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Numerical optimization of an impressed current cathodic protection system for reinforced concrete structures

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HIGHLIGHTS

- Numerical optimization method of ICCP system for RC structures has been presented.
- Accurate design parameters for ICCP system are obtained by numerical optimization.
- The optimized ICCP scheme can control the corrosion of RC structure well.
- The total cost of the optimized ICCP system has a significant drop.

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ABSTRACT

Impressed current cathodic protection (ICCP) has been verified to be an effective method to control the corrosion of reinforced concrete (RC) structures, and the use of numerical simulation methods has become a powerful technique to investigate ICCP systems. This paper presents a numerical optimization method to design an economical and effective ICCP system for RC structures. First, the numerical model of the ICCP electrical field is built. The potential of the reinforcing steel and service life of the ICCP system are constrained by the protection potential in *BS 12696:2012* and the life expectancy of the RC structure to be protected, and the accurate design parameters of the ICCP system, for example, the location and area of the anode overlay and the amplitude of the output voltage, are obtained by minimizing the total cost of the ICCP system. Finally, a small-scale RC T-shaped beam is adopted as an example to illustrate the numerical optimization method, and corresponding prototypes are developed to verify the corrosion control effect of the numerically optimized ICCP system.

1. Introduction

Reinforced concrete (RC) structures have always been the most significant style of structure in civil engineering. Unfortunately, the corrosion of the reinforcing steel severely degrades the durability and safety of RC structures [1–3], which not only results in huge economic losses but also brings about threats to the life and security of people. Therefore, it is very urgent and vital to find some effective methods to prevent and arrest the initiation and development of corrosion in new and existing RC structures. Over the past few decades, many active and passive corrosion control techniques for RC structures have been developed [4–9], e.g., cathodic protection (CP), electrochemical realkalization (ERA), electrochemical chloride removal (ECR), high-performance concrete (HPC), anticorrosion painting, coatings, corrosion inhibitors and stainless steel bars. However, CP has gradually been verified to be the most effective technique to directly control the corrosion of RC structures since it was first applied to protect an RC bridge deck contaminated by chloride in 1973 [8,10–12].

The principle of CP is to deliver an appropriate cathodic polarization current to the protected structure so that the potential of the protected structure is negatively shifted and the corrosion is arrested [10,11]. According to the means to provide a cathodic polarized current, CP is divided into impressed current cathodic protection (ICCP), where an external power is applied, and sacrificial anode cathodic protection (SACP), where a sacrificial anode is used [12]. Many studies based on many practical engineering structures have shown that ICCP is more suitable for some significant structures with a more severe corrosion and a longer life

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expectancy than SACP because it can provide a long-term and sufficient polarization current [13].

Currently, ICCP systems in practical engineering cases have been designed on the basis of engineering experience without the accurate design parameters, e.g., the magnitude of the impressed voltage or current required and the position and area of the anode [14,15], which causes a lower corrosion control efficiency and a higher cost of ICCP system. With the development of numerical calculation technology, numerical simulation has become a more and more important technology to investigate ICCP systems. For example, Bruns et al. studied the protective effect on the opposite reinforcement layer in an ICCP system based on the finite element method (FEM) [16]. Hassanein et al. analyzed the influence of the boundary conditions on the current distribution of the ICCP system based on FEM [17]. Muehlenkamp et al. investigated the influence of moisture on the CP based on FEM [18]. Liu et al. modelled cathodic prevention for unconventional concrete under salting environment by COMSOL [19]. Cheung et al. investigated the effect of CP for controlling macro cell corrosion in RC structures by employing FEM [20]. However, these numerical models are limited to discussing the influence of various factors on ICCP systems and then providing some good recommendations, but do not present a method to design an economical and effective ICCP system for RC structures.

Therefore, this paper aims to develop a numerical optimization method to design an ICCP system with an anode overlay for RC structures based on FEM. In this numerical optimization method, the life expectancy of the protected RC structure and the protection potential in *BS 12696:2012* [22] are used as the constraint conditions, and then the location and area of the anode overlay and the amplitude of the output voltage are optimized to achieve the goal, which is to minimize the total cost of the ICCP system.

2. Methods

2.1. Numerical optimization

Concrete is assumed to be a homogeneous conductive material, and thus, the electrical field applied to the concrete electrolyte should obey the law of charge conservation,

$$\nabla \cdot \vec{i} = 0 \tag{1}$$

where $\vec{i}$ denotes the current density vector.

