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Assessment of cracks in reinforced concrete by means of electrical resistance and image analysis

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HIGHLIGHTS

- Reinforced concrete specimens were subject to cracking.
- Influence of cracks on concrete electrical resistance was examined.
- Crack geometry and volume of cracks were assessed by image analysis.
- Relative increase in electrical resistance and crack volume were dependent on the crack opening displacement (COD).

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ABSTRACT

The durability of cracked reinforced concrete is a serious concern in the construction industry. Cracks represent fast routes for chloride penetration, which can result in reinforcement corrosion. Bending or tapered cracks have the characteristic of being wider at the surface and becoming narrower towards the reinforcement. In reinforced concrete, secondary cracks can be found at the concrete steel interface. Their influence on concrete durability remains uncertain. Electrical resistance and resistivity have been commonly related to transport properties of concrete. This paper studies bending cracks in reinforced concrete specimens by measuring the electrical resistance across the crack. Cut sections of the specimens were subsequently impregnated and photographed. Image analysis tools were employed for determining the crack dimensions. It was found that the relative increase in electrical resistance and the crack volume were related to the crack opening displacement (COD) at the concrete surface.

1. Introduction

The influence of cracks on the durability performance of concrete structures is still under research. Current design codes determine the maximum allowed crack width based on empirical studies and the influence of exposure conditions upon the structure. For marine environment or de-icing salt exposure, maximum crack values are between 0.15 to 0.30 mm [1–3]. Interestingly, crack width calculations may suggest that larger concrete covers result in larger surface crack widths, while a larger cover depth would generally be considered as improving durability. This contradiction discourages the design of concrete structures for durability performance. The condition assessment of cracked structures and their durability performance is currently based on the crack width at the concrete surface. Field engineers studying the condition of cracked structures are limited to crack width measurements at the concrete surface. So far, the relationship between crack width and durability performance remains unclear.

Current codes disregard the influence of cracks that remain undetected from the surface but that may influence the durability of a cracked concrete element. An experimental study performed by Goto [4] found that microcracks (secondary cracks) formed along the reinforcement when reinforced concrete specimens were subject to tensile stress. Since steel reinforcement is subject to tensile stresses when embedded in concrete, the presence of secondary cracks can be expected. Moreover, research studies have shown that defects in the concrete–steel interface could lead to deterioration mechanisms including reinforcement corrosion [5–8]. If these secondary cracks are present, the service life of reinforced concrete structures can be reduced significantly. The influence of this type of crack in both corrosion of steel reinforcement [9–11] or chloride penetration [12–14] requires further studies.

Electrical resistance and its durability indicator counterpart, electrical resistivity, are parameters that are commonly related to

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transport properties of concrete. Measured values are usually between 10^1 to 10^5 Ω m, which are dependent on concrete composition, cement type, age and environmental conditions [15–17]. Since electrical current is carried by ions dissolved in the pore solution, electrical resistance/resistivity can be used as an indirect measure of changes in transport of electrical current due to moisture. Differences between moist and dry concrete can be of several orders of magnitude [18]. Recently, Reichling and Raupach [19] developed a technique that simulates the behaviour of electrical equipotential lines in a reinforced concrete element. For this, a Wenner array with different configurations was employed. This technique would allow detecting the presence of layers within the concrete with different resistance properties (e.g. different saturation levels).

In the work carried out by Boulay et al. [20], a cylindrical specimen was subject to tensile splitting while a reservoir of a conductive solution filled the crack. Results showed a linear correlation between the COD (crack opening displacement) at the surface of the specimen and electrical conductivity. While conductivity increased according to larger COD values, electrical resistance decreased. Lataste et al. [21] used concrete resistivity as a non-destructive technique for localising cracks in reinforced concrete. In their approach, tapered cracks were considered to behave similarly to several resistors in parallel to account for conductive behaviour of the crack. This approach accounts for a combination of isolating and partially conductive crack properties. On the other hand, the behaviour of electrical resistance can be modified by the presence of a conductive element such as reinforcing steel. Karhunen et al. [22] focused on conductive materials embedded in concrete, such as steel, and their influence under electrical current flow. Results show that equipotential lines were disturbed by the presence of conductive materials such as steel reinforcement, but also by the presence of non-conductive materials. Air-filled cracks represent a non-conductive medium for electrical current and thus studying the behaviour of electrical current in concrete can assess their influence.

In this paper, reinforced concrete specimens were subject to continuous monitoring of electrical current during tensile cracking. Modelling of the influence of cracks on electrical resistance is performed by a Lattice-model, which accounts for air-filled cracks that are considered to be non-conductive. Changes in the behaviour of electrical current under cracking in both experiments and the model are discussed. Subsequently, image analysis is applied on photographs obtained from cut sections containing the crack. By these means, a crack volume in the specimens is estimated. Finally, correlations between the estimated crack volume and both COD and the relative increase in electrical resistance are presented.

