

Experimental study on the bond-slip behaviour between corroded bars and concrete

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Abstract. Pull-out tests were conducted to investigate the effects of corrosion of the both longitudinal bar on the bond-slip behaviour of reinforced concrete specimens. The main experimental variables include concrete strength (26.7 MPa, 37.7 MPa, 45.2 MPa) and expected corrosion rate (0%, 4%, 8%, 12%), with a total of 36 specimens fabricated. The results show that the relative bonding strength of specimens under different concrete strengths gradually decreases with increasing corrosion rate, but the higher the concrete strength is, the faster its degradation rate. Based on the experimental results of this work and the achievements of other scholars, a modified relative bonding strength degradation model is presented by accounting for the influence coefficient of concrete strength.

Keywords: reinforced concrete; longitudinal bar corrosion; concrete strength; bonding strength.

1. Introduction

Many scholars have conducted experimental studies on the bond-slip behaviour of corroded reinforced concrete. In early studies, the factors considered in models were relatively simple [1,2]. Zhang et al. [3], based on the pull-out test without stirrups, obtained a formula for calculating the relative bonding strength considering only the corrosion of longitudinal reinforcement and believed that the relative bonding strength decreased linearly with the corrosion rate. Yalciner et al. [4] showed that the degradation of the interfacial bonding strength between concrete and rebar with different concrete strength grades were different and that concrete with a higher strength was more sensitive to the deterioration of bonding properties caused by corrosion. Based on the pull-out test, Lin et al. [5] proposed a bonding strength degradation model that accounted for multiple coupling factors, such as longitudinal reinforcement corrosion, stirrup corrosion and stirrup spacing, but it did not account for the influence of concrete strength, resulting in deviations in the prediction results.

In view of this, to explore the influence of longitudinal bar corrosion on bonding strength under different concrete strength levels, three eccentric pull-out specimens with different concrete strengths were poured in this paper and subjected to electrochemically accelerated corrosion to obtain specimens with different steel mass loss rates. Based on the pull-out test results, a modified relative bonding strength degradation model of corroded reinforced concrete is proposed.

2. Overview of the test

2.1 Experimental design

The variables of the test are concrete strength grade (C25, C35, C45), corrosion rate (0%, 4%, 8%, 12%), with a total of 12 groups of different working conditions. The parameters of specific specimens are shown in Table 1. To obtain a reasonable bonding stress distribution, the bonding length of the longitudinal bar was 5 times the diameter of the steel bar [6], as shown in Fig. 1.

Table 1. Parameters of the specimens

Specimen name	Concrete strength	Expected corrosion rate	Number of specimens
A-25	C25	0%	3

M-2-4/8/12	C25	4%/8%/12%	3/3/3
A-35	C35	0%	3
M-3-4/8/12	C35	4%/8%/12%	3/3/3
A-45	C45	0%	3
M-4-4/8/12	C45	4%/8%/12%	3/3/3

where A-XX indicates the uncorroded control group, where XX represents the concrete grade. M-X-4/8/12 indicates only longitudinal reinforcement corrosion, where X represents the concrete strength, 2 represents C25, 3 represents C35, 4 represents C45, and 4/8/12 corresponds to different design corrosion rates.

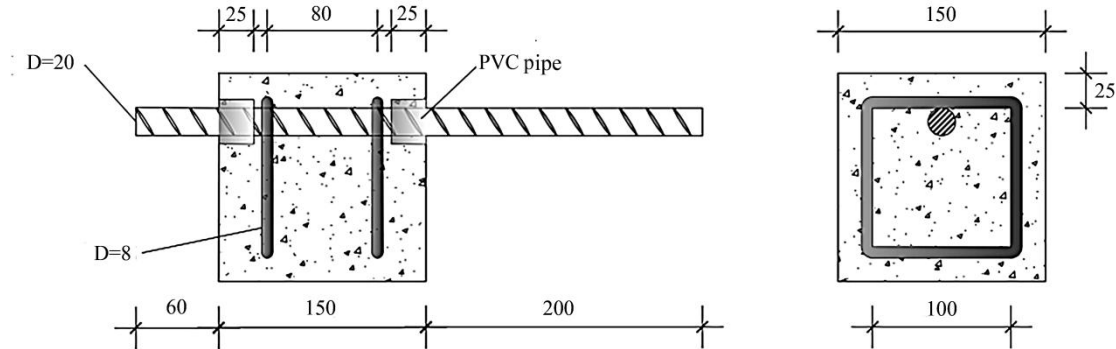


Fig. 1. Dimensions of the pull-out test specimens (unit: mm)

2.2 Electrochemical corrosion

Tian et al. [7] noted that the structural bearing capacity under the half soaking method (HSM) is basically the same as that in the natural environment. Considering the large number of specimens and the convenience of management, the HSM was chosen for the current test. The specimens were connected in parallel with copper wires. The current density was 0.4 mA/cm². The stirrup is insulated by wrapping insulation tape. The power supply was adjusted daily to ensure the stability of the current.