According to Ohm's law,

$$\vec{i} = -\sigma \nabla \phi \tag{2}$$

where σ and ϕ are the conductivity and the potential of the electrolyte, respectively.

The above equations are solved with three boundary conditions at the anode/cathode-concrete interfaces.

$$\phi^{a,c} = \phi_0^{a,c} \tag{3}$$

$$i^{a,c} = i_0^{a,c} \tag{4}$$

$$i_{a,c} = f(\phi_{a,c}) \tag{5}$$

where Eqs. (3) and (4) denote the potential and current boundaries of the anode/cathode-concrete interfaces, respectively, which are determined by the impressed current or voltage, and Eq. (5) denotes the polarization boundaries at the anode/cathode-concrete interfaces, which are determined by the electrode reactions at the interfaces, i.e., $Fe \rightarrow Fe^{2+} + 2e^-$ (if the reinforcing steel is less than protected), $2H_2O + O_2 + 4e^- \rightarrow 4OH^-$ or $2H_2O + 2e^- \rightarrow H_2 + 2OH^-$ (if the reinforcing steel is over protected) at the steel-concrete interface and $4OH^- - 4e^- \rightarrow 2H_2O + O_2$ or $2Cl^- - 2e^- \rightarrow Cl_2$ (if the concrete is contaminated by chloride) at the anode-concrete interface. However, some anodes are designed to only evolve oxygen, such as mixed metal oxide coated titanium anodes.

Research reports indicate that the service life of the ICCP system is primarily determined by that of the anode used [15]. Thus, the life expectancy of the ICCP system is assumed to be equal to that of the anode, which is mainly determined by the total charge density that it can survive [21]. Therefore, the life expectancy of an ICCP system is denoted by

$$N = \frac{Q}{ave(i_a)} \tag{6}$$

where Q denotes the total charge density that the anode overlay can survive and $ave(i_a)$ is the average impressed current density flowing through the anode.

The objective function to minimize is the total cost of the ICCP system, which includes the initial investment cost to build it and the cost to maintain its normal operation. The initial construction cost includes those of the anode system, rectifier, electric cable, labor fee, among other, and here all of the initial expenses are converted into the construction cost for coating a one square meter anode overlay. The cost to maintain the normal operation of the ICCP system primarily comprises the consumed power, the monitoring and maintenance and the management, which are converted into the consumed electricity fee. Therefore, the objective function is

$$\begin{aligned} &\min f(x_1, y_1, z_1, x_2, y_2, z_2, \ldots, x_n, y_n, z_n, S_1, S_2, \ldots, S_n, u) \\ &= T_1 \cdot u \cdot \left(\sum_{k=1}^{n} \int_{S_k} i_a(x, y, z) ds\right) \cdot N + T_2 \sum_{k=1}^{n} \int_{S_k} ds \end{aligned} \tag{7}$$

where n denotes the total amount of anode overlay; x_1, x_2,…… x_n, y_1, y_2,…… y_n, and z_1, z_2,…… z_n denote the location of each anode overlay; S_1, S_2,………… S_n denote the area of each anode; u is the output voltage of the ICCP system; i_a (x, y, z) is the anodic current density; T_1 and T_2 are the operating cost of the ICCP system per kilowatt hour consumed and the initial construction cost for coating one square meter of anode overlay, respectively; and N is the service life of the ICCP system.

To ensure that the life expectancy of the ICCP system is not less than that of the RC structure to be protected, a constraint condition is applied that

$$N \geqslant N_1 \tag{8}$$

where N_1 denotes the remaining service life of the RC structure to be protected.

According to the protection potential given by *BS 12696:2012*, the "Instantaneous Off" potential should be from −0.720 V to −1.100 V (vs. Ag/AgCl/0.5 M KCl) for plain reinforcing steels or to −0.900 V for prestressing steel [22]. If the potential is more positive than the upper limit of the protection potential, the protected steels may be corroded; if the potential is more negative than the lower limit of the protection potential, hydrogen evolution may take place, which can result in the hydrogen embrittlement of steel bar. Thus, a constraint condition should be adopted that

$$\phi_L \leqslant \phi_s \leqslant \phi_U \tag{9}$$

where ϕ_s denotes the potential of the protected steel bar and ϕ_L and ϕ_U are the lower and upper limits of the protection potential, respectively.

The BOBYQA algorithm, which is an iterative algorithm for bound constrained optimization without derivatives [23], is used to search for the optimal solution of the numerical model. The above equations with highly nonlinear boundary conditions are solved with COMSOL Multiphysics, an FEM numerical simulation software.