2. Experimental details

2.1. Materials and specimen fabrication

Reinforced concrete specimens were fabricated with ordinary Portland cement (CEM I 52.5R). In total, 4 specimens were made for cracking experiments. Two reinforcing steel bars of 120 mm in length and 12 mm in diameter were embedded at a cover depth of 60 mm as shown in Fig. 1a. The distance between reinforcing bars was 120 mm as shown in Fig. 1b. Before casting, a PVC profile with a cross section of 40 × 40 mm^2 was mounted on the mould to obtain a recess. Two stainless steel electrodes were employed for electrical resistance measurements. They were attached to the sides of profile, with an embedded length of 50 mm and a diameter of 6 mm. The horizontal distance between the electrodes was 50 mm. The PVC profile was removed 4 h after casting, leaving the electrodes embedded in the concrete.

Table 1 depicts the employed mix design for the fabrication of the concrete specimens. The specimens were cast inside plastic moulds of 150 × 150 × 150 mm^3. They were demoulded after 24 h and stored in a curing room with controlled conditions of 20 °C, and over 95% RH for 27 days. At the end of the curing period, a notch (5 mm width, 15 mm in depth) was made at the bottom of the recess using a water-cooled diamond saw. Finally, the specimens were exposed to laboratory conditions of 20 °C and approximately 50% RH for 7 days before the test.

2.2. Cracking and electrical resistance measurements

Cracking of concrete specimens was performed at a loading rate of 0.5 μm/s under displacement control. Two LVDTs (linear variable differential transformer) were placed on both front and back of the specimen at the bottom of the notch (see Fig. 1b). Their average displacement was used as a feedback signal for the machine in order to calculate the required load to continue at the prescribed loading rate.

A schematic of the cracking process is shown in Fig. 2. Monitoring of the electrical resistance between the embedded electrodes was performed under 120 Hz AC. The testing procedure was followed the protocol described below:

- Measurements of electrical resistance are initiated.
- Load applied at a rate of 0.5 μm/s.
- Maximum load was recorded (A) is obtained and the test continued.
- Maximum crack width is obtained (B) and the unloading process is initiated.
- Final crack opening displacement (C) is obtained.
- Stop the recording of electrical resistance.

2.3. Lattice model description

Lattice models have long been used for simulating fracture processes in concrete [23]. The model has been successfully used in fracture modelling of concrete on both the macro and mesoscale, fibre-reinforced concrete, amongst others; obtaining realistic crack patterns that are useful when comparing results with experiments. Details on the underlying equations for the 3D analysis, element matrices, and implementation can be found elsewhere [24–26]. In the mechanical lattice approach, concrete is discretised as a set of truss or beam elements. In the transport lattice approach, concrete is treated as an assembly of one-dimensional pipes, through which the flow takes place. The approach proposed here uses the same lattice network for both simulations. In this approach, mechanical simulation is performed first; its output is then used as an input for simulating equipotential lines under a voltage applied to the electrodes and conductivity values are assigned to the elements. Therefore, it is one-way coupling.

2.3.1. Electrical potential model

The proposed model treats concrete as an assembly of one-dimensional "pipe" elements, through which transport takes place, e.g. current flow [25,27]. An electrical current is applied at two nodes. The conductivity of the Lattice elements is assigned according to the role of the element: concrete; crack or steel (see below). An assembly of these elements in 3 spatial dimensions enables determination of electrical potential distribution in 3D.

The governing equation for the scalar potential simulation is the Poisson equation (for a one-dimensional case):

$$k\frac{\partial^2\varphi}{\partial x^2}=f(x) \tag{1}$$

for the whole domain, Ω. Here, φ is the scalar electrical potential, k the electrical conductivity, and x the spatial coordinate. The boundary conditions for this type of model are:

$$\varphi=\varphi_b \quad \text{on } \Gamma_b \tag{2}$$

$$q=-k\frac{\partial\varphi}{\partial n} \quad \text{on } \Gamma_b \tag{3}$$

where $\Gamma_b \cup \Gamma_q = \Gamma$ and $\Gamma_b \cap \Gamma_q = 0$ is the whole boundary of the domain. In the above, equation, q is outward flux normal to the boundary (i.e. in direction n), and φb is the prescribed electrical potential at the boundary. Note that Eq. (1) becomes Laplace's equation when $f(x) = 0$.

The electrostatic potential is discretised in space as:

$$\varphi(x)=\sum_{i=1}^{n}N_i\varphi_i \tag{4}$$

where N_i are the shape functions, n the number of nodes in an element, and φi nodal potential. The Galerkin approximation of Eq. (1) is:

$$\int_\Omega N_i\frac{\partial}{\partial x}k\frac{\partial\varphi}{\partial x}d\Omega=0 \tag{5}$$

Employing integration by parts on (5) yields:

$$-\int_\Omega\left(k\frac{\partial N_i\partial\varphi}{\partial x\ \partial x}\right)d\Omega+\int_{\Gamma_q}N_ik\frac{\partial\varphi}{\partial x}nd\Gamma_q=0 \tag{6}$$

From Eq. (3) it holds:

$$\int_{\Gamma_q}N_ik\frac{\partial\varphi}{\partial x}nd\Gamma_q=-\int_{\Gamma_q}N_iqd\Gamma_q \tag{7}$$

On substituting the spatial discretisation from Eqs. (4) and (6) becomes:

$$-\int_\Omega\left(k\frac{\partial N_i\partial N_j}{\partial x\ \partial x}\varphi\right)d\Omega-\int_{\Gamma_q}N_iqd\Gamma_q=0 \tag{8}$$