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# Types and Mechanisms of Corrosion in Prestressing Bars

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**ABSTRACT :** Prestressed bars, due to their high-stress state and small cross-sectional characteristics, often exhibit no obvious signs during the initial stages of corrosion. However, their corrosion hazards are more severe compared to those in ordinary reinforced concrete. An in-depth investigation into the corrosion types and mechanisms of prestressed bars is crucial for addressing durability issues in prestressed concrete structures. This paper categorizes the corrosion of prestressed bars in concrete into four types, systematically elaborating on the occurrence conditions, corrosion mechanisms, and influencing factors for each type. The study highlights that the steel strands in prestressed bars, owing to their unique lamellar pearlitic microstructure induced by stretching, are less prone to anodic dissolution-type and hydrogen-induced cracking-type stress corrosion. Additionally, prestressed bars may still suffer corrosion even in alkaline environments. Furthermore, compared to the other three corrosion forms, chloride-induced corrosion poses a more frequent threat to prestressed bars in concrete. The findings of this research provide critical references for the assessment, maintenance, and durability enhancement of existing prestressed concrete structures.

**KEYWORDS:** Prestressed concrete, Corrosion of prestressed bar, Corrosion type, Corrosion mechanism

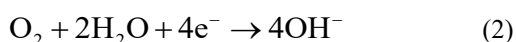
## I. INTRODUCTION

Due to imperfect construction technology, untimely maintenance and environmental effects, prestressing bars in prestressed concrete structures inevitably produce prestressing bar corrosion [1]. The prestressing bars are in a high stress state and have a small cross-sectional area. There are often no signs when rust occurs, and the rust hazard is greater than that of ordinary reinforced concrete structures [2]. The corrosion type and mechanism of prestressing bars are important factors affecting the durability of prestressed concrete structures. At present, the research on the types and mechanisms of prestressing bar corrosion mainly focuses on three aspects: corrosion type, corrosion mechanism and corrosion influencing factors. Prestressed bar corrosion types include electrochemical corrosion and stress corrosion. In concrete structures, due to the alkaline environment of concrete, a passivation film is usually formed on the surface of the steel bars to play a protective role. However, when cracks appear on the concrete protective layer or the concrete quality is poor, chloride ions, carbon dioxide and other harmful substances will invade the surface of the steel bars, destroying the passivation film, and leading to electrochemical corrosion. Its corrosion mechanism is closely related to the passivation film. In concrete, a passivation film formed on the surface of the steel bar can prevent the invasion of corrosive media. However, when cracks appear on the concrete protective layer or the concrete quality is poor, harmful substances such as chloride ions will invade the surface of the steel bars, destroy the passivation film, and lead to corrosion [3]. Stress corrosion refers to the fact that the prestressing bar is in a high stress state, especially under the action of corrosive media such as chloride ions, microcracks will appear on the surface of the steel bar, resulting in stress corrosion and cracking. This form of corrosion usually manifests itself as sudden breakage of steel bars under lower stresses. Its corrosion mechanism is closely related to the formation of micro-cracks of prestressed bars and hydrogen-induced cracking [4]. In addition, scholars have studied the effects of chloride ion concentration, stress level and concrete quality on prestressing bar corrosion [5].

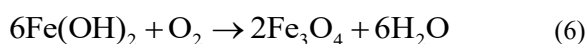
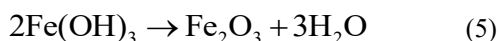
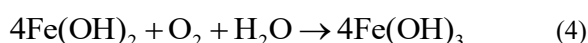
To sum up, the current research on the types and mechanisms of prestressing bar corrosion mainly focuses on one of the corrosion types. The corrosion mechanism is analyzed through experiments and theory, but the types of prestressing bar corrosion in all concrete are not compared and studied. To this end, this paper is based on extensive literature research and divides the types of prestressing bar corrosion in concrete into four categories, and explains in detail the conditions, rust mechanism and influencing factors of various rust types. The research results obtained can provide an important reference for the study of the durability of prestressed concrete structures.

## II. CHLORIDE ION CORROSION

The corrosion of Prestress bar is similar to ordinary steel bars. It is essentially an electrochemical process, including two basic electrode reactions, one is the oxidation reaction of the anode Fe, which releases electrons; the other is the reduction reaction of the cathode  $O_2$ , which generates  $OH^-$ , and the corrosion diagram is shown in Figure 1. The reaction of the anode must be preceded by the cathode reaction. After the electrons generated by the reaction are transmitted to the cathode through the prestressed tendon, the cathode reaction can be carried out.



The electrode reaction products ferrous ions and hydroxide ions first enter the pore solution near the surface of the steel bar, and then meet in the void solution and bind to insoluble ferrous hydroxide. Ferrous hydroxide encounters sufficient oxygen and further oxidizes to iron hydroxide. Iron hydroxide becomes red rust iron trioxide after dehydration; if the oxygen supply is insufficient, the ferrous hydroxide is not completely oxidized to black rust iron trioxide, see formulas 1-6.



