Corrosion Cracking Performance of Corrosion Resistant Steel Bars and Carbon Reinforced Concrete Columns under Axial Compression

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Abstract. In order to study the difference in the development of corrosion expansion cracks between corrosion-resistant steel bars and carbon reinforced concrete columns, the accelerated corrosion method of dry-wet cycle and constant current energization was used to study the distribution, shape and crack width of corrosion expansion cracks over time. The research results show that: under the coupling action of axial compression load and chloride salt, the initial corrosion cracks of 5Cr corrosion-resistant reinforced concrete columns appear later than carbon reinforced concrete columns, and the direction of corrosion cracks is along the direction of the main reinforcement. There is nearly no rust expansion crack of stirrup. In the early stage of corrosion (theoretical corrosion rate less than 5%), 5Cr corrosion-resistant reinforced concrete columns are dominated by single-sided cracking, and the total length and expansion width of cracks are less than that of carbon reinforced concrete columns; the later period of corrosion (theoretical corrosion rate between 5% and 15%) Two types of reinforced concrete columns have obvious double-sided cracking. After a long period of corrosion by chloride salt, the total length and corrosion expansion width of cracks of 5Cr corrosion-resistant reinforced concrete columns increase faster than that of carbon reinforced concrete columns. The corrosion resistance "reversed" in the later stage of corrosion.

Keywords. Chlorine environment, axial compression, concrete column, corrosion resistant steel, carbon steel, rust expansion crack.

1. Introduction
At present, reinforced concrete structures usually use ordinary carbon steel bars (ordinary steel bars) as the main force and structural steel bars. However, studies show that ordinary steel bars have poor corrosion resistance in the chloride salt environment and are easily corroded [1, 2]. On the one hand, the corrosion of steel bars reduces its own mechanical properties. On the other hand, it causes the protective layer to expand along the bars, peel off, and deteriorate the bonding performance between the steel bars and the concrete, which ultimately leads to the reduction of the structure's full life performance and shortens service life [3]. In order to control and improve the full-life performance of ordinary reinforced concrete structures in the chloride environment, in recent years, domestic and foreign scholars have developed new low-alloy corrosion-resistant steel products with excellent seawater corrosion resistance in response to the poor corrosion resistance of ordinary steel bars. This kind of low-alloy corrosion-resistant steel bar product is to change the composition and structure of the steel bar by adding a small amount of Cr, Ni and other corrosion-resistant alloy elements to improve the corrosion resistance of the steel bar [4, 5]. The introduction of new low-alloy corrosion-resistant steel bars have attracted the
attention of many researchers, and has carried out experimental and exploratory research on the corrosion process behavior of corrosion-resistant steel bars [6, 7], but the current research mainly focuses on the critical depassivation chloride ion concentration of corrosion-resistant steel bars. Research results show that the critical chloride ion concentration of low-alloy corrosion-resistant steel bars is related to the content of corrosion-resistant alloy elements. For example, the higher the Cr content, the greater the critical depassivation chloride ion concentration, and the greater the corrosion resistance is. For low-carbon steel bars with a mass fraction of 9% Cr, its critical Cl/OH is 2-10 times that of ordinary low-carbon steel bars [8, 9]. It is clear that corrosion-resistant steel bars can significantly delay the start when the steel bars are depassivated compared with ordinary steel bars. However, there are few studies on the corrosion and cracking performance of concrete members after the corrosion-resistant steel is depassivated. There is even fewer research on the corrosion and cracking performance of corrosion-resistant reinforced concrete columns under the coupled action of load and chloride salt. Therefore, this paper will use constant current-dry-wet cycle accelerated corrosion method to compare the distribution, shape, and crack width change with time of corrosion-resistant steel bar and ordinary reinforced concrete column under the coupling action of axial load and chloride salt, providing a theoretical basis for the impact on the service life and structural performance of concrete structures for evaluate the corrosion resistance Corrosion of steel bars

2. Experiment

2.1. Experiment Materials
Using ordinary commercial concrete with water: cement: sand: gravel: fly ash mix ratio as: JM-10A=160:340:712:1161:20:6.4. The water is deep well fresh water, and the fine aggregate is medium coarse sand, and coarse aggregate are 5-16 mm continuous graded stones, JM-10A is a water reducing agent. The 28-day compressive strength is 45 MPa.

