Combining Ultrasonic and Electromagnetic Techniques for Early Detection of Corrosion Damage in Reinforced Concrete Structures

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ABSTRACT

Corrosion of reinforcing bars has been established as a primary contributor to the deterioration of reinforced concrete (RC) structures. As corrosion products accumulate and expand, they generate tensile stresses within the concrete, ultimately leading to cracking and spalling of the concrete cover. Additionally, the reduction of cross-sectional area in reinforcing bars undermines the bonding strength of RC structures. To prolong the service life of RC structures, it is crucial to develop a robust monitoring system for early-stage corrosion damage assessment. Ultrasonic waves are sensitive to cracks and voids due to the large contrast in acoustic impedance between air and the background material, while electromagnetic waves are sensitive to metallic structures due to the substantial contrast in dielectric permittivity and conductivity. Therefore, this work studies the feasibility of combining ultrasonic and electromagnetic techniques for detecting early signs of corrosion damage, including cracks and reductions in the cross-sectional area of reinforcing bars. Ultrasonic coda wave interferometry method is used to monitor the growth of internal cracks in the reinforcing bar. A linear multiple-input-multiple-output (MIMO) GPR array is employed to image reinforcing bars in the concrete. In the early stages of corrosion, rust and small cracks grow, leading to changes in the GPR image. The performance of the proposed ultrasonic and electromagnetic methods has been demonstrated by the accelerated corrosion monitoring test in the lab.

INTRODUCTION

Reinforced concrete (RC) structures are widely used in civil engineering due to their high compressive strength, durability, and cost-effectiveness. However, corrosion of reinforcing bars has emerged as a crucial factor contributing to the degradation of RC structures. The accumulation of expansive corrosion products generates tensile stresses within the concrete, resulting in the formation of cracks and spalling of the concrete cover [1]. Moreover, the loss of cross-sectional area in reinforcing bars further compromises the bonding strength and load-bearing capacities of RC structures [2]. To enhance the service life of RC structures, it is imperative to develop efficient monitoring tech-

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niques for early detection and assessment of corrosion damage.

Non-destructive testing methods, such as ultrasonic and ground-penetrating radar (GPR), have been employed for the detection of corrosion damage in RC structures [3]. Studies have indicated that ultrasonic methods can detect corrosion damage by analysing the amplitude attenuation caused by corrosion-induced cracks [4]. In addition, ultrasonic techniques have been explored for imaging cracks and delamination resulting from severe corrosion using the SAFT algorithm [5, 6]. However, it is challenging to detect rust thinner than 1 mm due to the presence of aggregates in concrete, which attenuate and absorb wave energy. Additionally, ground-penetrating radar (GPR), which relies on electromagnetic (EM) wave propagation and reflection, has proven effective in monitoring corrosion development by detecting changes in the amplitude and arrival time of reflections from reinforcing bars [7, 8]. However, the initial stage of corrosion poses difficulties in reliable identification due to the utilization of a large wavelength in concrete.

In this study, we propose a monitoring method that combines ultrasonic coda waves and a multiple-input-multiple-output (MIMO) ground-penetrating radar (GPR) array for the reliable identification of early-stage corrosion. The coda wave interferometry (CWI) method is used to monitor the appearance of internal cracks. Additionally, a linear MIMO GPR array is used to obtain full-matrix data. The diffraction stacking algorithm is then applied to the acquired MIMO data to reconstruct reinforcing bars, which can be affected by the formation of rust and cracks with different dielectric permittivity. By examining the area enclosed by the reconstructed contour line, it becomes feasible to identify the progression of corrosion from a healthy state. The integration of ultrasonic and GPR array methods enables the determination of early-stage corrosion. Experimental corrosion monitoring tests were conducted to validate the effectiveness of this proposed monitoring method.