The chloride ions that invade the surface of the prestressing bars from the outside will destroy the passivation film on the surface of the steel bar to varying degrees, causing part of the surface of the steel bar to be reactivated. They will not be consumed during the corrosion reaction but will play a catalytic role, accelerating the corrosion rate of the prestressing bars. At present, the mechanism of destruction of chloride ions on passivation films is not clear, because it is difficult to study this process from the atomic scale in extremely thin passivation films. Steel strands show obvious pit corrosion patterns in chlorine salt environment. First, because the passivation film on the surface of the steel strand is relatively flat and complete, only few chloride ions can penetrate the passivation film, forming a corrosive nucleus and causing rust of the blocked battery, which continues to develop into pits and corrosion holes, while other surfaces protected by the passivation film are not rusted; second, because steel strands are similar to hot-rolled ribbed steel bars, they are uneven at the macroscopic, and the interface between the steel bars and concrete is prone to form microscopic or even macroscopic bubble defects, and the corrosion medium is prone to gather here and cause strong local corrosion [6].

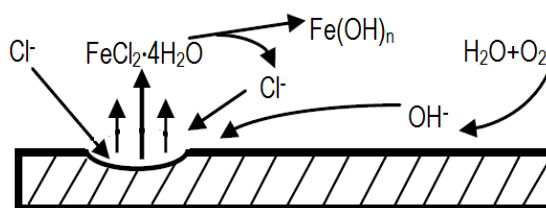


Fig. 1: Schematic diagram of steel strand corrosion in concrete under chlorine salt environment

## III. STRESS CORROSION

Stress corrosion is a brittle corrosion damage, which is a process in which metals cause hysteresis cracking or fracture under the coupling effect of tensile stress and special corrosion environment<sup>[7]</sup> The cracks caused by stress corrosion are very small and there are generally no obvious signs before brittle fracture. Scholars at home and abroad have conducted extensive research on prestressed tendon stress corrosion, and Klodt et al. [8] studied prestressed tendon

corrosion at different temperatures, solutions and stress levels. The research results show that the specimens have corrosion in the chloride salt environment, but the prestressed bars do not have brittle fractures. Cherry and Price[9] experimented with investigating whether the anodic polarization of cold-pull-removing stress-removing steel wires produces stress corrosion in chloride salt solutions with different pH values. Studies have shown that the fracture of steel wire is attributed to the reduction in cross-section caused by general corrosion and is not related to stress corrosion. Wu [10] used prestressed high-strength steel strands to accelerate corrosion in simulated corrosion solutions and under different stress states, and studied the impact of stress on the corrosion degree, corrosion rate and the loss of steel strands in steel strands. The experimental results show that the corrosion rate of steel strands under stress states is faster, the corrosion degree is greater, and the mechanical properties are severely degraded. Domestic scholars have conducted a relatively comprehensive study on the principle of stress corrosion from the perspective of materials[11-14]. The research results are: stress corrosion will promote metal dislocation, and metal dislocation is the local plastic deformation of metal materials, and the development of dislocation will lead to the formation of cracks. From the above series of studies, it can be seen that the occurrence of stress corrosion has specific conditions. First, a sufficiently large tensile stress is required to work together with the corrosion environment. In most stress corrosion systems, there is often a critical stress value. If the tensile stress is less than this critical stress value, stress corrosion will generally not occur. Secondly, stress corrosion does not occur in all metals, but only on metals that are sensitive to stress corrosion. Re-stress corrosion is selective for the metal medium, and a specific metal only undergoes stress corrosion in a specific medium.

