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# Experimental and analytical study on bond strength of normal uncoated and epoxy-coated reinforcing bars

Xiao-Hui Wang[a,*], Bing Chen[b], Peng Tang[a]

[a] *College of Ocean Science and Engineering, Shanghai Maritime University, Shanghai 201306, China*
[b] *Department of Civil Engineering, Shanghai Jiao Tong University, Shanghai 200240, China*

## HIGHLIGHTS

- Carrying out an experimental investigation on bond behaviour of epoxy-coated bars.
- Proposing a bond model for predicting the bond strength of epoxy-coated reinforcing bar.
- Verifying the proposed bond mode by published and the present tests.
- Suggesting values of the effective rib face angle for uncoated and epoxy-coated bars in the proposed bond model.

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## ABSTRACT

Although a lot of experimental research has been carried out to study the bond behaviour of the epoxy-coated reinforcement, corresponding predictive analytical models are quite limited. In order to solve this problem, first, an experimental investigation on bond behaviour of normal uncoated bars and epoxy-coated bars with two nominal coating thicknesses was carried out; following, a bond model for predicting the bond strength of epoxy-coated reinforcing bar was proposed by taking into account epoxy coating thickness, bar parameters, friction coefficient of the epoxy-coated bar and concrete, crushed concrete friction coefficient, cover-bar diameter ratio and the embedded length of the bar. The proposed bond model was verified by previously published tests and current one of the authors. Based on the model verification and discussion, taking into account the effect of bar size, embedded length and epoxy coating thickness, the proposed bond model suggests values of the effective rib face angle for the normal uncoated and epoxy coated bars, respectively.

## 1. Introduction

From the late 1970s, epoxy-coated reinforcement has been used to protect the reinforcement against corrosion in reinforced concrete (RC) structures exposed to aggressive environments [1]. In Florida, epoxy-coated rebars have been used in approximately 300 bridges, principally in an attempt to control corrosion of the substructures in the splash-evaporation zone of marine bridges [2]. Till 2008, the organic coating, specifically fusion-bonded epoxy coatings are the prevalent corrosion protection method in the U.S., supporting the need for further investigation [3].

Due to the epoxy coating at the surface of the reinforcing bars, rebar – concrete bond strength is influenced. In the past years, many experimental tests were carried out to study this problem [4–25]. For smooth bars, epoxy coating had no significant influence on the friction coefficient [16]; for deformed bars, when the bars were epoxy coated, the adhesion between the bar and concrete was destroyed, resulting in significant reduction of the bar-friction coefficient [16] and causing partial or complete loss of the friction capacity [5]. Thus, bond strength of the epoxy-coated reinforcing bar was also reduced. The magnitude of this reduction was influenced by the failure mode [5], epoxy coating thickness [6,20,22,23], bar parameters [6,8,13,14,18], confined steel [13,22], adopted bond test methods [13], depth of concrete cover [12], concrete strength and types [8], temperature effects [25] and other factors such as casting position, concrete slump and degree of consolidation [12].

Often, the epoxy-coating induced reduction in bond strength was believed from: 1) loss of adhesion between the concrete and epoxy-coated bar [5]; 2) partial or complete frictional characteristics between the reinforcement and concrete [5,13]; 3) the reduction of the rib height [8]. Although Treece and Jirsa [5] pointed out the transfer of force from coated-bar and concrete is accomplished

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* Corresponding author.
*E-mail address:* w_xiaoh@163.com (X.-H. Wang).

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only through rib bearing force exists at the rib face, friction tests carried by Cairns and Abdullah [13] and Idun and Darwin [18] showed that the average coefficients of friction for an epoxy-coated steel surface were 0.487 and 0.49, respectively. Based on the beam test results, Treece and Jirsa [5] pointed out that a splitting failure with a reduction of 35% in bond strength of the epoxy-coated bar was shown while only 15% reduction in bond strength was presented in a pull out failure. In addition, the reduction in this bond strength was independent of bar size and concrete strength. On the contrary, Choi et al. [6] pointed out that, in general, the reduction in bond strength caused by an epoxy coating increased with bar size. For No.5 (16 mm) bars, reduction in bond strength increased with the increase of the coating thickness; while coating thickness has little effect on the amount of bond strength reduction for No. 6 (19 mm) bars and larger. When bar sizes are different, the influence of the concrete strength on the ultimate bond strength ratio (uncoated/epoxy-coated) is also different. For No. 6 bars, the ultimate bond strength ratio was unaffected by concrete strength while this ratio increased as concrete strength increased for No.11 bars [8]. Other studies also showed that bond strength and bond-slip behavior of coated bars varied with the bar rib face angle, rib spacing and rib height [14,15]. For the reinforcing bar with different coating thicknesses, reduction in bond strength is also different. For No. 19 (No. 6) reinforcing bars with three deformation patterns [17,20], reduction in bond strength caused by epoxy coatings between 160 μm and 420 μm was largely independent of coating thickness while this reduction increased for coatings thicker than 420 μm. For the same thickness of green and gray coatings, similar reductions in bond strength were presented for the reinforcing bars with the same sizes [22].