EXPERIMENTAL SETUP

Accelerated Corrosion Test

A reinforced concrete slab measuring 500 mm $\times$ 400 mm $\times$ 130 mm was cast and subjected to a curing period of 7 months before initiating corrosion testing. The slab was reinforced with three reinforcing bars having diameters of 10 mm, 13 mm, and 16 mm, respectively, and these bars were positioned at a depth of 30 mm from the surface. To simulate a realistic distribution of chlorides, the specimen was initially immersed in a 5% sodium chloride solution for a period of 5 days. Subsequently, it was removed from the water bath and stored in the laboratory for 2 months to achieve a relatively stable moisture content within the concrete. An accelerated corrosion process was achieved by subjecting the reinforcing bars to direct current under dry conditions. As depicted in Figure 1, the 10 mm diameter bar was connected to the negative terminal of a DC power source, while the 13 mm diameter bar was connected to the positive terminal. A constant voltage of 5 mV was applied between the two bars. The specimen underwent accelerated corrosion for a duration of 156 hours.

Periodic monitoring test using ultrasonic methods

The ultrasonic acquisition system for corrosion monitoring utilized two V106 ultrasonic transducers, which were affixed to a concrete surface with a spacing of 70 mm, as shown in Figure 1. A high-power computer-controlled ultrasonic system (RITEC RAM-5000) was utilized to generate a 3-cycle Hann-windowed tone-burst signal with a central frequency at 250 kHz. This frequency range was selected to ensure that the ultrasound wavelengths were comparable to the size of the aggregates, thereby facilitating strong multiple scattering effects. The received signals were digitized using a Lecroy HDO6054 oscilloscope at a sampling frequency of 25 MHz with a time window of 700 μs. Measurements were conducted at regular intervals of 12 hours, with each measurement repeated 10 times. The mean value of the repeated measurements was calculated to reduce potential measurement errors.

Periodic monitoring test using GPR array

The experimental setup for monitoring the corrosion of reinforcing bars in concrete using an MIMO GPR array is depicted in Figure 1. A linear array comprising 6 y-polarized antennas with a spacing of 10 mm was positioned on the concrete surface, with the middle antenna placed at a distance of 5 mm from the center of the anode reinforcing bar. A total of 801 sample points were recorded across an ultra-wide frequency band spanning from 2.9 GHz to 9 GHz using a vector network analyzer (Keysight VNA 5022A). Each antenna served as both a transmitter and a receiver. Sequential transmission of signals was carried out by the antennas, and the received signals from all antennas were collected to obtain a 6 $\times$ 6 full-matrix MIMO dataset. Measurements were performed at regular intervals of 12 hours throughout the accelerated corrosion process. Each measurement was replicated 6 times to account for variability, and the mean value was calculated to minimize potential measurement errors.

