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Research on the Corrosion Behavior and Cathodic Protection of Defected-Epoxy-coated Reinforcement Exposed to Chloride Environment

Dongfang Zhang[1,2,3*], Guoqiang Liu[1,2], Haoxiang Chen[1,2], Zhihong Fan[1,2,3]

[1] Key Laboratory of Harbor & Marine Structure Durability Technology, Ministry of Transport, CCCC Fourth Harbor Engineering Institute Co., Ltd, Guangzhou 510230, PR China, zhangdf8@mail.sysu.edu.cn (Dongfang Zhang), lguoqiang@cccc4.com (Guoqiang Liu), chaoxiang@cccc4.com (Haoxiang Chen), fzhihong@cccc4.com (Zhihong Fan), xjianbo@cccc4.com (Jianbo Xiong), wshengnian@cccc4.com (Shengnian Wang)

[2] Southern Marine Science and Engineering Guangdong Laboratory (Zhuhai), Zhuhai 519080, PR China

[3] National Observation and Research Station of Material Corrosion and Structural Safety of Hong Kong-Zhuhai-Macao Bridge in Guangdong, Zhuhai 519060, PR China

Abstract. *The application of epoxy coated rebar (ECR) is an effective method to improve the durability of reinforcement in chloride environment. However, the coating defects caused in construction will significantly decrease its corrosion resistance to chloride. Herein, the corrosion behaviors of different defects rate in ECR under chloride attack in South China are investigated. The results indicate that the corrosion of ECR is due to the coating defects, the corrosion potentials of defected-ECR are shifted to negative, and the corrosion current density is significantly increased with increasing the defect rate. The corrosion resistance of defected-ECR is improved by applying the anode-mortar cathodic protection system, both the exposure test and engineering application all show that the durability of defected-ECR is increased with the high polarization potential (⩾200mV) and negative protection potential (<-800 mV).*

Keywords: *Epoxy Coated Rebar, Defect, Corrosion Behavior, Cathodic Protection.*

1 Introduction

Due to the diverse structure and complex service environment, the durability of the reinforced concrete caused by chlorine are prominent (Li et al. 2019, Qu et al. 2021). Epoxy coated-rebar is benefited with the high chemical stability and strong adhesion, helps to form an anti-corrosion barrier against external corrosive media on the surface of the steel bar, resulted in improving the corrosion resistance of the steel bar when applied in marine infrastructure (Cao et al. 2022). However, the effectiveness of epoxy-coated rebar as a corrosion control method in reinforced concrete exposed to marine environment is still a controversial condition (Mao et al. 2018, Sagues et al. 1994). The long-term observation of epoxy coated rebar in marine bridges conducted in USA, illustrated a serious durability problem, and even pushed the forbidden of epoxy coated rebar applied in marine structures (Kessler et al. 2001, Sagues et al. 2010, Sagues et al. 1996). However, the other studies revealed that the epoxy coated rebar could still be used as an alternate to steel after the coating was modified (Rahman, et al. 2022). The defects of epoxy-coated rebar that caused by construction are the main factor affecting its performance (Lliso-Ferrando et al. 2022). The defects and other parts of the coating will produce small anode and large cathode macro cell corrosion, which can accelerate the point corrosion of the steel bar at the defects, resulting in a faster decline in the durability of the concrete structure (Keßler, S. et al. 2015). The above studies are basically based on the indoor simulated environment to study the corrosion of defective coated steel bars. There are few reports on the corrosion behavior and protective method of the defective coated steel bars in high-performance concrete under the real marine environment. It is well known that damaged epoxy-coated reinforced concrete structures are already in service period, it is necessary to take measures to improve the service life of epoxy-coated reinforced concrete structures (Dong et al. 2012). In this paper, the corrosion behavior of defective coated steel bars in high performance concrete is studied in South China. A composite cathodic protection technology based on sacrificial anode and active mortar was developed to analyze the enhancement effects of cathodic protection technology on different damage rates of defective coated steel bars in concrete.