There are two types of main reinforcement, one is HRB400 steel bar with 5% Cr, which is referred to as 5Cr corrosion resistant steel bar; the other is ordinary HRB400 steel bar. The diameter of both main bars is 22 mm, and the stirrup adopts HRB400 ordinary steel bar with a diameter of 8 mm.

2.2. Specimen Design
In order to study the corrosion and cracking performance of 5Cr corrosion-resistant steel bars and ordinary reinforced concrete axial compression columns, two groups of axial compression members were designed: one group was 5Cr corrosion-resistant reinforced concrete axial compression columns, represented by the symbol NZ. There are 3 specimens in the NZ group, numbered NZ-1, NZ-2, NZ-3, and the target corrosion rates are 5%, 10%, and 15% respectively; the other group is ordinary reinforced concrete axial compression columns, represented by symbol PZ. There are 3 specimens in PZ group, numbered PZ-1, PZ-2, PZ-3, and the target corrosion rate is the same as that of the NZ group column. The dimensions of the columns are 180 mm×180 mm×800 mm. The reinforcement is shown in figure 1. The main reinforcement diameter is 22 mm, the protective layer thickness is 30 mm, the stirrup diameter is 8 mm, and the spacing is 100 mm. A prestressed pipe with a diameter of 32 mm is placed in the middle of the test piece, and two steel plates of size 120 mm×120 mm×10 mm are placed at both ends of the test piece to prevent local pressure damage to the end concrete during the prestressing process. The wires are tied at the end of the main bars before the specimen are poured to be used when constant current accelerates corrosion.
2.3. Preloading and Accelerated Corrosion

In order to simulate the actual working status of the serviced concrete axial compression column in the chloride environment, the specimens with 28-days pouring and curing were preloaded. The prestressed steel bar adopts steel strands with a diameter of 17.8 mm, and its tensile strength standard value is 1770 MPa; the anchorage adopts clamping piece-type anchorage. The preloaded member is shown in figure 2. The preload is 435 kN, 30% of the theoretical ultimate bearing capacity of the concrete axially compressed column.

After preloading the members, "constant current-dry-wet cycle" accelerated corrosion test is conducted on the corrosion-resistant steel bar and ordinary reinforced concrete columns under the coupling action of load and chloride salt. The dry and wet cycle is 12 days, and the ratio of dry and wet cycles is 1:1, that is, 6 days’ dry and 6 days’ wet. The accelerated corrosion device is shown in figure 3. The negative pole of the power supply is connected to the stainless steel net wrapped outside the concrete specimen, the positive pole is connected to the steel bar to be corroded inside the concrete, and a layer of absorbent sponge filled with 5% NaCl solution is wrapped on the outside of the wire mesh. The target corrosion area is a 500 mm area in the middle of the test piece. The energization starts in the wet state and stops in the dry state. The corrosion current density used to accelerate corrosion is \( i = 0.2 \text{ mA/cm}^2 \), and the surface area of the corroded steel bar is the sum of the surface area of the steel bar to be corroded. The energized current required for each specimen is calculated as \( I = 0.41 \text{ A} \). According to the expected theoretical corrosion rate of steel bar \( \rho = 5\%, 10\%, 15\% \), the expected power-on time calculated by Faraday's laws of electrolysis is 748 h, 1497 h, 2242 h, and the corresponding dry and wet cycle time is 48 d, 96 d, 144 d. The accelerated corrosion test ends after reaching the respective power-on time.