Stress corrosion is divided into anode dissolving type and hydrogen cracking type. Anode dissolution stress corrosion refers to the cathode process corresponding to the anode dissolution is an oxygen absorption reaction, or although it is a hydrogen evolution reaction, the hydrogen entering the metal has not yet caused hydrogen to crack, and the formation and expansion of corrosion cracks are controlled by the metal dissolution of the anode. Hydrogen-induced cracking stress corrosion refers to the cathode process corresponding to the anode dissolution is a hydrogen evolution reaction, and the formation and expansion of corrosion marks are controlled by hydrogen entering the metal. Schroeder et al. [15] conducted experimental research on stress corrosion and hydrogen embrittlement sensitivity on prestressing bars. The research results show that prestressing bars have a certain stress corrosion sensitive potential, and hydrogen embrittlement plays a certain role in stress corrosion. Parkins's research [16] shows that stress corrosion is mainly anode dissolving type and has little to do with hydrogen-induced cracking. Proverbio's [17] research is different from this conclusion. The analysis believes that the occurrence of stress corrosion cracks is caused by the anode dissolution caused by the rupture of the passivation film, while the expansion of the cracks is caused by hydrogen cracking. Toribio [18] studied the stress corrosion behavior of prestressing bars from the perspective of materials. The research results show that whether it is anode dissolving or hydrogen-induced cracking stress, the residual compressive stress of the crack tip will increase the stress corrosion resistance of the prestressing bars, while the residual tensile stress of the crack tip will reduce the stress corrosion resistance. From the 55research in literature [19], it can be seen that the stretched pearlite microstructure unique to steel strands is not easy to form a two-phase interface with good connectivity. Rust is difficult to develop in depth along one or several convenient transverse channels, and the possibility of anode dissolving stress corrosion is very small. At the same time, the complex production process of steel strands makes it have many hydrogen traps such as dislocations, phase boundaries, grain boundaries and microcracks. Even if hydrogen atoms are generated (caused by rust from blocked batteries in humid chloride environments; hydrogen atoms are generated by excessive cathode protection; hydrogen atoms produced by pickling during steel strands), it is difficult to achieve a higher enrichment in the above-mentioned large number of traps. Therefore, it is difficult to cause hydrogen-induced cracking stress corrosion in steel strands in concrete.

#### **IV. CONTACT CORROSION**

Contact corrosion occurs where two different metals come into contact. The specific schematic diagram is shown in Figure 2. For prestressed concrete structures, contact corrosion mainly occurs in post-tensioned prestressed reinforced concrete structures, which affects the fatigue performance of prestressing bars. According to Fontana's research[20] the following conditions must be met for the occurrence of contact corrosion:

- (a) The contact interface must be in a stressed state;
- (b) The contact interface must undergo repeated displacement misalignment;
- (c) The load and displacement of the contact interface shall cause relative slip and deformation on the two metal contact surfaces, and the slip and deformation shall be controlled within a smaller range.

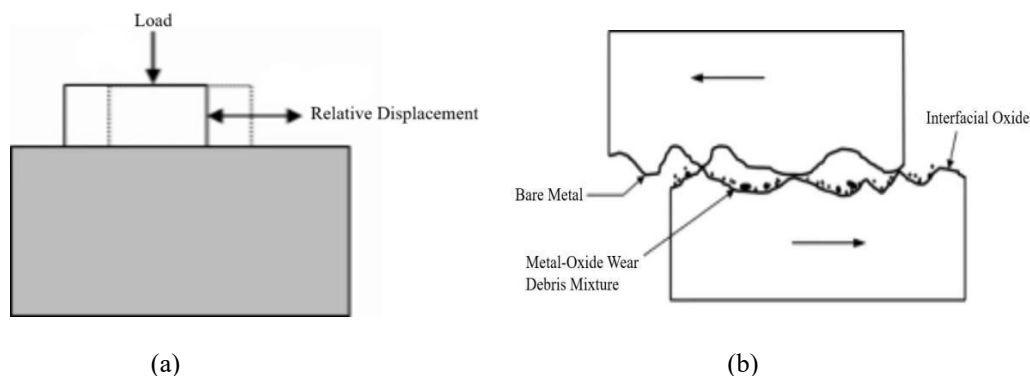


Fig. 2: Schematic diagram of contact corrosion (a)Contact corrosion generation conditions (b)Contact corrosion interface

The displacement staggering that causes contact corrosion can be as small as  $10^{-7}$  mm. If oxygen is also present in the displacement staggering area, it will cause wear and corrosion of the metal contact interface. In post-tensioned prestressed concrete, there will be displacement and dislocation between the anchoring end of the prestressed member and the prestressed. The prestressing bars in the bending prestressed steel bundle section and the pipeline will cause displacement and dislocation due to alternating loads. The displacement and dislocation between the prestressing bars and the stressed rib connectors and the prestressing bars will also occur due to alternating loads and solar radiation. Contact corrosion is very likely to occur at the location of the above-mentioned prestressed concrete structure. Fatigue cracks in prestressed bars will also cause during contact corrosion. Fatigue cracks can occur prematurely due to a combination of surface damage (from contact corrosion) and very high local contact stress

## V. THE OTHER CORROSION

In addition to the above common corrosion, some scholars have discovered a relatively special corrosion situation in the external prestressing bars, as shown in Figure 3.