2 Experiments

The detailed information of concrete material was shown in Table 1. The defect rates of the coating surface are 0%, 0.1%, 0.2% and 0.5% (accounting for coating surface area) respectively, denoting ECR-0%, ECR-1%, ECR-2% and ECR-5%. The rebar was connected with a cooper wire (the joint was sealed and the surface of cooper was coated with insulation layer to avoid the galvanic corrosion), all the concrete samples were coated with epoxy resin except for the expose surface, which was expose to the marine environment for 1 year. In addition, a sacrificial anode-active mortar composite cathodic protection system was used to improve the durability of defective coated steel bars in the marine environment, denoting ECR-0%/CP, ECR-1%/CP, ECR-2%/CP and ECR-5%/CP. The cathodic protection was worked by connect the wires between defected rebar and sacrifice anode-active mortar.

Table 1. The content of high performance concrete / %

Cement	Fly ash	Ganister	Sand	Gravel/mm		Water	NaCl	Admixture
				5-20	10-20			
0.719	0.25	0.03	1.74	0.50	2.00	0.36	0.004	0.0167

As shown in Figure 1a, the corrosion performance was determined by open circuit potential (OCP), potentiodynamic polarization and EIS in an electrolyte cell. The OCP measurement time was set as 600s. Potentiodynamic polarization tests were carried out at a scan rate of 0.167 mV s^{-1}. The corrosion potential (E_{corr}) and the corrosion current density (i_{corr}) were calculated using the Tafel extrapolation method. The EIS spectra were measured in a frequency range from 10 mHz to 100 kHz with a sinusoidal AC perturbation with an amplitude of 10 mV. As we try to evaluate the cathodic protection of sacrificial anode-active mortar composite cathodic protection system to defected ECR, a potentiometer was used to detected the potential of defected ECR and ECR/CP. The potential of ECR/CP was tested after break off the connected wire between defected rebar and sacrifice anode-active mortar for 0.5s (Figure 1b).

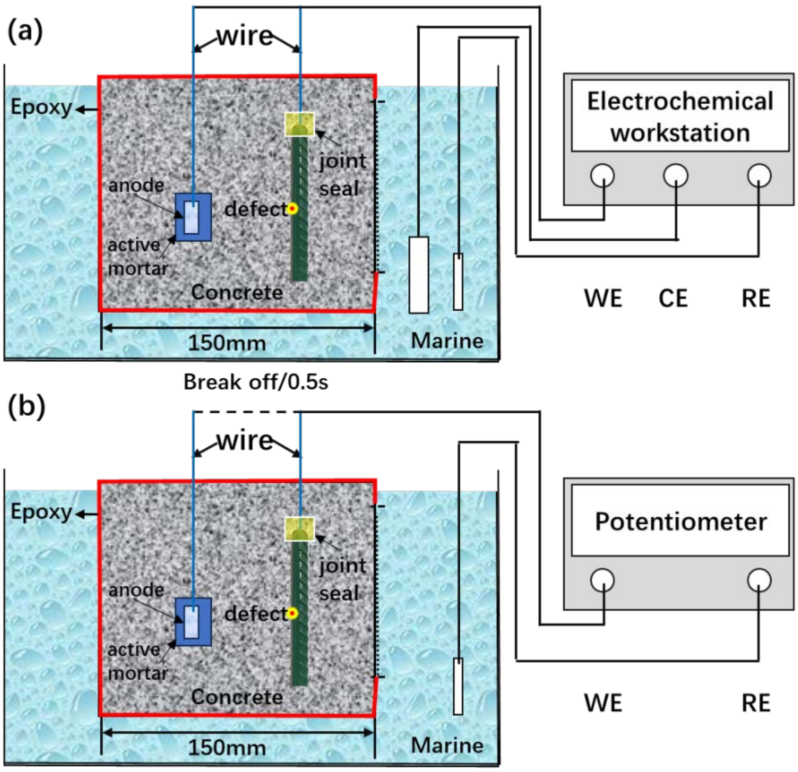

Figure 1. The schematic diagram of (a) corrosion test and (b) potential test.

