for damage detection in concrete, and potentially other nonconductive materials. In a follow up paper, we will use a more advanced imaging scheme (absolute imaging with Total Variation prior) to obtain quantitative results.

2. Background on electrical resistance tomography

In ERT spatial conductivity (σ) (or alternatively resistivity) distribution of an object is reconstructed. This is accomplished by measuring the electrode potentials at the boundaries of the object under the influence of an applied current. The current is applied between different pairs of boundary electrodes and the resulting electrical potential differences across the remaining pairs of electrodes are measured.

ERT belongs to the class of soft field (diffuse) tomography methods and the reconstruction problem in ERT is an ill-posed inverse problem in the sense that the solution is not unique and is extremely sensitive to measurement noise and modeling errors [20]. To reconstruct the conductivity distribution from the applied current and measured electrode potentials at the boundaries of the target, a physical model describing the dependence of the electrode potentials at the boundaries to the conductivity distribution within the target and the applied currents at the boundaries is necessary. Such a model is referred to as forward model. To date, the most accurate forward model for ERT that takes the contact impedances between the electrodes and the target into account is the Complete Electrode Model (CEM) [17,21]. The CEM consists of the partial differential equation shown in Eq. (1) and boundary conditions shown in Eqs. (2)–(4). Eq. (1) is derived from Maxwell equations for electromagnetism for a linear isotropic media under quasi-static assumption [22].

$$\nabla.(\sigma \nabla u) = 0 \tag{1}$$

$$u + \xi_\ell \sigma \frac{\partial u}{\partial \overline{n}} = U_\ell \tag{2}$$

$$\sigma \frac{\partial u}{\partial \overline{n}} = 0 \tag{3}$$

$$\int_{e_\ell} \sigma \frac{\partial u}{\partial \overline{n}} dS = I_\ell \tag{4}$$

$$\sum_{\ell=1}^{L} I_\ell = 0 \tag{5}$$

$$\sum_{\ell=1}^{L} U_\ell = 0 \tag{6}$$

In Eqs. (1)–(6), σ is the conductivity, u is the electric potential, ξ_ℓ is the contact impedance, $\overline{n}$ is outward unit normal, U_ℓ is the electrode potential, I_ℓ is the total current through the electrode and e_ℓ is the ℓth electrode. The term $\sigma\frac{\partial u}{\partial \overline{n}}$ is the current density through the boundary; and therefore, Eq. (4) indicates that the integral of current density over the electrode is equal to the current through the electrode [17]. Eq. (3) indicates that no current flows in and out of the electrode-free boundaries of the target. The second term on the left hand side of Eq. (2) introduces the contribution of contact impedance (ξ_ℓ) to the potential of the electrode (U_ℓ). In addition to the boundary conditions, Eqs. (5) and (6) need to be satisfied. Eq. (5) shows the charge conservation and Eq. (6) indicates that the potential reference level is fixed [17]. The complete derivation of variational form of CEM is presented by Somersalo et al. [23]. To solve the CEM for a target with arbitrary shape, numerical approximation of CEM is necessary. In this work, finite element method is used. The finite element formulation of CEM has been presented by many researchers (e.g., [24–27]).

As a consequence of the CEM, it can be shown that the relationship between computed electrode potentials (U) at the boundaries and the injected currents (I) is linear and can be written in the form of Eq. (7)

$$U = U(\sigma, I) = \mathcal{R}(\sigma)I = R(\sigma) \tag{7}$$

where $\mathcal{R}(\sigma)$ is the resistance matrix [28,29]. Note that the shape of Eq. (7) resembles the Ohm's law. The relationship $U = R(\sigma) = \mathcal{R}(\sigma)I$ between conductivity distribution (σ) and the electrode potentials ($U = U(\sigma, I)$) is nonlinear [22]. The physical electrode potential measurements (V) on the target can be expressed by Eq. (8)

$$V = U + \upsilon = \mathcal{R}(\sigma)I + \upsilon = R(\sigma) + \upsilon \tag{8}$$

where υ denotes observation noise.

In *difference* imaging, two sets of measurements are performed: one set of measurements are performed on the reference state (e.g., before damage) and the second set of measurements are performed after a change-of-state (e.g., cracking) occurs. In difference imaging the objective is to trace the change in electrical conductivity ($\delta\sigma$), from a reference conductivity state (σ_o) to the conductivity after the change-of-state (σ). In difference imaging a global linearization approach such as Taylor polynomial at σ_o can be used as shown in Eq. (9)

$$U(\sigma) = U(\sigma_o) + U'(\sigma_o)\,[\sigma - \sigma_o] + O(\|\sigma - \sigma_o\|^2) \tag{9}$$