Corrosion behavior of reinforcing bars in cracked reinforced concrete pile before and after CFRP wrapping

Hong-Lin Fan, Xiao-Hui Wang*, Lu-Lu Qi, Dan-Da Shi
College of Ocean Science and Engineering, Shanghai Maritime University, Shanghai, 201306, China

*Corresponding author’s e-mail: w_xiaoh@163.com and xiaohwang@shmtu.edu.cn

Abstract. Due to the drying-wetting cycle caused by the ocean tide, the pre-stressed reinforced concrete (RC) piles serving in the splash zone of the seaport wharf have more serious chloride-induced corrosion problem, resulting in urgent need of repair and maintenance of those RC piles by carbon fibre reinforced polymer (CFRP). In this paper, corrosion behavior of the reinforcing bars in cracked RC pile before and after CFRP wrapping is studied, where the RC piles were simulated by the cylinder specimens with embedded steel bar in the centre. The maximum corrosion crack widths were designed as 0.1mm, 0.15mm, 0.2mm, 0.25mm, and 0.3mm. Before CFRP wrapping, the concrete surfaces were treated by corrosion inhibitor and CFRP wrapping. Results show that, CFRP wrapping repair after corrosion inhibitor treatment and CFRP wrapping directly on the concrete surface, have a good effect on preventing the internal reinforcement from continually being corroded by chloride ions when the corrosion crack width in the concrete cover of the RC specimens is 0.25mm, especially for the former method.

1. Introduction
Fibre Reinforced Polymers (FRPs) have been widely used in repair and maintenance of the RC infrastructures under marine environment [1-5]. More attention was focused on the method of strengthening and repairing RC elements with Carbon Fibre Reinforced Polymer (CFRP), mainly focusing on the research of crack development and mechanical properties of those CFRP repaired RC elements [6-8]. However, there are few studies on the corrosion state of the reinforcing bars in RC piles before and after CFRP wrapping.

In this paper, corrosion behavior of the reinforcing bars in reinforced concrete pile before and after CFRP wrapping is studied, where the reinforced concrete pile is simulated by the cylinder concrete specimen with embedded steel bar in the centre. In the cylinder specimen, before CFRP wrapping, concrete was cracked by corrosion of the reinforcing bar and the designed crack widths in the concrete surface were 0.1mm, 0.15mm, 0.2mm, 0.25mm, 0.3mm respectively. In order to accelerate the test, the external DC power was used to accelerate the corrosion of steel bars in the cylinder specimen. After the finish of the accelerated corrosion test, 5 drying-wetting cycles were carried out on the corrosion-induced cracked cylinder concrete specimens to make the corrosion state of the reinforcing bars close to the natural corrosion state. The open-circuit potential and polarization curve of the reinforcing bars in all cylinder concrete specimens were measured by electrochemical workstation at the end of each wetting cycle. After 5 drying-wetting cycles, the cylinder concrete specimens with the same design crack width were divided into two groups: in one group, the concrete surface of the cylinders with corrosion-induced cracks was directly wrapped with CFRPs, and in the other group, the cylinders with corrosion-induced cracks were immersed in the corrosion inhibitor solution for 24 h, and then were wrapped with...
CFRPs. Then, 10 drying-wetting cycles were carried out on all cylinder concrete specimens and the electrochemical performance of the reinforcing bars was tested. Effects of corrosion inhibitor treatment and CFRP wrapping on the corrosion performance of steel bars in corroded concrete cylinders were discussed.

2. Experimental programme

2.1. Specimen design and preparation

![RC specimens before CFRP wrapped](image1)

![Cylinder specimens wrapped with CFRP](image2)

Figure 1. RC specimens before and after CFRP wrapped

11 cylinder concrete specimens with 200mm high and 100mm diameter were designed and mixed by simulated sea water (see Figure 1). One 16mm ordinary carbon reinforcing bar and one graphite rod were embedded, where the reinforcing bar was located in the centre of the cylinder. Test specimens were cured in the artificial sea water solution for 14 days.

2.2. Accelerated corrosion test

| Characteristic of the test specimen | Name of the cylinder concrete specimen |
|------------------------------------|---------------------------------------|
| Specimen with no corrosion crack and CFRP wrapping | U0 |
| Corroded specimens directly wrapped by CFRP | C0.1  C0.15  C0.2  C0.25  C0.3 |
| Corroded specimens treated by corrosion inhibitor and wrapped by CFRP | ZC0.1  ZC0.15  ZC0.2  ZC0.25  ZC0.3 |

After 14-day curing, except for the cylinder concrete specimen U0 shown in Table 1, the left 10 cylinder concrete specimens were cracked by accelerated test and external DC power was used to get the designed corrosion crack widths in the concrete cover, i.e. 0.1mm, 0.15mm, 0.2mm, 0.25mm and 0.3mm. Cylinder concrete specimens shown in Table 1 were named by letters “U”, “C” and “ZC” as well as designed corrosion crack widths.

2.3. Simulated sea water wetting-drying test and electrochemical monitoring before CFRP wrapping

After the finish of the accelerated corrosion test, 5 drying-wetting cycles (immersion in the simulated sea water for 4 days and natural drying for 3 days, a drying-wetting cycle for 7 days) were carried out on the U0, “C” and “ZC” series cylinder specimens. For “C” and “ZC” series cylinder specimens, those five drying-wetting cycles aimed to make the corrosion state of the reinforcing bars in the specimens close to the natural corrosion state. The open-circuit potential and polarization curve of the bars in all concrete cylinder specimens were measured by electrochemical workstation at the end of each wetting cycle.
2.4. Corrosion crack width treatment and CFRP wrapping
After the complete of 5 drying-wetting cycles, the concrete surface of “C” series cylinder specimens was directly wrapped with CFRPs; while for the “ZC” series cylinder specimens, the cylinders with different corrosion-induced cracks were immersed in the corrosion inhibitor solution for 24 h, and then were wrapped with CFRPs. Cylinder specimens wrapped with CFRPs are shown in Figure 1b.

