Review of Short-Term and Long-Term Bond Properties Between Epoxy-Coated Reinforcement and Concrete

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Abstract. Epoxy-coated rebars have been widely used to prevent steel corrosion problems in marine infrastructures of coastal cities. Based on the extensive studies on the bond behavior of epoxy-coated bars, the factors affecting the bond strength of epoxy-coated bars and the relative bond ratio, i.e., the bond strength ratio of epoxy-coated bars to uncoated bars were analyzed. The recommendations for the use of epoxy-coated bars are presented based on the evaluation of the calculated model of the bond strength in the current codes and specifications, which may provide some useful guidance for the widespread applications of epoxy-coated bars in the future.

Keywords. Epoxy-coated bars, bond properties, influenced factors, design recommendation.

1. Introduction

Reinforced concrete has been widely used as the most common constructional materials in civil engineering due to their desirable mechanical properties, i.e., high strength and stiffness, easy for construction and satisfactory fire resistance. Moreover, many marine infrastructures are being constructed with the rapid development of the coastal economy. However, due to the corrosive problems, ordinary rebars are prone to be corroded seriously. Oxidation products that are produced on the surface of bar may result in the volumetric dilation of the rebar, which can rapidly lead to the formation of cracks in the concrete. Thus, the spalling of concrete cover occurs and hence it may have a great impact on the long-term behavior of the structures. Studies have shown that the structural damage caused by corrosion is striking [1] and needs to be solved urgently. In general, the corrosion of bars is mainly caused by the penetration of chloride ions. Methods to prevent this phenomenon include increasing the thickness of the concrete cover, using cathodic protection, rust inhibitor and coating protection [2]. Among these choices, the first method only delays the time of the corrosive medium invading into the bars and cannot effectively alleviate the degree of corrosion. Cathodic protection has high requirements for the professionalization of workers and places, and it is also the most expensive anti-corrosive method. Although the rust inhibitors can delay the electrochemical process of corrosion by inhibiting action, only the concrete with low permeability is suitable for this technique. Therefore, the coating protection, especially for the epoxy coating on the rebars, is the best way to prevent steel corrosion to date.

Epoxy-coated bars have been widely applied due to their satisfactory properties, for example, good resistance to corrosion, simple production process, convenience to use and little pollution to the environment [3-4]. The epoxy-coated rebars were first applied in the decks of a bridge in Pennsylvania in 1973. Whereafter, Japan, Europe and other countries raised technical specifications on the epoxy-
coated bars. An increasing number of epoxy-coated bars were used in bridges, marine infrastructures and harbor wharfs.

The steel corrosion problem can be effectively diminished by using epoxy-coated bars instead of common black rebars. However, there are still some drawbacks of the epoxy-coated bars in the application. For example, the friction between the rebars and concrete weaken to some extent due to the smoother surface of coating. Moreover, the larger slip and wider cracks were detected during the test, which indicated that the bond strength of epoxy-coated bars decreased as a result. Therefore, many researchers have conducted extensive studies on epoxy-coated bars to explore their bond properties. It was found that the bond strength of epoxy-coated bars was lower compared with the black rebars under the same condition. Therefore, it is necessary to take measures such as increasing the bond length and the thickness of concrete cover to make up for the reduction in bond strength of epoxy-coated bars. Besides, limiting the thickness of epoxy coatings can restrict the negative impact. Against this background, this paper extensively summarized the research on short-term and long-term bond properties of epoxy coated bars. Many factors that affect the bond properties of epoxy-coated bars were analyzed. The reasonable development length modification factor of the bond lengths owning to epoxy coating was explored.

2. Test Method

The bond between the rebars and concrete is the basis for the deformation compatibility of reinforced concrete structures [5]. To investigate the bonding performance of epoxy-coated bars, extensive studies have been conducted under different test methods. The methods can be generally classified as two categories, i.e., the pull-out test and beam-splice test respectively.

The pull-out test, as shown in figure 1(a), is quite simple and easy. However, the obtained bond strength may be several times greater than that attained in practice, which may result from the following aspects. Firstly, the bond length is relatively short, so the rebars are surrounded by the thick concrete cover and confining reinforcement is heavy, which prevents the splitting type failures measured. Besides, the results from pull-out tests have little guidance for practical design since the condition that the bar is in tension and the concrete is in compression can hardly encounter in practice. As shown in figure 1(b), it is illustrated that the condition of tensile rebars in the shear span region and pure bending zone can be simulated more accurately by the beam-splice test due to the existence of bending moment and shear force simultaneously. However, considering that there are too many test parameters and the higher costs, the beam-splice test is rarely used compared with the pull-out test [6].

