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Simulation of a novel capacitive sensor for rebar corrosion detection

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HIGHLIGHTS

- A novel non-contact capacitive transducer (CT) sensor, for determining rust layer thickness, is developed.
- FEM is adopted to simulate the electric field distribution and calculate the capacitance outputs in the corrosion tests.
- The developed capacitive sensor proved to have strong potential in corrosion detection.
- Simulations have shown that the developed sensor is effective in accurately measuring rust layer thickness.

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ABSTRACT

Considering of the limitations of existing hardware sensors in quantitatively evaluating of rebar corrosion degree, a novel non-contact capacitive transducer (CT) as an alternative hardware sensor, which can directly determine the rust layer thickness, is being developed the first time for corrosion detecting. To help the design and experimental planning of the sensor, finite element methods are adopted to simulate the electric field distribution and to predict the capacitance outputs in the corrosion tests. In the simulation, a new corrosion process development model is built, and rust layer thickness growth hypotheses is raised for corrosion simulation. Corrosion simulations on various diameters of rebar with two different corrosion volume expansion ratios have been conducted. The simulation results have demonstrated that the developed capacitive sensor would be highly effective in measuring rust layer thickness of various rebar and the method is more sensitive for a larger diameter of rebar as well as a higher volume expansion ratio. The simulation has also been successfully conducted in both uniform and non-uniform corrosion tests of reinforced concrete for the sensor and the results have shown that the performance of the sensor could be quite promising. The simulation works provide theoretical base for such direct CT sensing method development, which can lead to a promising corrosion monitoring sensor networks in future to provide useful information for safety operation of civil infrastructures.
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1. Introduction

Rebar corrosion is one of the major causes that destroys the long-term performance of reinforced-concrete structures [1]. The concrete cover will be cracked or even spalled under the expansion of corrosion products [2–6], and the bond between the concrete and reinforcement is also affected by the rebar corrosion [7]. The concrete damage and structural capacity loss of corroded structures require a lot of repair work which is a multibillion dollar problem all over the world, and very time consuming [8,9]. Quality control, maintenance, and planning for the restoration of these structures require monitoring and recording of the corrosion status information. By properly monitoring the corrosion performance and taking suitable measures at the appropriate time, enormous savings can be generated [10]. Thus, non-destructive inspections and effective monitoring techniques that are applicable to detect corrosion at an early stage are of high significance [11].

There are many non-destructive techniques available for monitoring conditions of reinforced concrete structures. Electrochemical methods are generally applied in the assessment of rebar corrosion on existing structures such as half-cell potentiometer [12,13], linear polarization resistance (LPR) [14,15], electrochemi-

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cal impedance [16,17] and galvanostatic pulse transient method [18,19], etc. Half-cell potentiometer infer the probability of the corrosion of the rebar by establishing the structures potential map and is the most commonly applied electrochemical technique for rebar corrosion diagnostics; the limitation is that it must be complemented by other methods (such as resistivity survey) and a complicated statistical analysis to retrieve useful data is required. Besides, breaking the concrete cover to get electrical connection to the rebar is necessary [13,20]. As for the polarization resistance techniques, their performance can be affected by the concrete cover thickness, temperature, as well as humidity. Thus, the conditions at the time of measurement will influence the interpretation as well [21]. Many researchers have used Impedance Spectroscopy for the characterization of the corrosion behavior of the steel in concrete [16,22]. It can give more information than polarization resistance measurements, as a wide range of frequencies are adopted [23]. However, it is very time consuming to perform tests and its use has been generally confined to the laboratory rather than on structures in the field [24]. For laboratory conditions, the corrosion testing results will only be effected by the progression of the corrosion development itself, while in the on-site conditions, the corrosion measurement is hardly to be controlled due to the influence of the climatic factors such as temperature or relative humidity [24]. The difficulty with the galvano-static pulse transient technique is that the response to the pulse has to be stable to give an accurate measurement. The technique and the electrochemical impedance suffer from the same difficulty in measuring reinforced concrete structures in the field as does LPR measurement, i.e. the area of steel being measured is difficult to quantify [25–27]. The aforementioned electrochemical corrosion measurements are usually qualitative or semi-quantitative [28]. Although such benefits can be derived from them, the lack of quantitative data for the corrosion status remains an unresolved issue and the interpretation of the results becomes a difficult task as well. Moreover, these methods normally require a direct contact with the inside rebar, therefore, the concrete cover may be damaged in some situations.

