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An innovative corrosion evaluation technique for reinforced concrete structures using magnetic sensors

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HIGHLIGHTS

- The magnetic-based corrosion evaluation device is capable to assess the corrosion rate of rebar.
- The mass loss of corrosive rebar has a linear relationship with the voltage increment detected by Hall-effect sensor.
- The magnetic technique, half-cell potential and AE detection indicate good consistency.

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ABSTRACT

To investigate the fundamental relationship between corrosion rate and magnetic induction surrounding steel reinforcement, an innovative magnetic-based corrosion evaluation apparatus has been developed, which can be directly embedded inside reinforced concrete structures to monitor the corrosion rate of reinforcement. Preliminary calibration results show that the mass loss of corrosive reinforcement has a linear relationship with the voltage increment detected by Hall-effect sensor due to the variation of magnetic induction surrounding the corroded reinforcement. Subsequently, an experiment on the reinforced concrete beam subjected to chloride solution coupled with external loading has been conducted. Magnetic technique, half-cell potential measurement and acoustic emission detection have been utilized simultaneously in the experiment to monitor the corrosion process of reinforcement. The experimental results from the aforementioned techniques demonstrate good consistency. Especially, the magnetic corrosion monitoring device proposed in this study has the good capacity of quantitative analysis of corrosion rate.

1. Introduction

In engineering industry, corrosion is one of the most serious ageing mechanisms affecting the equipment and assets. It brings reduction in performance and reliability of core equipment by causing component failures [1]. Likewise, corrosion of reinforcing steel is the principal factor causing the reduction of loading capacity and invalidation of reinforced concrete structures [2–5]. Corrosion not only decreases the effective cross-section area of reinforcing steel, but also lessens the bonding stress between concrete matrix and steel rebar [6–8]. Meanwhile, decreasing of mechanical property concerns the durability and safety of reinforced concrete structures, even resulting in unexpected failures [9].

Corrosion detection methods in civil engineering are usually divided into destructive testing (DT) and nondestructive testing (NDT) [10–12]. The former is ocular to measure the diameter of corroded reinforced steel by removing the protective concrete layer, even by amputating a part of structure and taking it back to laboratory for testing when necessary. Nevertheless, in this way, the reinforced concrete structure may be destroyed to some extent. Thus, it is superior to monitor the corrosion of rebar in concrete using nondestructive methods. Nondestructive testing plays an important role in the effort by enabling the detection of early signs of corrosion so that renovation may be applied before the damage becomes severe [13–15].

Among various nondestructive testing techniques for detecting corrosion of reinforcements, half-cell potential and acoustic emission (AE) measurements prove to be reliable ones [16]. Currently,

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half-cell potential testing is the most widely-used method to detect corrosion condition of reinforcement in NDT area [17]. However, according to ASTM criteria, half-cell potential measurement only shows the corrosion probability of reinforcement. Additionally, this method is influenced by many factors in testing process, such as operators' proficiency. AE technique is also utilized to detect the corrosion and deterioration of reinforced concrete structures [18–21]. AE can be stress wave radiations generated by expansion and cracking of corrosion products. The traditional AE parameters, such as accumulated event number (AEN) and event rate (ER), have been widely recognized as indicators for corrosion accumulation [22–25]. Nevertheless, similar to half-cell potential, the drawback of AE technique is that the corrosion degree cannot be quantified from tested results.

The present study aims to investigate preliminarily the feasibility of corrosion rate evaluation method for reinforced concrete structures by magnetic sensors. Calibration results show that the mass loss of corroded reinforcement has a linear relationship with the voltage increment of magnetic induction detected by Hall-effect sensor. Therefore, the magnetic corrosion monitoring device has the capacity of quantitative analysis of corrosion rate. Then, the proposed magnetic technique, half-cell potential measurement and AE detection are employed simultaneously to monitor the corrosion process of a reinforced concrete beam subjected to 3.5% NaCl solution coupled with 40% ultimate bearing capacity. The experimental results indicate good consistency from the aforementioned techniques. The corrosion rate of reinforcement can be quantified from the voltage increment induced by the variation of magnetic induction surrounding the corroded reinforcement.