2.5. Simulated sea water wetting-drying test and electrochemical monitoring after CFRP wrapping
After the finish of the CFRP wrapping, the same drying-wetting cycles were continued carrying out on the U0, “C” and “ZC” series cylinder specimens for 10 drying-wetting cycles. Open-circuit potential and polarization curve of the reinforcing bars in all cylinder concrete specimens were also measured at the end of each wetting cycle.

3. Experimental results and discussion

3.1 Test results and analysis of open-circuit potential
Variation of the open-circuit potential (OCP) of the ordinary reinforcing bars in cylinder concrete specimens shown in Table 1 with cycle time is shown in Figure 2, where test specimens with the same corrosion crack width are compared. It can be observed from Figure 2 that, compared with the lower open-circuit potential (-0.34V) of the reinforcing bar in uncracked specimen U0, comparatively higher negative open-circuit potentials are shown in the reinforcing bars in cracked specimens with different corrosion crack widths, fluctuating from -0.42V to -0.51V. After the first five drying-wetting cycles, for corroded specimens C0.1, ZC0.1, C0.15, ZC0.15, the open-circuit potential difference of the bars decreases greatly as compared with that of the bar in uncracked specimen U0 (see Figure 2a and 2b). After CFRP wrapping, the open-circuit potential of the bars in corroded specimens moves toward the positive direction (see Figure 2a~2e) and larger moving is shown in specimens ZC0.1, ZC0.15 and ZC0.25 (see Figure “2a, 2b and 2d”), indicating good effect of the corrosion inhibitor treatment and CFRP wrapping on decreasing the open-circuit potential of the bars in corroded specimens with low corrosion crack widths. However, when the corrosion crack width reaches 0.3mm, the open-circuit potential of the bar in cylinder specimens C0.3 and ZC0.3 does not change much after CFRP wrapping (Figure 2e), indicating CFRP wrapping as well as corrosion inhibitor treatment and CFRP wrapping have no obvious effect on preventing the internal reinforcement from continually being corroded by chloride ions.
3.2 Test results and analysis of polarization curve

The polarization resistance and Stern-Genry coefficient B value are fitted from the polarization curve, and the corrosion current density was calculated, that is, the polarization resistance and corrosion current density are inversely proportional [9]. Variation of the corrosion current density (\(i_{corr}\)) of the ordinary reinforcing bars in cylinder specimens shown in Table 1 with cycle time is shown in Figure 3.

According to the corrosion level Table in [9], the corrosion grades of the reinforcing bar can be divided into four levels: high, medium, low and negligible, and each grade corresponds to a threshold value of the corrosion current density. For uncracked specimen U0, the corrosion current density of steel bars increases gradually in the whole cycle time. This value changes in the range of 0.17~ 0.52 \(\mu\)A/cm\(^2\) and the maximum value exceeds 0.5 \(\mu\)A/cm\(^2\), indicating that the corrosion grade of steel bars in uncracked specimen U0 gradually increases from low corrosion state to medium one. For CFRP wrapped cylinder concrete specimens, before CFRP wrapping, the corrosion grade of the reinforcing bars in specimens with corrosion crack widths less than 0.2mm is in the middle and low corrosion state (Figure 3a~3c); while for specimens with corrosion crack widths larger than 0.2mm, i.e. 0.25mm and 0.3mm, the corrosion current density is more than 1\(\mu\)A/cm\(^2\) (Figure 3d and 3e) and the corrosion grade of steel bars in those specimens is in a high corrosion state. After CFRP wrapping, the corrosion current density of the rebars in all corroded specimens decreased, indicating that the corrosion state of the rebars was effectively reduced due to CFRP wrapping. However, for specimens with corrosion crack widths less than 0.2mm, the corrosion current density of the reinforcing bars decreases greatly and even less than that of the bar in uncracked specimen U0 due to the CFRP wrapping. The first corrosion inhibitor treatment and then CFRP wrapping result in lower corrosion current density of steel bars in specimens ZC0.1, ZC0.15, ZC0.2 and ZC0.25 (see Figure 3a~3e).
Figure 3. Variations of the corrosion current density of the ordinary reinforcing bars in cylinder concrete specimens shown in Table 1 with cycle time

4. Conclusion
The following conclusions are drawn:

1) For corroded cylinder concrete specimens with maximum corrosion crack widths 0.1mm, 0.15mm, 0.2mm, 0.25mm and 0.3mm, the corrosion inhibitor treatment and CFRP wrapping decrease the open-circuit potential of the reinforcing bars in those specimens with corrosion crack widths less than 0.25mm; when the corrosion crack width reaches 0.3mm, the open-circuit potential of the reinforcing bar in cylinder specimens does not change much after CFRP wrapping.

2) Two repair methods, i.e., CFRP wrapping after corrosion inhibitor treatment and CFRP wrapping directly on the concrete surface, play a good role in decreasing the corrosion current density of the steel bars in specimens with corrosion crack width less than 0.25mm.
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