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Measurement of reinforcement corrosion in concrete adopting ultrasonic tests and artificial neural network

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HIGHLIGHTS

- The research used non-destructive test in measuring rebar corrosion.
- Two different neural network models were applied in predicting corrosion.
- RBF was found outperforming BP.
- The corrosion depth in the reinforced prism was identified between 80 μm and 200 μm.
- Moisture content above 1.5% in concrete would cause significant increases of ultrasonic velocity.

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ABSTRACT

Limited research has been performed in testing and measuring the reinforcement corrosion levels using non-destructive tests. This research applied ultrasonic-based non-destructive test and artificial neural network to the diagnosis and prediction of rebar's non-uniform corrosion-induced damage within reinforced concrete members. Ultrasonic velocities were tested by applying ultrasonic to reinforced concrete prisms before and after the rebar corrosion. Input parameters including concrete strength, ultrasonic velocity, and the specimen dimension-related variable were used for the prediction of reinforcement corrosion level adopting artificial neural network models. Using totally *50* experimental observations, Radial Basis Function-based model was found with higher accuracy in predicting corrosion levels compared to Back Propagation-based model. This study leads to future research in high-accuracy non-destructive measurement of reinforcement corrosion in concrete.

1. Introduction

Concrete structural damage due to reinforcement corrosion is not uncommon and could be significant [1]. For example, chloride-induced durability problems shorten the service life of concrete structures [2]. The durability of concrete materials under chloride penetration requires particular attention [3]. However, reinforcement corrosion is not easily noticed. How to identify and measure the rebar corrosion within reinforced concrete structure remains a key issue in the concrete durability research. The commonly adopted non-destructive test approaches for the measurement include half-cell potential method [4] and concrete resistivity method (e.g., Wenner Four-Electrode Method [5]). These existing methods have their own advantages of being easy to operate for on-site tests with simple detection facility. However, both methods can only be used for the probability analysis of rebar corrosion within concrete but are unable to quantify the corrosion level or the corrosion-induced damage, especially for the non-uniform corrosion-induced damage within reinforced concrete. A more effective approach to test the rebar corrosion level would be to separate the rebar from concrete and measure the shape and depth of rebar etch-pits. Nevertheless, the separation of rebar from concrete would cause further structural damage and hence being not feasible. Therefore, it cannot be widely applied. There is hence an urgent need of developing a more applicable and practical measurement technology for the non-destructive test of rebar corrosion within concrete structures.

Ultrasonic measurement can be used to test concrete mechanical properties and internal defects through the elastic wave signals sent to concrete structures. The ultrasonic test implemented in concrete structure is based on the artificial method to generate elastic wave signals, which contains the information of propagation time (or speed), amplitude and frequency. The concrete

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structure is elastic-viscoplastic, with variations of acoustic impedance among its internal interfaces. The ultrasonic waves have strong reflection, scattering, diffraction, absorption, and waveform distortion when passing through the concrete structure. By extracting the information carried out in the signals and performing inversion analysis, the data of mechanical properties and defect distribution of materials and structures can be obtained.

Huygens-Fresnel Principle [6] can be applied in supporting the ultrasonic measurement by comparing the defect size and the wave length, as the wave path would be different depending on the defect size within concrete structures. The predication of concrete strength by integrating ultrasonic wave and artificial neural network (ANN) has been performed in some existing studies such as Trtnik et al. [7] and Kewalramani and Gupta [8]. However, there has not been sufficient research on applying ultrasonic wave in measuring the rebar corrosion within concrete structures. ANN, as one of the data mining methods that have been widely applied in estimating concrete mechanical properties (e.g., strength) in existing studies such as Chithra et al. [9], Omran et al. [10], Sadowski et al. [11], Wang et al. [12], Wang et al. [13], has not been sufficiently used in the prediction of corrosion level of reinforcement in concrete.

Non-destructive tests have been applied in the test and evaluation of properties of construction materials, such as bond between concrete layers [11], compressive strength [12,14] and other types of mechanical properties [15]. However, limited studies have been performed in applying non-destructive tests to measure reinforcement corrosion level in concrete members in a quantitative approach. Yeih and Huang [16] adopted ultrasonic testing for the non-destructive detection of concrete reinforcement corrosion, and found certain correlation between the reduction of ultrasonic amplitude and the electrochemical parameters of corrosion. Continued from the research of Yeih and Huang [16], this study aims to apply the ultrasonic test in measuring the corrosion level of non-uniform surfaces of rebar, and to evaluate the accuracy of ultrasonic test-based measurement on reinforcement corrosion level. Radial Basis Function (RBF)-based and Back Propagation (BP)-based models are applied and to be compared of their accuracies in the prediction. The study serves as the initial exploration of non-destructive tests of rebar corrosion level in non-uniform surfaces, leading to further research in establishing the non-destructive test procedure in measuring steel corrosion within reinforced concrete structures.

