Reliable Corrosion Monitoring in RC Structures Using a Temperature-Insensitive GPR Approach

WEIXIA CHENG, ZIQIAN YANG and ZHENG FAN

ABSTRACT

Corrosion of reinforcing bars is a primary cause of deterioration in reinforced concrete structures. Early detection of corrosion is critical for timely maintenance and ensuring structural safety. Ground penetrating radar (GPR) has shown strong potential for corrosion monitoring due to its sensitivity to changes in material properties induced by corrosion. However, conventional GPR systems face challenges in detecting early-stage corrosion and tracking variations in corrosion rate, primarily due to their limited responsiveness to subtle material changes and susceptibility to signal dispersion caused by temperature fluctuations. To address these limitations, we propose a monitoring method based on a perpendicular-polarized antenna system, which enhances electromagnetic interaction with the cross-section of rebars. This configuration enhances sensitivity to subtle corrosion-induced material changes surrounding the rebars. In addition, a temperature-insensitive intersection point, derived from second-order rebar reflections, is introduced as a reliable indicator for tracking corrosion progression. This point amplifies the detection of subtle corrosion-induced changes through multiple signal interactions while maintaining robustness against temperature-induced signal dispersion. Experimental results validate the effectiveness of the proposed method, demonstrating enhanced sensitivity to early-stage corrosion and improved tracking of corrosion rate variations. The approach offers a reliable and robust solution for long-term, non-destructive corrosion monitoring in reinforced concrete structures.

INTRODUCTION

Corrosion of reinforcing bars (rebars) is one of the leading causes of degradation in reinforced concrete (RC) structures. It is typically initiated by the ingress of chlorides or carbon dioxide, in the presence of oxygen and moisture, leading to the formation of expansive corrosion products (rust) [1]. This expansion induces cracking and spalling of the concrete cover, posing safety risks and increasing maintenance costs. Therefore, early detection of corrosion is essential for timely intervention and cost-effective maintenance.

Zheng Fan, Associate Professor, Email: zfan@ntu.edu.sg School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore

Ground penetrating radar (GPR) has shown promise for corrosion assessment due to its sensitivity to changes in dielectric properties caused by corrosion processes [2]. Conventional GPR systems, typically employing parallel-polarized antennas, monitor amplitude and arrival time variations in rebar reflections during corrosion progression [3, 4]. However, their effectiveness in detecting early-stage corrosion remains limited, owing to the subtle nature of permittivity changes and the influence of temperature-induced signal dispersion. To enhance detection performance, multiple-input-multiple-output (MIMO) GPR systems with temperature compensation mechanisms have been developed [5]. Although improved sensitivity has been reported, these systems are generally characterized by high complexity and elevated cost. Alternatively, dual-polarized GPR systems have been proposed to enhance electromagnetic interaction with the rebar cross-section through perpendicular polarization [6, 7]. Despite an observed enhancement in sensitivity, these systems still exhibit limited capability in identifying corrosion in the early corrosion stages (within 10 days) [6].

Despite these limitations, perpendicular-polarized antenna systems offer greater potential for early-stage corrosion detection than conventional parallel-polarized systems, owing to their enhanced interaction with the cross-section of rebars. To further improve sensitivity to minor corrosion damage and variations in corrosion rate, this study proposes a monitoring method based on second-order rebar reflections acquired using a perpendicular-polarized antenna. These second-order rebar reflections, resulting from multiple signal interactions, amplify corrosion-induced changes in the received signals, thereby enhancing the detectability of subtle damage. To mitigate temperature-induced dispersion, a temperature-insensitive intersection point within the second-order reflections is introduced as a reliable indicator for corrosion monitoring. This point exhibits consistent signal characteristics across varying temperatures, ensuring robust and reliable corrosion monitoring. Experimental results validate the effectiveness of the proposed approach in detecting early-stage corrosion and capturing changes in corrosion rate throughout the corrosion process.