Optical fiber sensors are proposed to test the corrosion of the reinforced rebar. The technique is obviously attractive due to the low cost, ease of termination and coupling, and their relatively high resistance to fracture [29–31]. There is still no obvious relationship between the real time continuously monitoring outputs and the rebar corrosion condition directly. Other visual methods include X-ray/gamma radiography [32–34], infrared tomography [35] as well as visual inspection technique [36]. Although information about concrete quality, chloride content and rust stains can be obtained, none of them can provide quantitative evaluation on the rebar corrosion degree.

1.1. Research significance

As the existing electrochemical testing techniques such as half-cell potentiometer [12,13], linear polarization resistance (LPR) [14,15], electrochemical impedance [16,17] and galvanostatic pulse transient method [18,19] are mostly for indirect determination of the corrosion degree of reinforcements inside concrete. The corrosion degree is indicated from the corrosion current or open circuit potential and the results can only give a corrosion level condition such as the corrosion condition is to a certain extent, and this is a qualitative result.

In this paper, a capacitive sensor, which can give a direct measurement results on the rust thickness, is proposed for the first time. It provides the possibility to quantitative evaluation of the direct rust thickness through the capacitance outputs.

The working principle of the new sensor is based on the differences of the dielectric properties of steel and corrosion layer (main content of rust is iron oxide), which will affect the apparent capacitance of the capacitive sensor during the corrosion monitoring process [37,38]. To verify the applicability of the new corrosion detecting method, a series of simulation work have been conducted first to provide useful guidelines for the new sensor development and corrosion test planning. The simulation work consists of two stages: (i) Rebar corrosion model and hypothesis development; (ii) Simulations on uniform and non-uniform corrosion testing. In the simulation works, finite element methods are adopted to simulate the electric field distribution and to compute the capacitance value during the corrosion tests. The research is considered of high value since most corrosion testing related research focused on a qualitative evaluation and no direct quantitative relationship between a measuring capacitance output signal and the real rust thickness has been built previously.

2. Methodology

2.1. Corrosion model of pure rebar and hypothesis development

There are several assumptions in the built corrosion simulation model.

(1) The rust layer is assumed to be uniform distributed along the whole surface of the reinforced rebar.
(2) The dielectric constant of the rust layer is assumed to be the same with ferric oxide, since ferric oxide is the main component of the corrosion products. (The dielectric constant of ferric oxide is 14.2 and the electrical conductivity is 100 s/m [38]).
(3) In the built rebar reinforced concrete models, the dielectric constant of concrete is assumed to be 6 and the corresponding electrical conductivity is 0.003 s/m [39]. The conductivity of concrete is calculated from the reciprocal of the concrete resistivity, which is 30 kΩ·cm–60 kΩ·cm.
(4) The corrosion volume expansion is insensitive of the way corrosion obtained [40,41].
(5) It is reported that the corrosion volume expansion ratio of rebar in the reinforcement concrete is from 2.26 to 3.0 [42].

Based on the above assumptions, two corrosion volume expansion ratios, 2.0 and 3.0, have been selected for building the model. In the simulations, a series of 3-D corrosion cases have been considered. The considered geometry includes a fixed computing domain (150 mm × 150 mm × 150 mm), the monitoring capacitive sensor with two sensing electrodes (100 mm × 100 mm × 1 mm) and rebar of various sizes (ϕ8 mm, ϕ12 mm, ϕ16 mm, ϕ20 mm, ϕ24 mm, ϕ28 mm) were placed in between the two capacitive electrodes during the whole corrosion development process. Electrostatic field were simulated under COMSOL Multiphysics® environment in the corrosion developing model and the capacitance testing outputs has been calculated by Finite Element Method in order to monitor the rust layer thickness. The whole corrosion developing process was marked by various rust layer thickness (represented by the value of x_1). A rust thickness development model of a ϕ8 mm rebar has been demonstrated in Fig. 1.

2.1.1. Case I (with a corrosion volume expansion ratio of 2.0)

The corrosion volume expansion ratio of 2.0 is defined when the thickness of rust layer is 2 times of the radius loss of original steel during the corrosion process. In the developed corrosion model, the original rebar radius is set as R_0 and the corrosion development step is set as x_1. During corrosion process, the remained steel radius is set as ($R_{inside} = R_0 - x_1$) and the diameter of rebar with corrosion thickness is set as ($R_{outside} = R_0 + x_1$). When there is an

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