3 Results and Discussion

3.1 Corrosion Behaviors of the Defected-ECR

As shown in Figure 2a and Table 2, corrosion behaviors of coated steel bars with different defect proportion in concrete are tested. All the samples maintain relatively stable OCP, range from -0.077V, -0.554V, -0.626V to -0.683V with increasing the defect proportion. The potential of the ECR-0% is significantly higher than that of other samples with defect, which is mainly due to the shielding effect of the complete epoxy coating on the corrosive medium. According to the relevant provisions of Technical Specifications for the Inspection and Evaluation of Hydraulic Buildings of Water Transportation Engineering, when the test potential is less than -350 mV/CSE, the corrosion probability of steel bar is greater than 90%, which indicates that the defected ECR have corroded.

In order to further evaluate the corrosion performance of different samples, potentiodynamic polarization curve was conducted. The fitting results of corrosion potential and corrosion current were shown in Figure 2b and Table 2. The corrosion potential moves positive by 500mV compared with the defected ECR, and the corrosion current density drops to 4×10^{-5} μAcm^{-2}. When the epoxy coating is damaged, the corrosion current density of the ECR-1% increases significantly to 0.41 μAcm^{-2}, indicating that the defected ECR has been corroded with the attack of chloride. And the corrosion current density increases further when the defect rate increases to 0.2% and 0.5%.

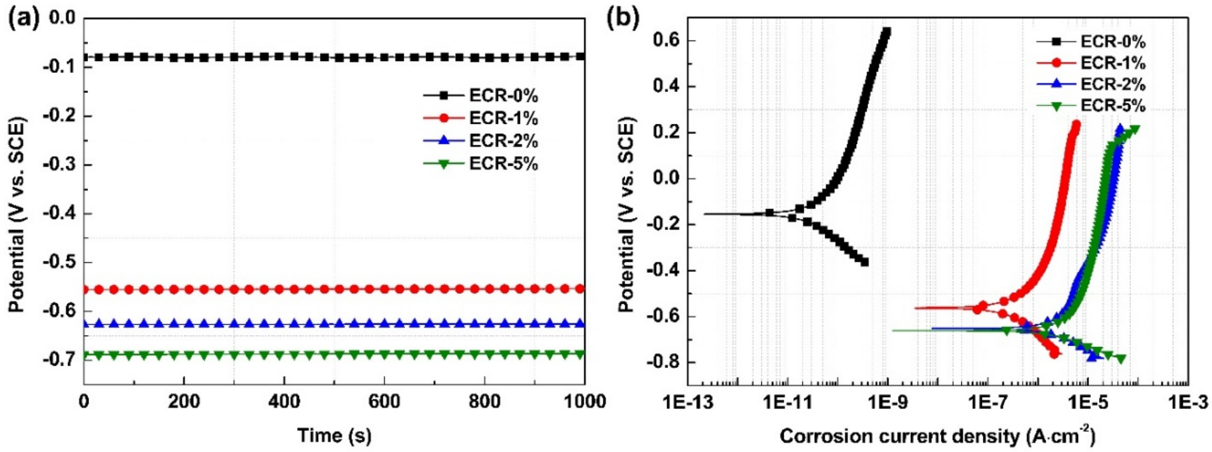

Figure 2. Open circuit potential (a) and tafel curves (b) of the ECR with different defect proportion.

Table 2. The calculated corrosion data of different defected epoxy coated reinforcement

NO.	OCP (V vs. SCE)	E_{Corr} (V vs. SCE)	i_{corr} (μAcm^{-2})
ECR-0%	-0.077	-0.155	4×10^{-5}
ECR-1%	-0.554	-0.560	0.41
ECR-2%	-0.626	-0.652	2.54
ECR-5%	-0.683	-0.661	3.62