3. Experiment Results and Analysis

3.1. Distribution of Rust Expansion Crack

The two types of reinforced concrete columns are unfolded on each surface, as shown in figure 4, and the rust expansion cracks are depicted in figure 4. The ZBL-F130 crack visualiser is used to track and measure the width of rust expansion cracks after each dry-wet cycle. Figure 4 shows the final crack width value at the end of accelerated corrosion of each member. The black line in the figure represents the rust expansion cracks that occurred during the dry and wet cycle for 24 days (2 wet and dry cycles), and the red line represents the subsequent occurred rust expansion cracks.
During the experiment, it is observed that the distribution of rust-swelling cracks is mainly related to the stress state of the members, the position of the reinforcement, and the external environment. Under the coupling action of axial compression load and chloride salt, the initial appearance of rust expansion cracks seems to be random. Rust expansion cracks of ordinary reinforced concrete columns (PZ-1, PZ-2, PZ-3) appear about 5-10 days after electrification. And rust expansion cracks of 5Cr corrosion-resistant reinforced concrete columns (NZ-1, NZ-2, NZ-3) appear about 7-12 days after electrification. The initial appearance of corrosion expansion cracks of 5Cr corrosion-resistant reinforced concrete columns is about 2-3 days later than that of ordinary reinforced concrete columns. Comparing the expansion diagrams of the two types of reinforced concrete columns in Figure 4, it is observed that the initial rust and expansion cracks on the surfaces of the NZ and PZ columns are discontinuous (black lines in the figure) with 24-days dry-wet cycle, but rust expansion cracks are all along the direction of the main reinforcement. With the increase of corrosion time, the rust expansion cracks on each side of the two types of reinforced concrete columns increased, and the length of the cracks gradually extended and penetrated (the red line in the figure), but nearly no stirrup expansion cracks appeared. In addition, the corrosion expansion and cracking caused by the corrosion of the steel bars in the column corners are mainly manifested in two configurations: one is that the corrosion causes the protective layer to crack on both sides; the other is that the corrosion only causes the protective layer to crack on one side. In the early stage of corrosion (theoretical corrosion rate is less than 5%), 5Cr corrosion-resistant reinforced concrete columns are dominated by single-sided cracking (figure 4(a)), while ordinary reinforced concrete columns occur double-sided cracking earlier (figure 4(b)). This may be because the corrosion-resistant steel bars are dominated by superficial corrosion pit at the early stage of corrosion, while the corrosion area of ordinary steel bars is larger in the circumferential direction, and the two adjacent surfaces have large expansion forces. Thus, tendon cracks are more likely to occur on both sides. In the later stage of corrosion (theoretical corrosion rate is between 5%-15%), the expansion of
rust expansion cracks is stable, and two-side cracks on both kinds of reinforced concrete columns are obvious.

When the concrete column cracks on both sides, the protective layer is likely to break off along the cracks, exposing the steel bar directly to the chloride environment, which accelerates the corrosion of the steel bar. As a result, double-sided cracking is more harmful to the safety and reliability of compression columns than single-sided cracking. At the initial stage of corrosion, the falling off risk the concrete protective layer of 5Cr corrosion-resistant reinforced columns is less than that of ordinary reinforced concrete columns.

3.2. Length of Rust Expansion Crack

The total length of corroded expansion cracks can reflect the overall damage degree of the compression column and the corrosion of the steel bars, which can provide certain reference for judging the health of the compression column. Figure 5 shows the total length of the expansion cracks of the NZ group and PZ group columns after the corrosion. It can be seen from figure 5 that the total length of the corrosion expansion cracks of the two reinforced concrete columns shows an increasing trend with the increase of the corrosion time. In the early stage of corrosion, the total length of corrosion expansion cracks of 5Cr corrosion-resistant reinforced concrete columns is less than that of ordinary reinforced concrete columns, but in the later phase of corrosion, the total length of corrosion expansion cracks of 5Cr corrosion-resistant reinforced concrete columns increases faster than that of ordinary reinforced concrete columns, showing that the corrosion degree of ordinary steel bars and the overall damage of concrete columns are more serious than those of corrosion-resistant steel columns in the early stage, and vice versa in the later stage.

![Crack length vs. time](image)

**Figure 5.** Corrosion expansion crack length of compression column.

3.3. Variation Law of Rust Expansion Crack Width

Under the coupling action of long-term axial load and chloride salt, the axial load causes the member to be compressed longitudinally and stretched laterally; and the corrosion and expansion force of the steel bar caused by the corrosion of chloride salt causes the concrete around the steel bar to produce circumferential tensile stress. Therefore, under the coupling action of the axial pressure and the chloride salt, the concrete surrounding the steel bar stays in a bidirectional force state. In order to analyze the change of rust-expanded crack width with corrosion time under two-way stress state, figure 6 shows the changes with time of average value $W_{\text{average}}$ of rust-expanded crack width on each side (side, top and bottom) of NZ-3 and PZ-3 columns during dry-wet cycles. Since the local environmental conditions on the front and back of the pressure column are the same, the two are treated as a combination of side.