2. Experimental program

2.1. Linking reinforcement corrosion level to ultrasonic velocity

The corrosion process of reinforced concrete was defined by Zhao and Jin [17] in terms of three stages, namely: 1) the first stage of free expansion of rust, in which the steel corrosion products fill the rebar/concrete interface voids; 2) tensile stress within concrete cover, in which the concrete cover starts cracking; and 3) cracking within concrete cover, when the cracking continues to be filled with the rust products. Empirical formulas have been established to estimate the rebar corrosion level in concrete structures. Zhao and Jin [17,18] further proposed empirical formulas to estimate the corrosion depth of reinforcement. Zhao et al. [19] used stereoscopic microscope to observe the seriously corroded layer and found that the corrosion depth was not more than 500 μm. Following Huygens-Fresnel Principle [3], when the corrosion layer size is smaller than the wavelength, the ultrasound would diffract, resulting in a longer receiver signal. In addition, since the acoustic impedance of the air is far lower than that of concrete, sound energy would decrease and the sound duration would increase resulting from the reflecting and scattering of pulse wave at the corrosion surface. Therefore, it is feasible to detect the corrosion level of reinforcement in concrete according to the ultrasonic velocity. The effect of test specimen size described in Fig. 1 in ultrasonic velocity was studied by Zhang and Qiu [20].

As illustrated in Fig. 1, R denotes the rebar radius, δ represents the depth of steel corrosion layer, and L is the distance between the emission transducer and receiving transducer within the ultrasonic generator. It was previously found by Zhang and Qiu [20] that under the same ultrasonic velocity in concrete, the effect of rebar in ultrasonic velocity would be reduced as the ratio of rebar to the test distance (denoted as $2R/L$) decreases. When this ratios is lower then $1/12$, the effect of rebar size could be ignored according to Zhang and Qiu [20].

2.2. Experimental set-up

Four different types of reinforced concrete specimens, namely *C20, C25, C30*, and *C35*, were prepared by Gutetong Company from Ningbo China. The mix design details of these four types of specimens are provided in Table 1.

Totally *50* groups of concrete specimens were cast, among them *44* were prisms sized at $100\,mm \times 100\,mm \times 400\,mm$, and six of them being prisms sized at $150\,mm \times 150\,mm \times 550\,mm$, each prism was embedded with a hot-rolled round steel rebar with the diameter of *12 mm*. Cured at the standard laboratory condition for *28* days, specimens were placed in the chloride salt and stray current condition to reach different levels of rebar corrosion. Specifically, two types of corrosion tests were adopted in this study, namely chlorine salt wet-dry cycle and stray current method. In the chlorine salt wet-dry cycle approach, specimens after *28* days' standard curing were soaked and placed in 5% sodium chloride solution for *12 h*, and then oven dried in the temperature of 50 ± 1 °C for another *12 h*. This was counted as one wet-dry cycle. The same cycles were repeated to corrode reinforcement

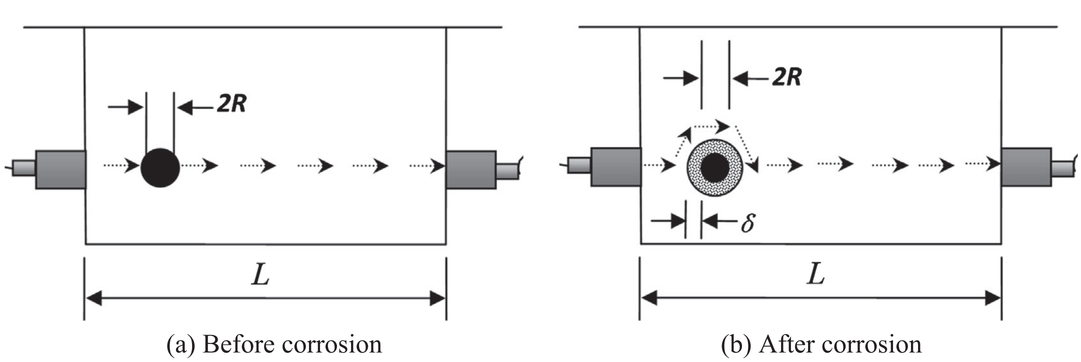

Fig. 1. Ultrasonic propagation path in reinforced concrete.