![Figure 1. Pull-out test (a). Beam-splice test (b).](image)

3. Influenced Factors

3.1. Influenced Factors of Short-Term Bond Strength

Lower bond strength of epoxy-coated bars was detected in extensive studies compared with the ordinary rebars under the same condition. Reduction in bond strength of epoxy-coated bars is about 10-20% compared with the ordinary ribbed bars while about 50% compared with the plain bars yet.
The main influenced aspects for the reduction of bond performance between coated rebars and concrete are listed below.

3.1.1. Bar Diameter. Although many tests included various bar diameters, there was limited studies that explored the influence of bar diameters on the bond strength of epoxy-coated bars and uncoated bars.

Xu [7] reported that the bond strength of epoxy-coated bars with a larger diameter was relatively smaller. The bearing area ratio \( R_b \) (i.e., the ratio of the rib-bearing area per inch of length to the nominal cross-sectional area of the bar) may explain the phenomenon. \( R_b \) decreased with the increasing bar diameter, which caused the lower bond strength. However, Darwin [8] et al. found that bond strength of epoxy-coated bars was increased with bar diameter. Darwin [8] et al., Choi [9] et al., Hamad [10] et al. and Grundhoffer [11] et al. examined that bar diameter had a significant impact on bond strength ratio, i.e., \( C/U \), (with \( C \), the bond strength of epoxy-coated bars and \( U \), the bond strength of uncoated bars). The test results manifested that the value of \( C/U \) was decreased with the increase of bar diameter, which meant that the reduction in bond strength due to epoxy coating increased with bar size. However, Treece and Jirsa [12] compared the bond properties of epoxy-coated bars with a diameter of 19 mm and 36 mm and found that there was no significant difference in \( C/U \) ratio as bar diameter increasing. The different coefficients of friction for epoxy coated bars with different bar diameters were confined by transverse reinforcement. Besides, Hester [13] et al. found that deformation patterns would affect bond strength. \( R_b \), the major factor reflecting deformation pattern, had an effect on failure mode and bond strength in the research conducted by Moen and Sharp [14]. Pull-out failure was more likely to occur when \( R_b \) was low while the failure mode was dominated by concrete splitting for the specimen with high \( R_b \). In addition, the specimens with higher \( R_b \) would achieve higher bond strength. However, the improvement in bond strength owning to \( R_b \) was not applied to all conditions. Idun and Darwin [8] reported that the deformation pattern of bars appeared to have no effect on the bond strength of uncoated bars without transverse reinforcement, while the bond strength of uncoated bars confined by transverse reinforcement increased with \( R_b \). The improvement in bond strength of epoxy-coated bars with higher \( R_b \) was detected whether the epoxy-coated bars were confined by transverse reinforcement or not.

Although it is demonstrated that rib face angle \( \gamma \) play a limited role in the bond strength of uncoated bars, the rib face angle still has an obvious effect on the \( C/U \). Choi et al. [9] derived a theoretical statistical relationship between \( C/U \) and the rib face angle \( \gamma \) based on a constant maximum confining force provided by the concrete, as shown in equation (1).

\[
C/U = \frac{(\tan \gamma + \mu_\gamma)(1 - \mu_\gamma \tan \gamma)}{(\tan \gamma - \mu_\gamma)(1 + \mu_\gamma \tan \gamma)}
\]

where, \( \mu_\gamma \) and \( \mu_\gamma \) represent coefficients of friction for epoxy-coated bars and uncoated bars, respectively. Illustrated by the curved line in figure 2, \( C/U \) increased rapidly to a value of 1.0 for values of greater than 43 deg. The test results of Idun and Darwin [15] supported the above-mentioned
theoretical relationship and concluded that the value of greater than or equal to 45 deg. appeared to minimize the negative impact of epoxy coating on bond strength.

![Figure 2](image-url)  
**Figure 2.** Relative bond strength of epoxy-coated bars to uncoated bars versus rib face angle.