It can be seen from figure 6 that with the same corrosion time, the average value of the rust expansion crack width on each surface of the NZ-3 column is different, the bottom surface is the largest, the top surface is the second, and the side surface is the smallest; there is no rust expansion crack on the top of the PZ-3 column. The width of rust expansion cracks on the bottom surface is larger than that on the side. This is because there is less water loss in the bottom surface of the water-absorbing sponge, the humidity and chloride ion concentration are relatively stable, and the steel bars near the bottom surface have a greater degree of corrosion, so the width of the rust expansion crack is the largest. However, affected by
gravity, the chloride salt solution in the top and side water-absorbing sponges is easy to flow downwards, and the humidity and chloride ion concentration are unstable, resulting in the rust expansion crack width smaller than the bottom surface. This shows that the microenvironment will have a certain influence on the development of the crack width of rust expansion. In general, the average width of rust expansion cracks in NZ-3 and PZ-3 columns increases with corrosion time. However, in the early stage of corrosion, the average width of NZ-3 column expansion cracks at the same position (bottom or side) is smaller than that of PZ-3 column, and in the later stage of corrosion, the average value of rust expansion crack width of NZ-3 column is larger than that of PZ-3 column. In order to further investigate the difference in the width of corrosion expansion cracks between corrosion-resistant steel columns and ordinary steel columns, the rust expansion cracks of 3 NZ columns (NZ-1, NZ-2, NZ-3) and 3 PZ columns (PZ-1, PZ-2, PZ-3) are calculated. And the average rust expansion crack width of 3 NZ columns and 3 PZ columns changes with the rust time, as shown in figure 7. It can be seen from figure 7 that the average rust-expansion crack width of multiple columns is similar to that of a single column, that is, in the early stage of corrosion, the average rust-expansion crack width of the NZ column grows slower than the PZ column, but grows faster than the PZ column latter. This phenomenon shows that the corrosion rate of 5Cr corrosion-resistant steel bars after a long period of corrosion in chloride salt is greater than that of ordinary steel bars, that is, the corrosion resistance of 5Cr corrosion-resistant steel bars has "reversed" in the later stage of corrosion, which is consistent with the literature [10]. The phenomenon of "reversal" of the corrosion resistance of Cr-containing corrosion-resistant steel bars in the later stage of corrosion will have an adverse effect on the durability of the structure. This should be paid attention to in actual engineering applications.

![Figure 6](image6.png)  
**Figure 6.** The relationship between NZ-3 and PZ-3 column $W_{\text{average}} - t$.

![Figure 7](image7.png)  
**Figure 7.** The relationship between NZ group and PZ column $W_{\text{average}} - t$.

4. Conclusions

1. With the coupling action of axial compression load and chloride salt, the initial appearance of rust expansion cracks is random. On the whole, initial rust expansion cracks of 5Cr corrosion-resistant reinforced concrete columns appears later than that of ordinary reinforced concrete columns. The rust expansion cracks of the two kinds of reinforced concrete columns are all rust expansion cracks along the direction of the main reinforcement, and there is no rust expansion crack of stirrups.

2. The corrosion expansion and cracking caused by the corrosion of the steel bars in the column corners mainly manifests in two configurations: one is that the corrosion causes the protective layer to crack on both sides; the other is that the corrosion only causes the protective layer to crack on one side. In the early stage of corrosion (theoretical corrosion rate less than 5%), 5Cr corrosion-resistant reinforced concrete columns are dominated by single-sided cracking while ordinary reinforced concrete columns have early double-sided cracking. In the late stage of corrosion (theoretical corrosion rate between 5%-15%), both sides of the two reinforced concrete columns cracked are more obviously.
Double-sided cracking is more harmful to the safety and reliability of the axial compression column than single-sided cracking.

(3) With the coupling effect of axial compression load and chloride salt, the total length and width of the cracks of the two types of reinforced concrete columns corroded and expanded with the corrosion time increased. However, in the early stage of corrosion, the total length and width of the corrosion expansion cracks of 5Cr corrosion-resistant reinforced concrete columns increased less than that of ordinary reinforced concrete columns. In the later stage of corrosion, the total length and width of corrosion expansion cracks of 5Cr corrosion-resistant reinforced concrete columns increased faster than that of ordinary reinforced concrete columns. After a long period of corrosion of 5Cr corrosion-resistant steel bar in chloride salt, its corrosion resistance has "reversed". When Cr-containing corrosion-resistant steel bar is used in chloride salt environment, attention should be paid to the unfavorable effect of its corrosion resistance "reversion" and durability of structure.

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