EXPERIMENTAL SETUP

Accelerated Corrosion Test

An RC specimen with two embedded steel rebars (16 mm in diameter) was prepared for the accelerated corrosion test. The specimen measured 600 mm $\times$ 300 mm $\times$ 100 mm and was cured for 28 days before being submerged in a 5% sodium chloride solution for 5 days. After immersion, it was removed from the solution and stored under laboratory conditions for two months to allow moisture equilibration. Subsequently, an accelerated corrosion test was conducted by applying direct current (DC) power. One rebar was connected to the positive terminal and served as the anode, while the other was connected to the negative terminal and served as the cathode. To evaluate the responsiveness of GPR signals to changes in corrosion rate, the applied voltage and current at various time intervals are summarized in Table I. The RC sample was subjected to abrupt changes in applied voltage between 15 V and 31 V, allowing the evaluation of GPR signal sensitivity to changes in corrosion intensity. Furthermore, to examine the influence

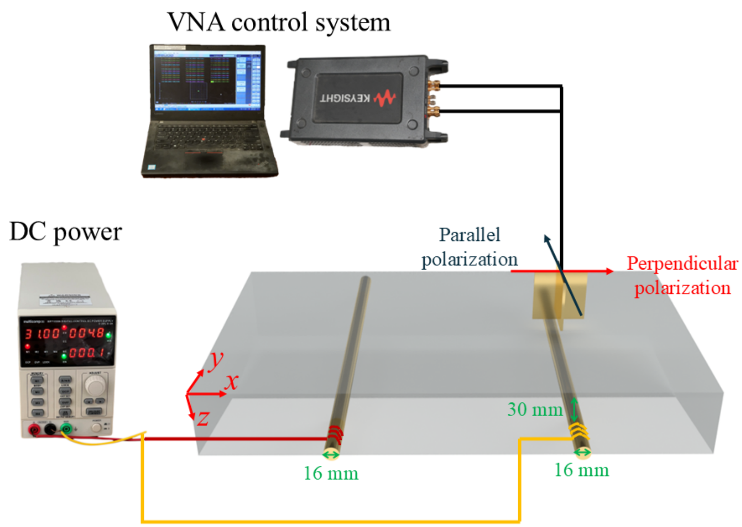

Figure 1. The setup of periodic GPR monitoring test.

TABLE I. Voltage Regime of RC Sample During Accelerated Corrosion

Corrosion Time (h)	**Voltage (V)**	**Current (A)**	**Crack Codition**
0-69	15	0.0018	
69-153	31	0.0048	Surface crack appeared at 420th corrosion
153-257	15	0.0018	
257-467	31	0.0048	

of cracking on GPR performance, the experiment was terminated when surface crack propagation was observed to significantly interfere with signal detection.

Periodic monitoring test using dual-polarized GPR system

The monitoring setup for tracking corrosion progression using a dual-polarized GPR system is illustrated in Figure. 1. The system employed two antennas: one aligned parallel to the longitudinal axis of the rebar and the other perpendicular, enabling the excitation of horizontally and vertically polarized electromagnetic waves, respectively. Each antenna functioned as both transmitter and receiver and was positioned on the surface of the RC specimen. A total of 2001 sample points were recorded across an ultra-wide frequency range of 500 MHz to 9 GHz using a vector network analyzer (Keysight VNA 5002A). Measurements were conducted at predefined intervals throughout the accelerated corrosion process. During the early stages, data were collected every three hours to capture subtle changes in material properties. As the corrosion progressed, the measurement interval was extended to 24 or 48 hours to monitor long-term trends.