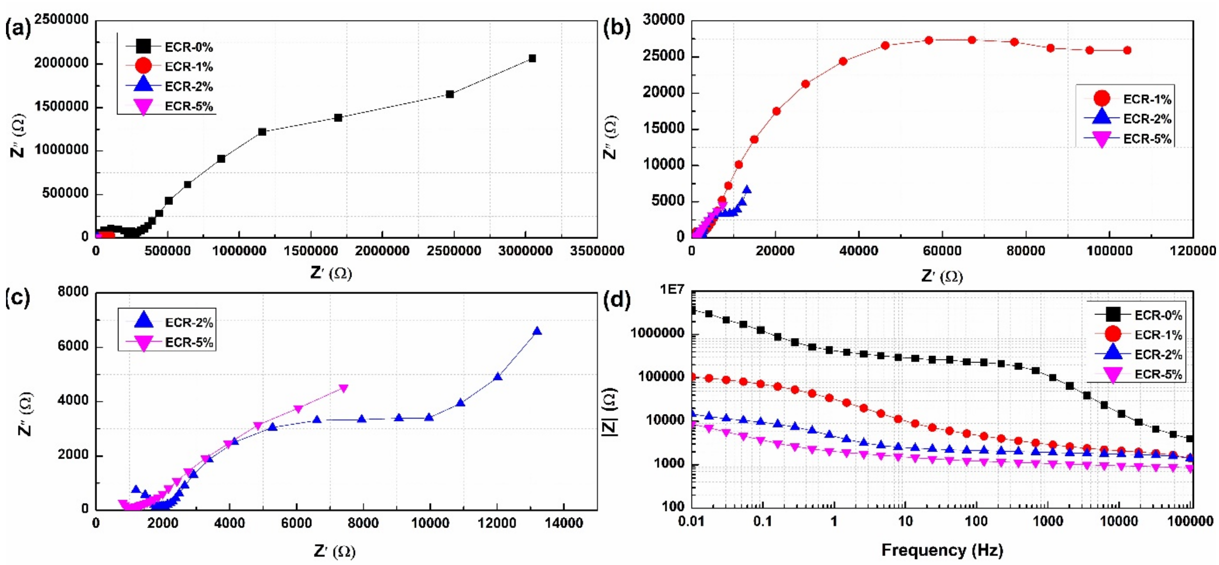

Figure 3. EIS of different defected epoxy coated reinforcement: (a-c) Nyquist and (d) Bode

The AC impedance spectrum test results are shown in Figure 3. The steel bar with undamaged coating shows a two time constants in concrete, respectively representing the concrete protective layer and epoxy coating. The impedance values in the low-frequency region are significantly greater than those of other test samples. Once the coating is damaged, the time constant caused by the coating disappears, which further indicates that the chlorine in concrete has caused the corrosion of the steel bar at the defect. Both the OCP and polarization curves reveal that the coating defect could lead to a significant decrease in durability of ECR in marine environment.

3.2 Corrosion Behaviors of Defected-ECR with Cathodic Protection

In order to improve the durability of defected ECR, based on the principle of cathodic protection, a composite cathodic protection system of sacrificial anode and active mortar was prepared and buried in concrete and connected with damaged coated bars to avoid the corrosion problem (Figure 1). The corrosion behaviors and fitting results of corrosion potential and corrosion current density were shown in Figure 4 and Table 3. Compared with Figure 1, once the cathodic protection is applied, the OCP of all samples is lower than -800mV, which is lower than the protection criterion of -780mV/CSE. The corrosion current density of ECR/CP samples were increased significantly than that of the defected ECR samples, it mainly due to the corrosion of anode (Zn). As for the ECR-0%/CP, the corrosion current density of 4.48 μAcm^{-2} can be deduced to the corrosion of anode, because the epoxy coating was intact. So, the much higher and continuous emission current of the Zn anode under the action of active mortar provides protection for the defected ECR. On the other hand, the anode could maintain activity even in concrete, that produce a key factor to the cathodic protection system.