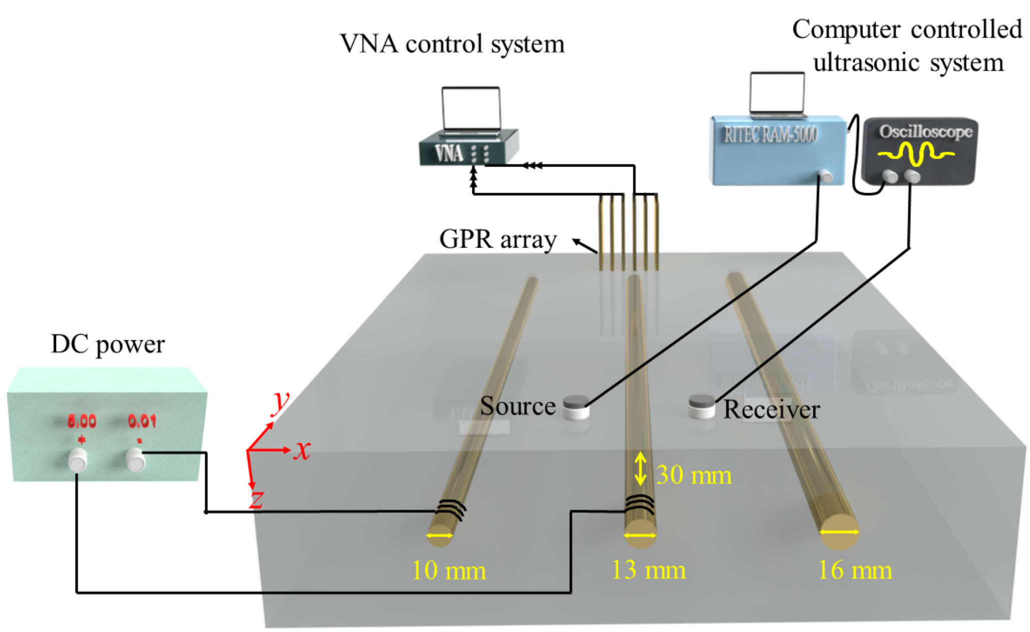

Figure 1. The setup of periodic monitoring test.

SIGNAL PROCESSING

Coda Wave Interferometry

The Coda Wave Interferometry (CWI) method was used to detect perturbations in the velocity of wave propagation within a medium by utilizing multiple scattering media as an interferometer [9]. The quantification of similarity between the reference signal $E_d(r, t')$ and the testing signal recorded after the perturbation $E_d{}'[r, t'(1 - \varepsilon')]$ was achieved by employing the cross-correlation function within a time window [T - T_w, T + T_w]. This enabled the calculation of a normalized correlation coefficient CC.

$$CC(T, T_w, \varepsilon') = \frac{\int_{T-T_w}^{T+T_w} \langle E_d{}'[r,t'(1-\varepsilon')]E_d(r,t')\rangle dt'}{\sqrt{\int_{T-T_w}^{T+T_w} E_d{}'[r,t'(1-\varepsilon')]^2 dt' \int_{T-T_w}^{T+T_w} E_d(r,t')^2 dt'}}. \quad (1)$$

Here ε' denotes the relative velocity variation; *T* represents the centre time of a time window with a duration of $2T_w$. Figure 2 shows an example of ultrasonic response obtained from the test concrete specimen, showing a comparison between the response acquired prior to accelerated corrosion and after a 12-hour corrosion duration. The inset highlights a waveform segment within the coda wave, specifically from 250 μs to 300 μs, where the variations associated with the presence of corrosion can be observed.