SIGNAL PROCESSING

Figure 2 presents waveforms from a healthy rebar with temperature variations from

22.14°C to 26.25°C. Even in the absence of corrosion, noticeable changes in both amplitude and arrival time are observed — particularly in the second-order reflections — highlighting the significant influence of temperature fluctuations. To mitigate this effect, a temperature-insensitive intersection point within the second-order reflections is employed as an indicator for corrosion monitoring. At this intersection point, the amplitude remains stable across varying temperatures, providing a robust indicator for assessing corrosion progression. The existence of this intersection point is attributed to the dual influence of the dielectric permittivity on both the attenuation and phase constants of the electromagnetic waves. These concurrent changes in amplitude and velocity can offset each other at a specific time instant, resulting in a temperature-invariant response. In contrast, if only one of these parameters were affected by temperature, such an intersection point would not be observed.

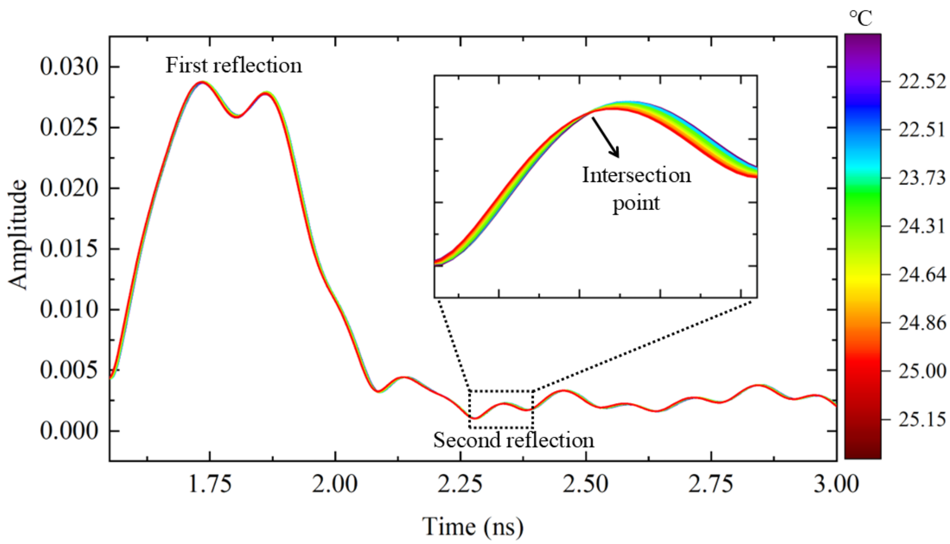

Figure 2. Waveforms of a healthy rebar acquired using a perpendicular-polarized antenna with temperature changing from 22.14°C to 26.25°C.

Figure 3 compares the normalized amplitudes at the peak and intersection points of second-order rebar reflections under temperature variations from 22.14°C to 26.25°C. The results show that temperature-induced amplitude fluctuations are significantly reduced at the intersection point, with the standard deviation decreasing from 0.007 to 0.001. These findings demonstrate that the intersection point provides a robust, temperature-insensitive indicator for corrosion monitoring.

RESULTS AND DISCUSSION

To assess the effectiveness of the proposed method in early-stage corrosion detection, we compared monitoring results over a 101-hour corrosion period obtained using two approaches: the conventional GPR method, which relies on the maximum amplitude of first-order rebar reflections, and our method, which utilizes the intersection point of second-order reflections. In both cases, amplitude increases over corrosion time due to

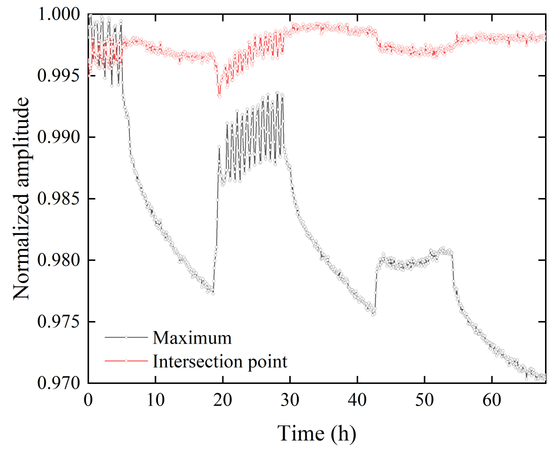

Figure 3. Normalized amplitudes at the peak and intersection points of second-order rebar reflections acquired using the perpendicular-polarized antenna under temperature variations from 22.14°C to 26.25°C.