The principle of Faraday's law is that the amount of charge transferred in the electrochemical reaction is equal to the number of electrons transferred in the corroded steel bar, so the charging time of the specimen was calculated according to Faraday's law:

$$t = \frac{\Delta m Z F}{M I} \#(1)$$

where t is the power at time (s), Δm is the corrosion mass (g), and M is the relative molecular mass of iron, which was 56 g/mol here. I is the average current (A) used in the electrical acceleration process, and Z is the number of electrons lost by the iron atom, which was 2 here. F is Faraday's constant, which was 9.65×10^4 C/mol here.

The current required to initiate the corrosion of each specimen was calculated to be 0.025 A, and the electrification times required to reach the expected corrosion rates of 4%, 8% and 12% were 15.7 d, 31.5 d and 47.2 d, respectively.

The corrosion rate of the longitudinal reinforcement can be calculated with formula (2):

$$\eta = \frac{m_0 - m_1}{m_0} \#(2)$$

where η is the corrosion rate of the longitudinal reinforcement, m_0 is the mass of the steel bar without corrosion in the anchoring section (g), and m_1 is the mass of the steel bar after rust removal in the anchoring section (g).

After the electrical corrosion is complete, it can be seen from Fig. 2 that the side near the concrete cover was more seriously corroded because the ion concentration on this side was higher

as a result of the HSM method. As shown in Fig.3, the regional corrosion and pitting of the steel bars were visible to the naked eye as the corrosion rate increased.



Fig. 2 Corroded steel bars in the specimen

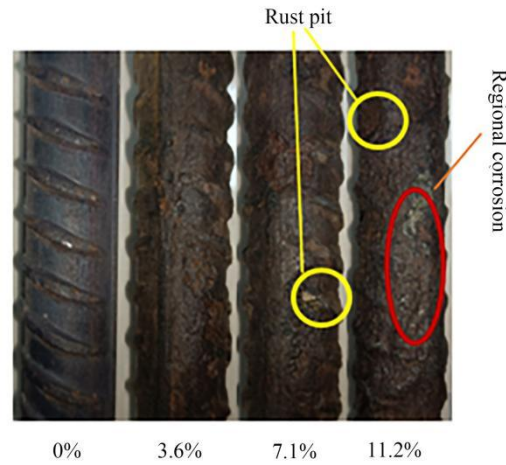


Fig. 3 Shape of steel bars after rust removal

2.3 Loading of the specimens

The loading device is shown in Fig. 4(a). The loading rate of the test was 0.5 mm/min, and the end was marked by the stability of the pull-out force or the failure of the specimen. The test site is shown in Fig. 4(b). The bonding strength of the specimen is calculated as follows:

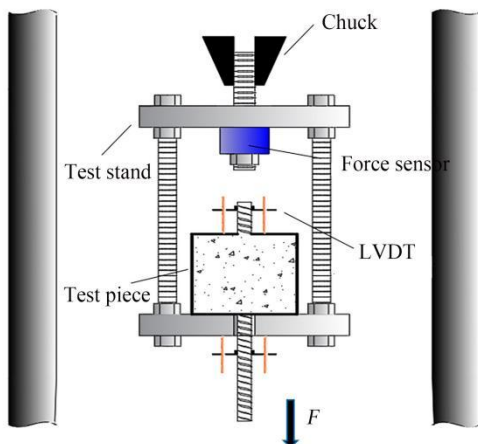
$$\tau = \frac{F}{\pi D l} \quad \#(3)$$

where τ is the average bonding strength, F is the pull-out force, D is the diameter of the longitudinal bar, and l is the length of the bonding zone.