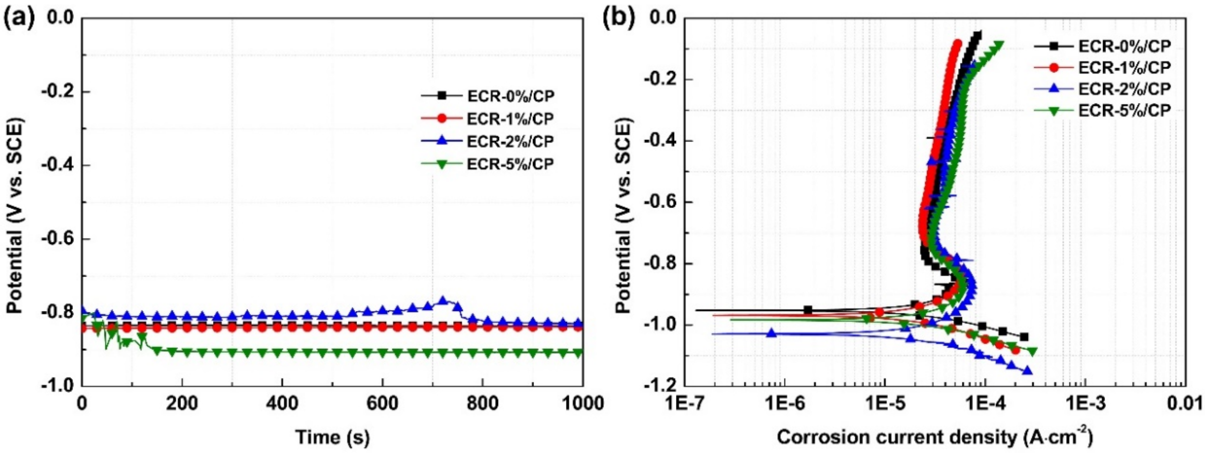

Figure 4. The open circuit potential (a) and tafel curves (b) of different defected epoxy coated reinforcement with cathodic protection

Potential test was conducted to evaluated the effect of cathodic protection to defected ECR (according to Figure 1b). Figure 5 shows the potential changes of the ECR with different defected rates and after connecting with the cathodic protective system. Compared with the results in Figure 1, the potential of the defected ECR was varied greatly over time. The steel bars at defects continued to react with OH^- generated by hydration, so the potential changed greatly in about 2 months at the initial stage of the test. By comparing the put-off potential difference between the cathodic protection samples and the steel samples with different coating defects (Figure 5b), that the cathodic protection system can provide a protective overpotential with a value of no less than 200mV for the defected ECR, and the overpotential further increases with the decrease of the defect proportion.

Table 3. The calculated corrosion data of different defected epoxy coated reinforcement with cathodic protection

NO.	OCP (V vs. SCE)	E_{Corr} (V vs. SCE)	i_{corr} (μAcm^{-2})
ECR-0%/CP	0.838	-0.969	4.48
ECR-1%/CP	0.829	-0.952	4.02
ECR-2%/CP	0.835	-1.092	4.24
ECR-5%/CP	0.907	-0.983	4.43