the formation of additional reflection interfaces caused by rust accumulation around the rebars. However, a notable difference in sensitivity is observed: while the amplitude of first-order reflections begins to increase only after 50 hours of corrosion, second-order reflections exhibit a clear response as early as 6 hours. This enhanced sensitivity is attributed to the extended propagation path of second-order reflections, which amplifies signal variations linked to subtle material changes. These findings demonstrate that the proposed method significantly outperforms conventional GPR analysis in the early detection of corrosion.

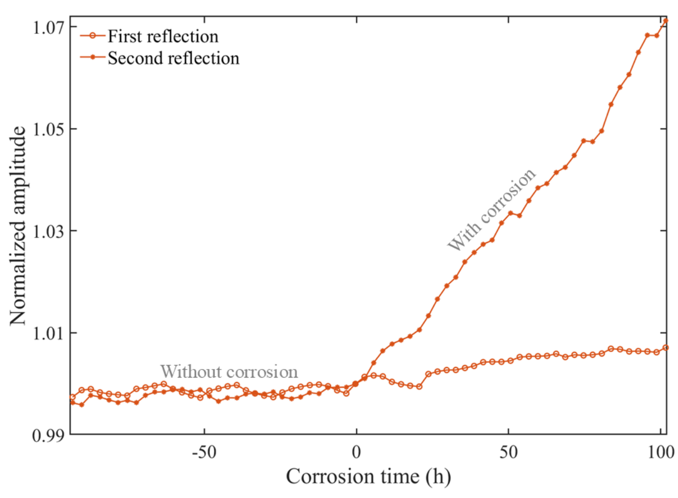

Figure 4. Normalized amplitude at the intersection point of second-order rebar reflections during the initial 101 hours of accelerated corrosion, acquired using the perpendicular-polarized antenna.

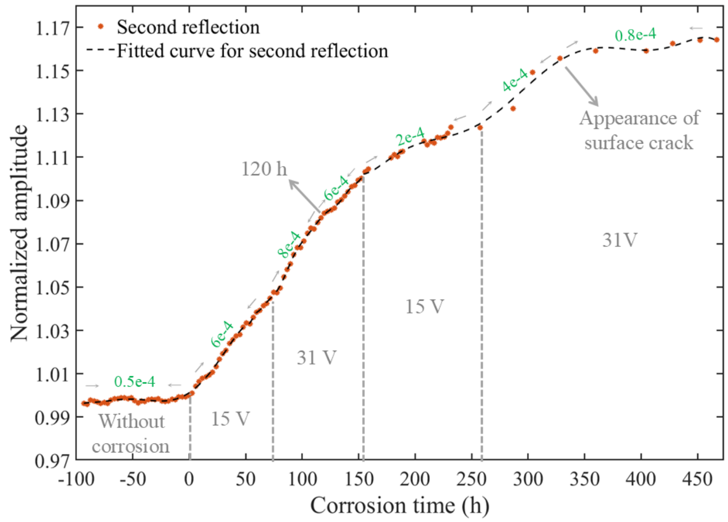

Figure 5. Variation in amplitude at the intersection point of second-order rebar reflections over a 467-hour accelerated corrosion period, with the corresponding slope of the fitted amplitude variation curve highlighted in green.

To further evaluate the sensitivity of the proposed monitoring method to changes in corrosion rate, we examined the normalized amplitude at the intersection point of second-order reflections over a 467-hour corrosion period, as shown in Figure 5. During this period, the applied voltage varied between 15 V and 31 V, which led to corresponding increases or decreases in corrosion rate according to Faraday's law [8]. A distinct change in the slope of the monitoring curve is evident when the applied voltage increases from 15 V to 31 V, indicating an accelerated corrosion process. To quantify this trend, a fitted curve is shown as a black dashed line. The corresponding slope values under different voltage conditions are highlighted in green in Figure 5, which clearly illustrates that the slope of the amplitude variation curve increases with higher applied voltage (i.e., higher corrosion rate). This behavior can be attributed to greater rust accumulation around the rebar, leading to changes in both the material and geometric properties at the interface, and thereby enhancing electromagnetic reflectivity. In contrast, lower applied voltages result in slower corrosion rates, reduced rust formation, and smaller amplitude changes, leading to a reduced slope.