3.1.3. Concrete Cover. As concrete cover increasing, there is an approximately linear increase of bond strength due to the confinement from concrete cover for epoxy-coated and uncoated bars. The improved trend for coated and uncoated bars were nearly parallel, but the absolute magnitude of the increase in bond strength with cover was slightly greater for uncoated bars than for coated bars [16]. C/U ratio increased with concrete cover, which indicated the increase of concrete cover can make up for the negative effect on the bond strength caused by epoxy coating. Nevertheless, the increase of bond strength provided by concrete cover is not unlimited. The research of Choi [9] et al. showed that no transition from splitting to a pull-out failure was detected with concrete cover ranging from 1 to 3 times of bar diameter, while with larger c/d (approximately equal to or larger than 5 bar diameter), pull-out failure rather than splitting failure generally occurred. Unlike splitting failure, the greater concrete cover has little influence under pull-out failure. As a result, the ultimate bond strength no longer increased.

3.1.4. Stirrup Ratio. The transverse reinforcements have a significant influence on load-slip behavior. Specimens without stirrups behave in a brittle manner, with the load dropping immediately after attaining the peak load. In contrast, specimens confined by sufficient transverse reinforcement fail in a ductile manner, which illustrates that the much more gradual post-peak load degradation can be obtained. Splices with stirrups exhibit higher strengths than those without stirrups under the same condition. Furthermore, the increase in bond strength was nearly linear with increasing stirrup ratio whether bars were coated or not [17]. However, the results of the researches on the effect of stirrups on C/U ratio are not completely consistent. Hester [10] et al. reported that stirrups had little effect on the C/U ratio, indicating that the percentage increase in strength was approximately the same for both coated and uncoated bars with equal amounts of transverse reinforcement. Hamad [18] et al. reached the conclusion that bond strength increased sharply with transverse reinforcement while C/U ratio increased slightly based on the results of the pull-out test and beam-splice test. Jones and Ramirez [19] studied the bond strength of high-strength concrete and believed that C/U ratio decreased as stirrups increased.

3.1.5. Concrete Strength. Bond strength of rebar generally increases with concrete strength and is approximately proportional to the square root of concrete strength [7]. However, the effect of concrete strength on C/U ratio has no complete consensus. Hamad [18] believed that C/U ratio increased with concrete strength. However, Alkaysi and El-Tawil [20] explored the bond strength of epoxy-coated
bars in ultra-high performance concrete specimens and found that the effect of factors, containing bar diameter, coating and embedded length, did not substantially differ from those of ordinary concrete and epoxy-coated bars.

3.1.6. Epoxy Coating. Epoxy coating significantly reduces the bond strength of reinforced bars to concrete and the amount of the bond strength reduction is greatly related to the thickness of the epoxy coating. Thicker coating causes a greater reduction of bond strength than thinner coating. Besides, it was found from early studies that bar diameter can affect the reduction, which indicated that rebars with smaller diameters were more sensitive to the variation of the thickness of epoxy coating [21]. From the study of Xue [4], the coating of 0.18 mm had a slight effect on bond strength for all diameter bars. When the coating is between 0.22 and 0.35 mm, the reduction of bond strength was small and the variation of coating thickness had almost no effect on bond strength for large diameter bars. Oppositely, the coating caused a significant reduction on bond strength and the reduction of bond strength increased with coating thickness for small diameter bars. Moreover, the coating of 0.35 mm was too thick to apply for the epoxy-coated bars of small bar diameter due to the overlarge reduction in bond strength. The thickness of the epoxy coating can be slightly increased for rebars with a large diameter. For instance, it was detected that the maximum allowable coating thickness should be increased to 0.42 mm for bar diameter over 19mm [22].

3.2. Influenced Factors of Long-Term Bond Strength

Marine infrastructures have been widely constructed, which manifests that it is important to pay attention to the corrosion effect on bond properties of rebars. Comparing the specimens hung in the tidal zones to capture the actual effect of seawater with the specimens in the laboratory and in open air, it was detected that although both epoxy-coated bars and uncoated bars still were corroded, epoxy-coated bars exhibited good corrosion resistance indeed [23]. The bond strength of all specimens was dropped due to corrosion at the first time-step of 6 months and the bond strength increased back with time after the drop. The reduction in bond strength was higher for the specimens hung in the sea than the specimens kept in the laboratory and in open air due to the effects of wetting and drying cycles, biodeterioration and wave impact which can accelerate the deterioration rate of concrete. The increase in bond strength followed the initial drop was attributed to the seashell layer which can increase concrete stiffness and strength. Specimens in the actual seawater environment possessed a greater increase in bond strength than those in the laboratory and in the open air after 6 months, leading the higher final bond strength. In summary, while epoxy coating caused reduced bond strength in the marine environment, the loss of bond strength was not very significant after a long period.