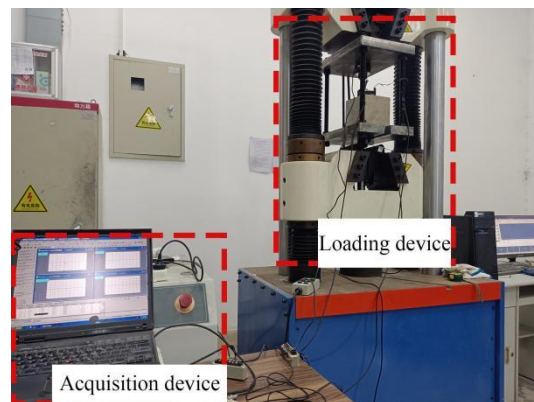
The slip value is expressed as the average of the displacement data of the free end and the loaded end:

$$s = \frac{s_1 + s_2}{2} \quad \#(4)$$

where s is the average slip value of the specimen, s_1 is the displacement of the free end, and s_2 is the displacement of the loading end.



(a) Loading device



(b) Test site

Fig. 4 Loading device and test site

3. Results and discussions

The pull-out test results of the A-series and M-series specimens are summarized in Fig. 5. The actual corrosion rate of the rebar was mostly lower than the expected corrosion rate, which may be caused by the loss of current in the conduction process. With the increase in the longitudinal reinforcement corrosion rate, the ultimate bonding strength of corroded concrete specimens with different concrete strengths also decreased and only reached 40% of the uncorroded specimens in severe cases. The bond-slip curve of the specimen were divided into three parts, the "rising section" (from the start of the test to the peak slip), "falling section" (from the peak slip to the slip point of 8 mm) and "residual section" (from the slip point of 8 mm to the end), reflecting the sharp rise in the bonding stress of the specimen after the start of the test and then the relatively gentle decline to the residual stress. In addition, with increasing concrete strength, the span of the peak points of the bond-slip curve along the abscissa also increased correspondingly. The maximum limit bonding strength of the uncorroded specimen of C25 grade reached 11.74 MPa, while the minimum limit bonding strength of the corroded specimen was 6.69 MPa, and the span was 5.05 MPa. The ultimate bonding strength span of the C35 grade specimens was 6.89 MPa, while the span of the C45 grade specimens was 8.73 MPa, which indicates that the higher the concrete grade is, the greater the absolute value of the decline in the ultimate bonding strength.