At present, preparation of the test specimens with epoxy-coated bars is similar to that of the test specimens with normal uncoated bars. So, besides the factors mentioned above, two other main factors, such as cover-bar diameter ratio $h_c/d$ and embedded length-bar diameter ratio $l_{em}/d$ also affect the bond behaviour (see Table 1), where in Table 1, $d$ is the nominal diameter of the reinforcing bar; $h_c$ is the clear concrete cover and $l_{em}$ is the embedded length of the reinforcing bar; $f'_c$ is the compressive cylinder strength of concrete; $f_{cu}$ is the compressive cube strength of concrete. Table 1 indicates that, in most cases, when the cover-bar diameter ratio $h_c/d$ is lower than 5, splitting-type failure mode is observed; while pull out failure mode is observed when cover-bar diameter ratio $h_c/d$ is larger than 5. As for the embedded length of normal uncoated bars, the normalized bond strength was found to increase with the increase of embedded length from 100 (7 times the bar diameter) to 200 mm (13 times the bar diameter) [31].

In the present paper, an experimental investigation on bond behaviour of normal uncoated and epoxy-coated bars was carried out firstly, where the main considered parameter is the epoxy coating thickness and two nominal coating thicknesses (200 μm and 600 μm) were used for comparison; in addition, considering the influence of the above-mentioned parameters, such as epoxy coating thickness, bar parameters, friction coefficients, cover-bar diameter ratio and embedded length of the reinforcing bar, on the bond behavior of the epoxy-coated bar, a bond model is proposed and verified by previously published tests and current one of the authors. The values of key parameter in the proposed model are suggested on the basis of the model verification and discussion.

## 2. Descriptions of test specimens

### 2.1. Reinforcing bars

12 mm deformed bars were used to prepare the pull-out test specimens, being normal uncoated bars and epoxy-coated bars

**Table 1**
Summary of cover-bar diameter ratio $h_c/d$ and embedded length-bar diameter ratio $l_{em}/d$ in published tests on bond behavior of normal uncoated reinforcing bars.

| Reference | Test method | Type of concrete | Diameter $d$ (mm) | $f'_c$ (MPa) | Lateral pressure | $h_c/d$ | $l_{em}/d$ | Failure mode |
|---|---|---|---|---|---|---|---|---|
| Xu [26] | Pull out | Normal concrete | 16 | $f_{cu}$ = 11.7–45.8 | – | 0.69–5.75 | 5 | Splitting |
| Walker et al. [27] | Pull out and beam | Normal concrete | 8, 12, 16 | $f_{cu}$ = 25 | 0, 0.2$f_{cu}$ | 1, 2 | 10–15 | Splitting |
| | | | | | | 3, 5 | | Splitting, Pull out |
| Walker et al. [27] | Pull out and beam | Normal concrete | 8, 12, 16 | $f_{cu}$ = 25 | 0.4$f_{cu}$ | 1, 2 | 10–15 | Splitting |
| | | | | | | 3, 5 | | Pull out |
| Hamad and Sabbah [28] | Pull out | Silica fume concrete | 25, 32 | 59, 86, 89, 93, 102 | – | 1–2 | 10, 8 | Splitting |
| Esfahani and Rangan [29] | Pull out | Normal and silica fume concrete | 19.3, 23.3 | 26, 50, 75 | – | 0.93–2.59 | 2.3–4.1 | Splitting |
| Hamad and Akik [30] | Pull out | Silica fume concrete | 25, 32 | 66–107 | – | 1–2 | 10, 8 | Splitting |
| Lachemi et al. [31] | Pull out | Lightweight self-consolidating concrete | 15 | 36.2–43.6 | – | 4 | 7, 13 | Splitting |
| Sarker [32] | Pull out | Fly ash –based geopolymer concrete and OPC | 20, 24 | 25.5–55.3 | – | 1.71–3.62 | 4–6 | Splitting |
| Looney et al. [33] | Pull out | Normal | No.13 and No.19 | 39.9, 47.2 | – | >4.5 | 5 | Pull out |
| | | High | | 66.4, 67.2 | | | | |
| Wu et al. and Li et al. [34–35] | Pull out | Normal concrete | 12, 16, 22 | $f_{cu}$ = 25, 40, 55 | Two directions | 2.91, 4.19, 5.75 | 5 | Pull out and splitting |
| Metelli et al. [36] | Pull out | Normal | 12, 16, 20, 40, 50 | 42.7–47.8 | – | 0.5–3.67 | 5 | Pull out and splitting |
| | | High | 12, 16, 20 | 63.4–74.3 | | 2.0–3.67 | | |
| Kaffetzakis et al. [37] | Pull out | Lightweight Aggregate Self-Compacting Concrete | 12, 16 | 33.2–46.1 | – | 4.5, 4.8 | 5 and 10 | Pull out and splitting |
| Daud et al. [38] | Pull out | Normal concrete | 16 | $f_{cu}$ = 55 | – | 5.25 | 5 | Pull out and splitting |

*Note*: $d$ is the nominal diameter of the reinforcing bar; $h_c$ is the clear concrete cover; $l_{em}$ is the embedded length of the reinforcing bar; $f'_c$ and $f_{cu}$ are the compressive cylinder and cube strength of concrete, respectively.