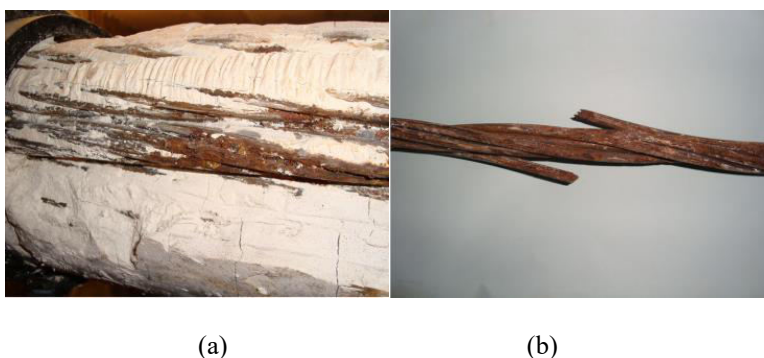


Fig. 3: Prestressing bar corrosion in white grout body in extracorporeal prestress cable[16] (a)White paste-like substances isolated from grouting bodies (b) Rust-broken prestressing bars

This corrosion mainly occurs at the highest part of the box beam prestressing bars near the anchor end. The cement mortar slurry poured by the prestressed pipeline at the rust location is uneven. The bottom of the pipeline is gray hardened cement slurry, the middle is a white crumbly slurry part, and the upper part is a moist white paste substance, which becomes brittle after hardening. It was found that prestressed bars often have serious corrosion in the isolated white paste substances. Through the chemical analysis of this substance, it is characterized by alkaline pH and high content of sulfate ions, and does not contain any chloride ion components.

Due to the high pH value in the segregated slurry and the absence of chloride ions, this is different from the prestressing bar corrosion caused by the usual chloride environment. At the same time, this corrosion is obviously not

caused by concrete carbonization, because the segregated slurry around the corrosion prestressing bars are highly alkaline, and the prestressing bars show obvious pit corrosion forms, which is different from the uniform rust caused by carbonization. In addition, there are a large number of rust products on the rusted prestressing bars, which shows that prestressed corrosion is generated through the dissolution process rather than the development of cracks. The fractured prestressed steel wire has no brittle fracture (only tough fractures are observed in the area not covered by the corrosion product), and there is no secondary crack caused by hydrogen embrittlement expansion on the outer surface of the prestressed steel wire. From this we can see that this type of corrosion does not belong to the type of stress corrosion and hydrogen embrittlement corrosion. Bertolini and Carsana[22] studied the mechanism of this type of corrosion through a series of experiments. The wet segregation slurry dissolves the alkali ions and forms an alkaline solution with a pH value of close to or above 14. There are gaps between the wires of a single prestressed steel strand and between adjacent prestressed steel strands.

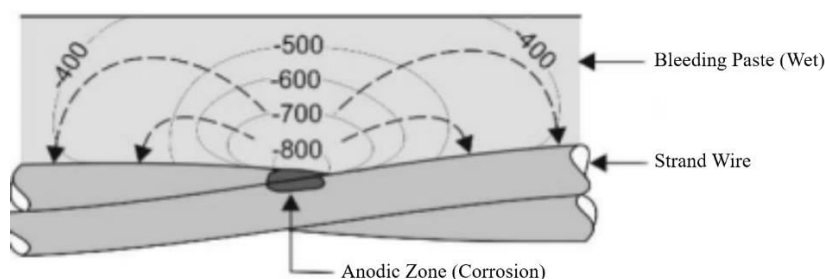


Fig. 4: Schematic diagram of prestressing bar corrosion in high alkaline environment[13-25]

The available environment of low oxygen generated in the gap is similar to the conditions of gap corrosion and is the cause of initial rust of prestressing bars. The alkaline environment and sulfate ions in the separating slurry will accelerate the occurrence of initial rust of prestressed bars. The subsequent corrosion development is mainly caused by corrosion of macrocells. Macrocells are mainly formed by deblunt zones, passivation zones and conductive separators around the prestressing bars, as shown in Figure 4. Initial corrosion usually starts from the contact point between the steel stranded wires, the area of the deblunt zone is very small (i.e. the anode area), while the passivation area of the corresponding steel stranded wire (the cathode area) is very large. The smaller the area ratio between the anode and the cathode, the higher the penetration rate of corrosion. The resistivity of the segregated slurry is a key factor affecting corrosion and is affected by the composition of the slurry, microstructure and its moisture content. The isolated slurry has a fairly low resistivity due to high ion content ( $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{OH}^-$ ,  $\text{SO}_4^{2-}$ ) and low hydration (high void ratio) under wet conditions. Under the influence of the above factors, the prestressed tendon pits in the segregated slurry are significantly corroded.

## VI. CONCLUSION

1. The tensile pearlite microstructure unique to the steel strands in the prestressing bar is not prone to anode dissolving and hydrogen-induced cracking stress corrosion.
2. Prestressing bar may also rust in an environment without chloride ions and concrete carbonization and are in an alkaline environment.
3. From the conditions and corresponding mechanisms of prestressing bar, chloride ion corrosion, stress corrosion, contact corrosion and other corrosion, it can be seen that in civil engineering structures, especially in high-speed railway bridge structures, prestressing bar in concrete may often encounter chloride ion corrosion.

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