NDT&E International 44 (2011) 583–588

Contents lists available at ScienceDirect

NDT&E International

journal homepage: www.elsevier.com/locate/ndteint

Remote corrosion monitoring of the RC structures using the electrochemical wireless energy-harvesting sensors and networks

Guofu Qiao [a,*], Guodong Sun [b], Yi Hong [c], Yuelan Qiu [a], Jinping Ou [a,d]

[a] School of Civil Engineering, Harbin Institute of Technology, Harbin 150090, China
[b] Department of Computer Science and Technology, Tsinghua University, Beijing 100084, China
[c] Center for Composite Material and Structure, Harbin Institute of Technology, Harbin 150090, China
[d] School of Civil and Hydraulic Engineering, Dalian University of Technology, Dalian 116024, China

ARTICLE INFO

Article history:
Received 25 February 2011
Received in revised form
13 June 2011
Accepted 14 June 2011
Available online 23 June 2011

Keywords:
RC structures
Corrosion monitoring
Electrochemical
Wireless sensor
Energy-harvesting

ABSTRACT

Essentially, the corrosion process of the steel bar in reinforcing concrete structures is a series of electrochemical reactions. Therefore, the released energy during these reactions provides the opportunities to identify the corrosion status and power the wireless corrosion monitoring sensors. Furthermore, the recognition of the corrosion status has been realized with active monitoring techniques (AMTs) and passive monitoring techniques (PMTs). Additionally, the sensor mote platform that harvests the corrosion energy has been designed for corrosion monitoring, and then how to network these sensors to remotely access the corrosion data has been discussed. The preliminary experiment has been conducted to validate the micro corrosion energy.

1. Introduction

Reinforcing concrete (RC) structures are the most important structural style in civil engineering. Unfortunately, the corrosion of the reinforcing steel has been a world-wide problem, which deteriorates the durability of RC structures and degrades the serviceability severely for a long time [1–4]. With the development of global warming and further deterioration of the environment, the service environments of RC structures become much more atrocious now. Fortunately, structural health monitoring (SHM) systems enable scientists and engineers to identify the status of structures, and then provide the foundation for safety assessment, service-life prediction, maintenance and reinforcement, and full-life design of structures [5–8].

Currently, most academic researches are focused on the development of advanced sensing technology and sensors, and health diagnosis approaches. A large number of smart sensors, such as optic fiber sensors [9,10], piezo-electric ceramics sensors [11], cement-based strain sensors [12,13], nano material-based sensors [14], etc., have been implemented in various structures, such as offshore structures, bridges structures, building structures, high-speed railway infrastructure, petroleum industry, and so on. Many useful variables, such as load, environmental factors, effect of the load, have been achieved to evaluate the safety and durability of a structure during its service life, to ensure its serviceability and sustainability.

Considering the corrosion monitoring, there are some wired and wireless devices, which have been developed to detect the durability of the structures in civil engineering. Kumar et al. [15] have accomplished an important and outstanding work where an integrated sensor system has been applied to monitor the corrosion rate, chloride ion concentration and the resistivity of the concrete. The authors aim to identify the corrosion status by simultaneously monitoring the environmental factors and the corrosion results. Also, Dong et al. [16] have also developed a multifunctional sensor to investigate the pH, chloride ion concentration, and the corrosion rate of the steel bar. Furthermore, Andringa has proposed a simple low-cost resonant-based embeddable sensor to monitor the corrosion of the reinforcing steel [17]. Recently, Ahmad [18], Luping [19], Song and Saraswathy [20], etc. have reviewed the corrosion monitoring approaches and sensors. These pioneer works led to the development of the corrosion monitoring in civil engineering.

According to the research presented in the previous sections, some significant challenges should be considered in the actual SHM systems that monitor the corrosion of RC structures. Firstly, the designed service life of RC structures is so long that the required service period of corrosion monitoring systems is no less

* Corresponding author. Tel.: +86 451 6282209; fax: +86 451 86282209.
E-mail addresses: qgf_forever@hit.edu.cn, qgfhit@163.com (G. Qiao).

0963-8695/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ndteint.2011.06.007

than the service life of RC structures. Secondly, the evolution of the reinforcing steel's corrosion could be influenced by the environment conditions. Therefore, scientists and engineers dream to identify the corrosion status of RC structures in-situ, real-time, and on-line [21]. Also, the foregoing engineering practice indicates that the emplacement of tremendous conducting wires, which demands massive labors and financial resources to implement, is another annoying problem in SHM for civil engineering.

Essentially, the corrosion process of the reinforcing steel in RC structures is series of electrochemical reactions [22,23]. The most interesting and fascinating fact is that the corrosion process is an energy release process. This vital energy provides the possibilities to realize in-situ, real-time, and on-line corrosion monitoring by wireless energy-harvesting sensors and networks. This work is not hitherto been reported in the prior art. Therefore, we investigate the generation of corrosion energy in RC structure and its availability as a power source. Furthermore, powered by the energy harvested from corrosion environment, a new smart sensor platform is then designed to detect the corrosion status via wireless links to the end user. This work represents a tremendous step towards the realization of the practical corrosion monitoring for RC structures.

2. Reinforcing steel's corrosion—a micro energy delivery process

As the hydration reactions of the cement are completed, the cement is changed to a complex, multi-phase, heterogeneous body [24]. Generally, hydration products provide a high degree of protection to the reinforcing steel against corrosion, and keep the steel in a passivated state by virtue of the high alkalinity ($Ca(OH)_2$, pH > 13.5) of the pore solution. However, when the pH value of the pore solution drops greatly by the carbonation reaction $Ca(OH)_2+CO_2+H_2O \rightarrow Ca(HCO_3)_2+CaCO_3$ or as sufficient chloride ions penetrate into the reinforcement, the protective film could be destroyed and depassivated. The fundamental factors, which lead to the corrosion of RC structures and the corrosion processes of the reinforcing steel, are illustrated in Fig. 1.