Diffraction Stacking Algorithm

The diffraction stacking algorithm is an imaging technique that combines signals

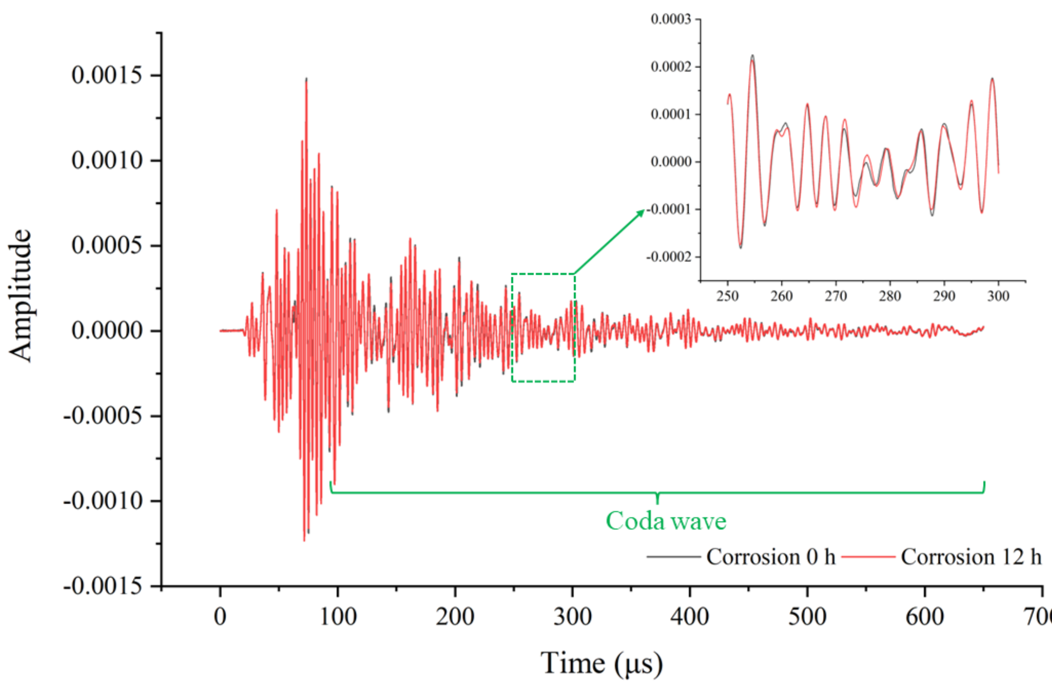

Figure 2. Waveforms acquired before accelerated corrosion and after a 12-hour corrosion duration with a black line and a red line, respectively.

acquired from various positions based on their respective time of flight [10, 11]. At each pixel position (x, z) within the image, the resulting intensity I represents the amplitude of the combined signal, which is calculated by

$$\begin{aligned} I(x,z) &= \left| \sum_{i=1}^{N} \sum_{j=1}^{N} CS_{ij}\left(\frac{d_i + d_j}{v}\right) \right| \\ &= \left| \sum_{i=1}^{N} \sum_{j=1}^{N} CS_{ij}\left(\frac{\sqrt{(x_i - x)^2 + z^2} + \sqrt{(x_j - x)^2 + z^2}}{v}\right) \right|, \end{aligned} \tag{2}$$

where N represents the total count of transmitters and receivers involved in the imaging process; The variable CS_{ij} denotes the complex signal in the time domain, referring to the transmission from antenna i and its reception by antenna j. x_i and x_j denote the x-coordinate of the transmitting antenna and receiving antenna, respectively; d_i represents the distance from the transmitter to the pixel position (x, z), while d_j represents the distance from the pixel position (x, z) to the receiver; v is the velocity of EM waves propagating through concrete. Figure 3 shows a reconstructed image of the reinforcing bar using this imaging algorithm. The area enclosed by the reconstructed contour line of -3 dB of the maximum intensity was analysed to monitor the corrosion damage.

RESULTS AND DISCUSSION

The correlation coefficient (CC) between the signals acquired from the specimen without corrosion and with different levels of corrosion was plotted in Figure 4(a). It is noteworthy that no surface cracks were observed during the monitoring test, indicating the early stage of corrosion. A slight decrease in CC value was observed during the initial 36 hours. This is believed to be a result of tensile stress induced by the generation of

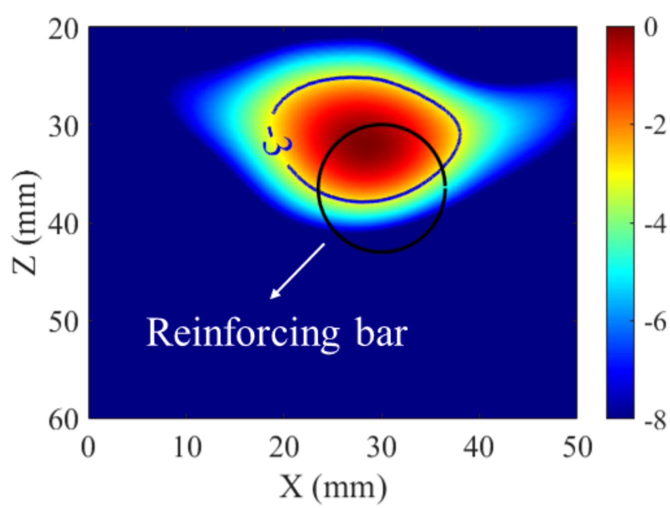

Figure 3. Diffraction stacking migration imaging for the anode reinforcing bar without corrosion. The black circle represents the actual reinforcing bar.