Notably, during the 153–257 h period under 15 V, the slope decreases compared to the initial application. Under 31 V, two significant reductions in slope are observed: the first near 120 hours, and the second after the appearance of surface cracks. These reductions are likely due to the development of internal cracking. The associated decrease in dielectric permittivity and effective rebar area attenuates the signal amplitude and diminishes the slope of the monitoring curve.

Overall, the results demonstrate that the intersection point of second-order reflections provides a reliable indicator of corrosion progression, showing high sensitivity to both early-stage corrosion damage and changes in corrosion rate.

CONCLUSION

In this study, we propose a corrosion monitoring approach that leverages second-order rebar reflections acquired using a perpendicular-polarized antenna system to detect early-stage corrosion and variations in corrosion rate. The perpendicular configuration enhances sensitivity by increasing electromagnetic interaction with the rebar cross-section, while second-order reflections amplify subtle material changes through multiple signal interactions. To mitigate temperature-induced signal dispersion, we employ a temperature-insensitive intersection point within the second-order reflections as a reliable indicator for corrosion tracking. This point demonstrates both high sensitivity to corrosion progression and robustness against thermal fluctuations. Experimental results confirm that this approach outperforms conventional first-order reflection analysis, providing reliable early detection and assessment of changes in corrosion rate.

Overall, this study presents a temperature-insensitive and highly sensitive technique for non-destructive corrosion monitoring, offering significant potential for structural health assessment. Future work will explore the influence of crack formation on signal interpretation and aim to enhance the accuracy of rebar mass loss estimation under real-world conditions.

ACKNOWLEDGMENT

The authors acknowledge funding from the Ministry of Education of Singapore Tier-1 grant (RG149/23).

REFERENCES

1. Cabrera, J. G. 1996. "Deterioration of concrete due to reinforcement steel corrosion," *Cement and Concrete Composites*, 18(1):47–59.
2. Sbartaï, Z., S. Laurens, J.-P. Balayssac, G. Arliguie, and G. Ballivy. 2006. "Ability of the direct wave of radar ground-coupled antenna for NDT of concrete structures," *NDT E Int.*, 39(5):400–407.
3. Sossa, V., V. Pérez-Gracia, R. González-Drigo, and M. A. Rasol. 2019. "Lab non destructive test to analyze the effect of corrosion on ground penetrating radar scans," *Remote Sens.*, 11(23):2814.
4. Lai, W.-L., T. Kind, M. Stoppel, and H. Wiggenhauser. 2013. "Measurement of accelerated steel corrosion in concrete using ground-penetrating radar and a modified half-cell potential method," *J. Infrastruct. Syst.*, 19(2):205–220.
5. Cheng, W., H.-H. Sun, K. H. Tan, and Z. Fan. 2024. "Early detection of corrosion damage in reinforced concrete using GPR array imaging method," *IEEE Transactions on Instrumentation and Measurement*.
6. Liu, H., J. Zhong, F. Ding, X. Meng, C. Liu, and J. Cui. 2022. "Detection of early-stage rebar corrosion using a polarimetric ground penetrating radar system," *Constr Build Mater.*, 317:125768.
7. Sun, H.-H., W. Cheng, and Z. Fan. 2023. "Diameter Estimation of Cylindrical Metal Bar Using Wideband Dual-Polarized Ground-Penetrating Radar," *IEEE Trans. Instrum. Meas.*, 72:1–14.
8. Perez, N. 2004. *Electrochemistry and corrosion science*, Springer.