Although the corrosion process is very complicated, it must be kept in mind that the electron is presented and transferred inside the barrier layer or on the surface of the reinforcing steel. The energy accumulated during the steelmaking process is delivered by the electrochemical reactions. Therefore, this delivered energy provides the opportunities to realize the corrosion monitoring by electrochemical wireless energy-harvesting sensors and networks.

3. Recognition of the corrosion status based on AMTs and PMTs

Equivalent circuit (EC) is the transfer function of the electrochemical system. The EC in Fig. 2 is the universal transfer function, which could be used to simulate and characterize the electrochemical characteristics of the steel–concrete system [25–28]. Once the elements in the EC are confirmed, the corrosion characteristics of the concrete–steel system are identified.

The constant phase element (CPE) in Fig. 2 is used to describe the non-ideal capacitance characteristics of the steel–concrete interface. This phenomenon is caused by the dispersion effect. The CPE is expressed as Eq. (1) by the International Union of Pure and Applied Chemistry (IUPAC) as follows:

$$Z_{CPE} = \frac{1}{Y_{0dl}}(j\omega)^{-n} = \frac{1}{Y_{0dl}}\omega^{-n}\left(\cos\frac{n\pi}{2} - j\sin\frac{n\pi}{2}\right) \quad (1)$$

where Y_{0dl} is the basic admittance and n is the constant in the region [0.1]. According to Eq. (1), CPE will change to a pure resistance or a pure capacitance as $n=0$ or 1, respectively. On the other hand, Warburg impedance Z_W in Eq. (2) is used to describe the semi-infinite plane diffusion's characteristic of the oxygen in the concrete.

$$Z_W = \frac{1}{Y_{0W}}(j\omega)^{-1/2} = \frac{\sigma}{\sqrt{\omega} - j\frac{\sigma}{\sqrt{\omega}}} \quad (2)$$

where σ is the Warburg coefficient, and Y_{0W} is the basic admittance.

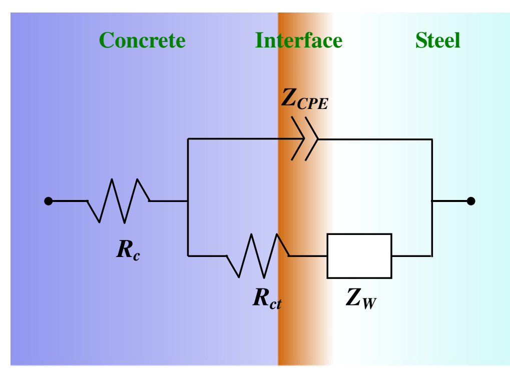

Fig. 2. EC of steel–concrete system. R_c, R_{ct}, Z_W, and Z_{CPE} are the resistance of concrete, Faraday resistance, impedance of the diffusion process and the impedance of CPE, respectively.

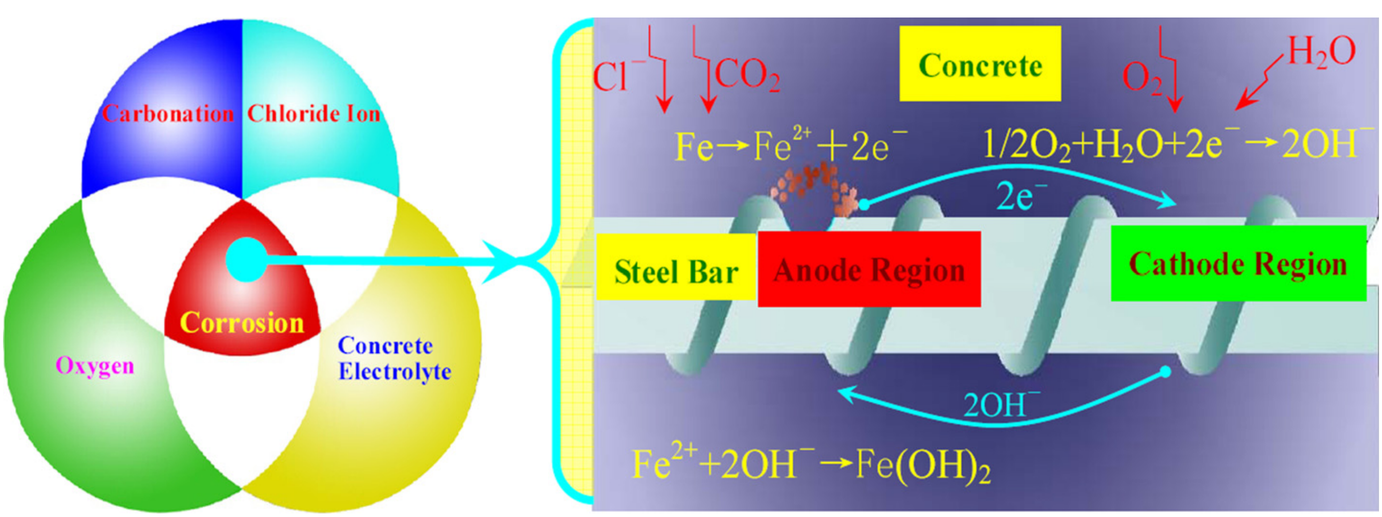

Fig. 1. Schematic plan of the reinforcing steel's corrosion process in concrete.