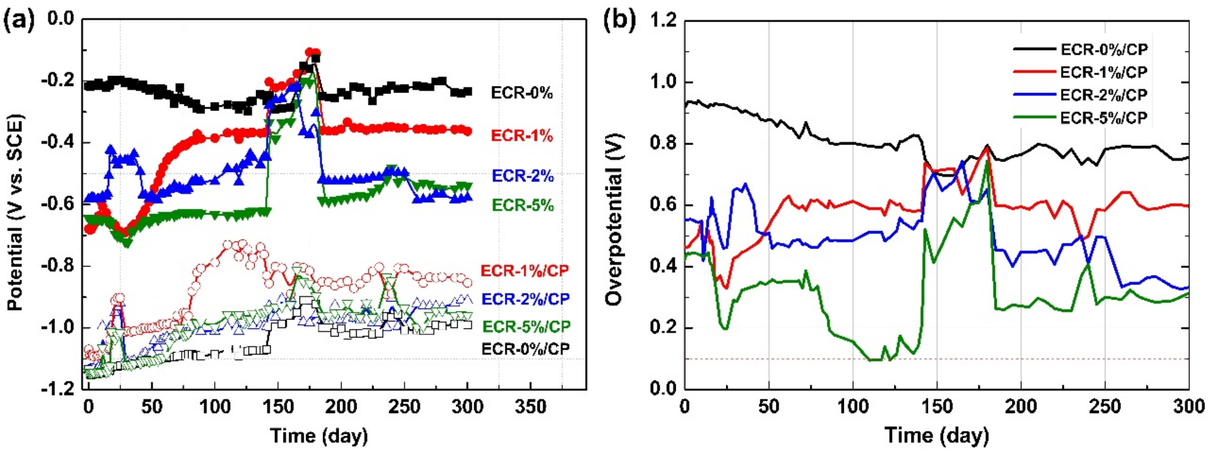

Figure 5. Potential curves (a) and overpotential (b) of different defected epoxy coated reinforcement with increasing the exposed time.

4 Conclusion

Epoxy coated rebar can effectively improve the durability of concrete structures in marine environment, while coating defects are the main factors that reduce the corrosion resistance of coated steel bars to chloride. However, the coating defect proportion of 0.2% can significantly reduce the corrosion resistance of ECR. The sacrificial anode-active mortar composite cathodic protection system can repair the defective coated steel, and both the cathodic corrosion current density and overpotential could meet the protective requirements.

Acknowledgements

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References

Li, K., Zhang, D., Li, Q., & Fan, Z. (2019). *Durability for concrete structures in marine environments of HZM project: Design, assessment and beyond.* Cement and Concrete Research, 115, 545.

Qu, F., Li, W., Dong, W., Tam, V. W., & Yu, T. (2021). *Durability deterioration of concrete under marine environment from material to structure: A critical review*. Journal of Building Engineering, 35, 102074.

Cao, H., Lyu, Z., Dong, W., Zhao, Z., Gan, W., & Wang, Y. (2022). *Corrosion Experimental Research on Local Damage of Epoxy-Coated Steel Bars in Concrete Under Marine Environment.* Frontiers in Materials, 8, 821716.

Sagüés, A. A., Powers, R. G., & Kessler, R. (1994). *Corrosion processes and field performance of epoxy-coated reinforcing steel in marine substructures (No. CONF-940222).* NACE International, Houston, TX (United States).

Kessler, R. J., Sagues, A. A., & Powers, R. G. (2001). *Corrosion performance of epoxy-coated rebar in Florida Keys Bridges*. CORROSION, NACE-01642.

Sagues, A. A., & Powers, R. G. (1996). *Coating Disbondment in Epoxy-Coated Reinforcing Steel in Concrete? Field Observations*. In CORROSION 96. OnePetro.

Sagües A.A. Lau K., Powers R.G. Kessler R.J., (2010). *Corrosion of Epoxy-Coated Rebar in Marine Bridges—Part 1: A 30-Year Perspective*. Corrosion (NACE), 66(6), 1-13.

Rahman, M. M., & Akhtarul Islam, M. (2022). *Application of epoxy resins in building materials: progress and prospects*. Polymer Bulletin, 79(3), 1949-1975.

Mao, Y. Z., Wei, Y. H., Zhao, H. T., Lv, C. X., Cao, H. J., & Li, J. (2018). *Corrosion behavior of epoxy-coated rebar with pinhole defect in seawater concrete*. Acta Metallurgica Sinica (English Letters), 31, 1171.

Lliso-Ferrando, J. R., Gasch, I., Martínez-Ibernón, A., & Valcuende, M. (2022). *Effect of macrocell currents on rebar corrosion in reinforced concrete structures exposed to a marine environment.* Ocean Engineering, 257, 111680.

Keßler, S., Angst, U., Zintel, M., & Gehlen, C. (2015). *Defects in epoxy-coated reinforcement and their impact on the service life of a concrete structure: A study of critical chloride content and macro‐cell corrosion.* Structural Concrete, 16(3), 398.

Dong, S., Zhao, B., Lin, C., Du, R., Hu, R., & Zhang, G. X. (2012). *Corrosion behavior of epoxy/zinc duplex coated rebar embedded in concrete in ocean environment.* Construction and Building Materials, 28(1), 72.