4. Design Recommendation

The ACI 318-14 [24] and the AASHTO LRFDUS-2017 [25] specify that the structures using epoxy-coated bars need a development length modification factor to compensate for the reduction in bond strength due to the smooth surface of epoxy-coated bars. The provisions in ACI and the AASHTO adopted a development length modification factor equal to 1.5 for epoxy-coated bars with the concrete cover less than 3 times of bar diameters or a clear spacing between bars less than 6 times of bar diameters, while the factor was adjusted to 1.2 (ACI 318-14 [24]) and 1.15 (AASHTO LRFDUS-2017 [25]) when the concrete cover and clear spacing beyond the above-mentioned limit value.

However, many studies revealed that the ACI and the AASHTO overestimated the required development length of epoxy-coated bars in virtually all cases. It should be noted that the adopted modification factor was derived from the tests of Treece and Jirsa [12] containing 12 epoxy-coated reinforced concrete beams and 9 uncoated reinforced concrete beams. Only 21 testing specimens were too limited to make the applicable conclusion. Furthermore, the test did not consider the effect of stirrups, which may have a significant improvement of the bond strength, leading to the underestimation of bond strength for the specimens strengthened with stirrups. Besides, the
modification factor was proposed based on the specimens with diamond-shaped ribbed bars, thus whether it can be applied to the epoxy-coated bars still remains to be explored.

Grundhofer [11] et al., Hester [16] et al. and Kayyali [26] et al. considered that the modification factor in the ACI and the AASHTO can be appropriately reduced to save material and alleviate bar jams while maintaining the bond strength. For epoxy-coated bars, the aforementioned development length modification factor of 1.50 can be reduced to 1.35 for specimens without stirrups. If bar diameter was taken into account, it can be further reduced to 1.25 for the rebars smaller than 19 mm. A development length modification factor of 1.25 and 1.20 would be appropriate for confined epoxy-coated bars in place of uncoated bars with and without stirrups respectively. When the specimens were at low levels of confinement, however, the modification factor was equal to the specimens with no stirrups. Besides, for the specimens with the concrete cover equal to 3 times of bar diameter cover or the clear spacing between bars equal to 6 times of bar diameters or more, the development length modification factor was reasonable to be set as 1.0, because the bond strength of the epoxy-coated bars exceeded the bond strength of the uncoated bars whose concrete cover were less than bar diameter. Therefore, the present codes for the design of concrete structures reinforced with uncoated bars can be applied to that reinforced with epoxy-coated bars under several special circumstances with a thick concrete cover. Nevertheless, it is interesting to be noted that epoxy-coated bars are usually used in marine infrastructures with a relatively thick concrete cover.

5. Conclusions
A large number of studies have been conducted on the bond properties of epoxy-coated bars and concrete. The reduction in bond strength due to the epoxy coating was detected in the studies and the influenced factors of bond strength have been well presented. However, the effect of factors on the bond strength and the relative bond ratio is not completely consistent. Besides, the development length modification factor in ACI 318-14 [24] and AASHTO LRFD-US-2017 [25] can be appropriately reduced and it is possible to increase the thickness of concrete cover to compensate for the reduction in bond strength owning to the epoxy coating instead of increasing bond length.

Based on the existing research on the bond property of epoxy-coated bars and concrete, the following recommendations should be considered in future research.

1) It is necessary to study the effect of bar diameter on bond strength and concrete strength on relative bond ratio which have not reached the consistent conclusion in former research.

2) According to the existing tests, the bond strength is influenced by various factors. Effect of each individual factor on bond strength has already been fully tested, nonetheless, the effect methods minimize the negative impact on bond strength under the couple influence of different factors has not been researched.

3) The research investigating the bond behavior in high-strength concrete remains limited. The effect of factors such as concrete cover has not been tested and many further studies are needed.

4) There are few studies on the long-term bond strength between corroded epoxy-coated bars and concrete. It is necessary to conduct further study to propose a long-term bond strength model for corroded epoxy-coated bars.

5) The rapid development of coastal areas has raised the need for the construction of concrete structures. Seawater sea-sand concrete is recently proposed to replace ordinary concrete owning to convenience in transportation and lower costs. Epoxy-coated bars can prevent steel corrosion in marine infrastructures of coastal cities. Therefore, the combination of epoxy-coated bars and seawater sea-sand concrete will have great economic and practical significance. However, the bars with epoxy coating is detected to reduce the bond strength. The bond property of epoxy-coated bars and seawater sea-sand concrete should be studied in subsequent research.

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