2. Setups and measurement

2.1. Magnetic-based corrosion evaluation apparatus

Table 1 shows the relative permeability of common component materials in reinforced concrete structures. As a ferromagnetic material, the permeability of carbon steel is 100 times higher than that of other components, i.e. concrete, water, air as well as iron oxide. Therefore, based on the extreme difference of permeability between rust corrosion products and reinforcing steels, an innovative magnetic-based corrosion evaluation apparatus is developed in this study, the major structure of which is demonstrated in Fig. 1. In this apparatus, the magnetic field is generated by a group of series-wound permanent magnets and magnetic circuits are formed through the stainless steel frame structure. The equivalent model of this magnetic apparatus is shown as Fig. 2. Obviously, once corrosion has commenced, the reluctance R_{m1} of the detected reinforcing steel changes definitely due to the substantial permeability difference between rust and steel. Consequently, the magnetic flux through the Hall-effect sensors alters correspondingly. In other words, the voltage output of Hall-effect sensor is governed by the effective cross-section of uncorroded reinforcing steel.

The SS495A Hall-effect sensor, featuring the advantage of small size, low power consumption and current sourcing linear output, is employed in this study. Fig. 3 shows the transfer characteristics of the selected Hall-effect sensor. This kind of MRL (Miniature Ratiometric Linear) sensor has a ratiometric output voltage, varying in linear proportion to the magnetic field intensity. High precision data acquisition board, ADS1256IDB from Texas Instruments, is selected for collecting signals of Hall-effect sensor, the schematic diagram of which is shown in Fig. 4.

Table 1
Relative permeability of common component materials in RC structures.

Medium	Relative permeability μ/μ_0
Carbon Steel	100
Iron oxide (FeO)	1.0072
Concrete (dry)	1
Water	0.999992
Air	1.00000037
Vacuum	1 (exactly)

2.2. Half-cell potential measurement

Half-cell potential testing is a simple, inexpensive and nondestructive testing, which is commonly used in detecting corrosion status of reinforcing steel in concrete structure. The copper-copper sulfate half-cell potential measurement, according to ASTM C876-91 [26], is employed in this study as a comparison and supplement for the proposed magnetic corrosion evaluation method. As shown in Fig. 5, the reference electrode is connected to the negative pole of voltmeter and the reinforcement steel is connected to the positive one. A voltage is generated by the potential difference between these two 'half cells'. The recorded half-cell potential is used to indicate the corrosion probability of the steel reinforcement, as shown in Table 2.

2.3. Acoustic emission technique

Acoustic emission (AE) technique is generally conducted to detect the corrosion progress of reinforcement in concrete structures. AE is a class of phenomena whereby transient elastic waves from a localized source within a material and conversion of the waves into electrical signals through coupled piezoelectric sensors [27–29]. The acoustic emission waves transmit the source information and directly reflect the corrosion condition of the reinforcement. Based on the authors' previous research, the cement-based piezoelectric sensors have high sensitivity and good compatibility with concrete matrix, and are suitable for corrosion monitoring of reinforced concrete structures [30–32]. The detailed fabrication procedure of the sensor refers to Ref. [33]. In this study, the cement-based piezoelectric sensors are employed for acoustic emission detection. The traditional AE parameter, i.e. accumulated event number (AEN), is utilized as the indicator for corrosion accumulation.

3. Experiments

3.1. Calibration of magnetic-based corrosion evaluation apparatus

Calibration is necessary before practically using this apparatus for corrosion detection of reinforced concrete structures. The overwhelming advantage of this magnetic-based corrosion evaluation apparatus over half-cell potential measurement and acoustic emission technique is able to quantitatively analyze the corrosion level of reinforcement. As mentioned previously, this apparatus is developed based on the extreme difference of permeability between rust corrosion products and reinforcing steels. The variation of magnetic induction intensity surrounding reinforcement induced by corrosion products can be detected by Hall-effect sensor. Therefore, the calibration process aims to establish the relationship between the mass loss of corrosive reinforcement and the voltage increment of Hall-effect sensor. The technological process of calibration is as following:

a. Weigh a steel reinforcement before rusting;
b. Measure the initial voltage signal of the uncorroded reinforcement using the magnetic monitoring apparatus;