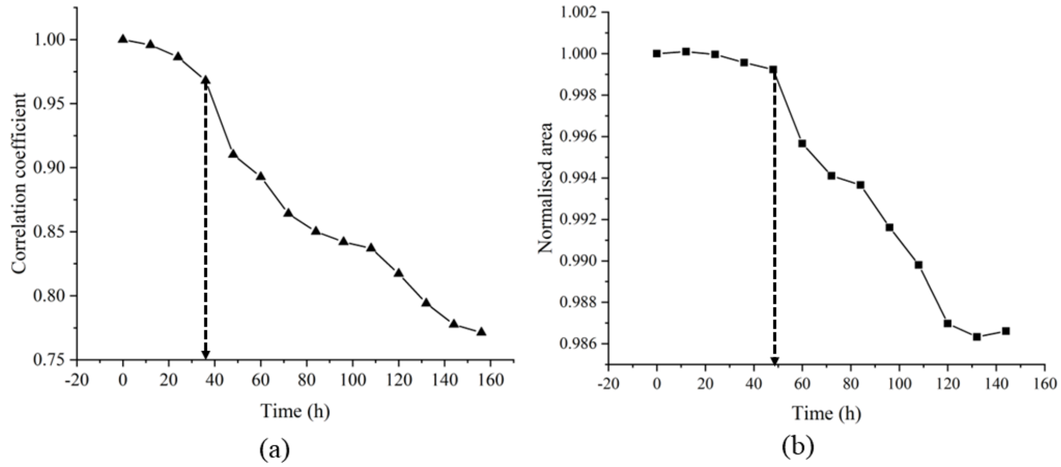

Figure 4. The variation in (a) correlation coefficient (CC), and (b) areas enclosed by the reconstructed contour lines during the corrosion monitoring test.

expansive corrosion products (rust). As the corrosion progressed, a substantial decrease in the CC value became evident after a 36-hour duration of corrosion. This decrease is likely attributed to the emergence of internal cracks within the concrete, resulting in significant variations in wave velocity due to multiple scattering from them.

Figure 4(b) illustrates the variation of the area enclosed by the reconstructed contour line of -3 dB for experimental corrosion monitoring using GPR array measurements. Initially, there was a minimal change in the enclosed area within the first 48 hours of corrosion. This occurrence can likely be attributed to the insensitivity of the radar wave to the formation of rust (thinner than 1 mm), owing to the utilization of a large wavelength (approximately 15 mm) in concrete. However, as the corrosion damage progressed and accumulated, a notable decrease in the enclosed area was observed. This decrease can be attributed to the presence of internal cracks, resulting in lower dielectric permittivity.

Through the integration of monitoring results obtained from ultrasonic coda wave and the GPR array methods, it can be seen that during the initial 36 hours of corrosion, a slight decrease in the CC value was observed, accompanied by a minimal change in the enclosed area of the reconstructed image. As the corrosion developed, a substantial decrease in the CC value was observed after the 36-hour accelerated corrosion period, while a notable decrease in the enclosed area was observed after the 48-hour accelerated corrosion period. This observation suggests the appearance of internal cracks within the concrete. The discrepancy in crack detection between the ultrasonic and GPR results can be attributed to the greater sensitivity of ultrasound in detecting cracks, primarily due to the large contrast in acoustic impedance between concrete and air.

CONCLUSION

This study presents a monitoring method for the early-stage detection of corrosion damage in concrete. The CWI method was used to monitor the appearance of internal cracks based on the variation in wave propagation velocity of ultrasound. Additionally, a linear MIMO GPR array was employed to reconstruct the reinforcing bars within the concrete, which would be affected by rust and cracks with various dielectric permittivity. By integrating ultrasonic coda waves and MIMO GPR array, the accumulation of rust and subsequent cracking can be indicated. The experimental monitoring results demonstrated the effectiveness of the proposed method, highlighting its potential for practical application in RC structure maintenance and preservation.

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