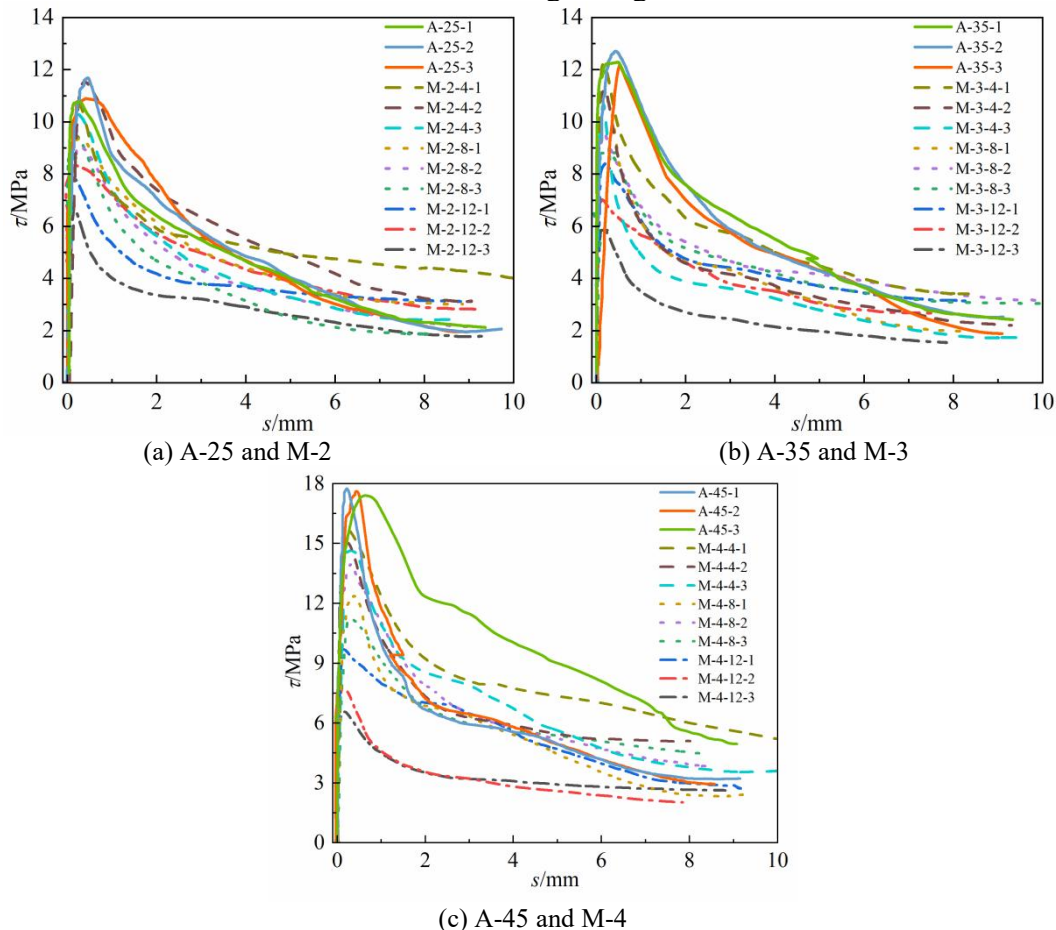


Fig. 5 Bond-slip curves of A-series and M-series specimens

Lin et al. [8] proposed a formula for calculating the relative bonding strength by considering various factors based on the test results of 18 beam members and existing databases. As shown in equation (5a), when the corrosion rate of the longitudinal bar is less than 1.5%, the influence of corrosion on bonding strength can be negligible. The relative bonding strength deteriorates exponentially with the corrosion rate. The prediction curve of the formula, the three sets of M-series data and their fitting curves are drawn in Fig. 6, from which it can be found that in specimens with similar corrosion rates, the greater the concrete strength is, the lower its relative bonding strength,

indicating that the higher the concrete strength grade is, the more serious the bonding strength degradation caused by the steel bar rusting. In addition, the three data fitting curves have good correlation, and the exponential form is reasonable to describe the degradation of the relative bonding strength. However, since the influence of concrete strength is not considered in formula (5b), the degradation coefficient calculated with this formula is not much different from the degradation coefficient fitted based on the M-3 series test results, and there is a large deviation from the fitting values of the M-2 series and M-4 series, with a maximum error of 81%, which indicates that the relative bonding strength of the specimens is also related to the concrete strength. Therefore, this paper adds a concrete strength correction coefficient k_1 on the basis of the original degradation coefficient δ_0 in equation (6a), namely, $\delta = k_1 \delta_0$. Table 2 lists the concrete correction coefficient calculated based on the three strength series here and the data of other tests presented in the reference. The concrete strength used in formula (5a) is 33 MPa, so it can be considered that the concrete correction coefficient under this strength is 1. Furthermore, it can be seen from Fig. 7 that the concrete correction coefficient k_1 presents a good linear correlation with the concrete strength, and the relation is $k_1 = 0.083f_{cu} - 1.82$. See (5c) for the revised δ formula.

$$R_m = \begin{cases} 1 & \eta \leq 1.5\% \\ e^{-\delta_0(\eta-1.5\%)} & \eta > 1.5\% \end{cases} \quad \#(5a)$$

$$\delta_0 = \begin{cases} \frac{13.28 - 0.57(c/d)}{43.54\xi_{st} + 1} & i_{corr} \leq 200 \mu A/cm^2 \\ \frac{13.28 - 0.57(c/d)}{43.54\xi_{st} + 1} \left(0.17 \ln \left(\frac{i_{corr}}{200} \right) + 1 \right) & i_{corr} > 200 \mu A/cm^2 \end{cases} \quad \#(5b)$$

$$\delta = \begin{cases} \frac{13.28 - 0.57(c/d)(0.083f_{cu} - 1.82)}{43.54\xi_{st} + 1} & i_{corr} \leq 200 \mu A/cm^2 \\ \frac{13.28 - 0.57(c/d)}{43.54\xi_{st} + 1} \left(0.17 \ln \left(\frac{i_{corr}}{200} \right) + 1 \right) (0.083f_{cu} - 1.82) & i_{corr} > 200 \mu A/cm^2 \end{cases} \quad \#(5c)$$

where R_m is the relative bonding strength of the specimen only considering the corrosion of the longitudinal bar, equal to the ratio of the ultimate bonding strength $\tau_u(\eta)$ of the corroded specimen to the bonding strength $\tau_u(0)$ of the uncorroded specimen. δ_0 is the degradation coefficient, which is related to the relative concrete cover c/d , stirrup coefficient ξ_{st} and corrosion current density i_{corr} . The stirrup coefficient $\xi_{st} = A_{st}/nDS_{st}$, where A_{st} is the cross-sectional area of the stirrup, n is the number of anchorage reinforcement bars, D is the diameter of the longitudinal reinforcement, and S_{st} is the distance between the stirrups.

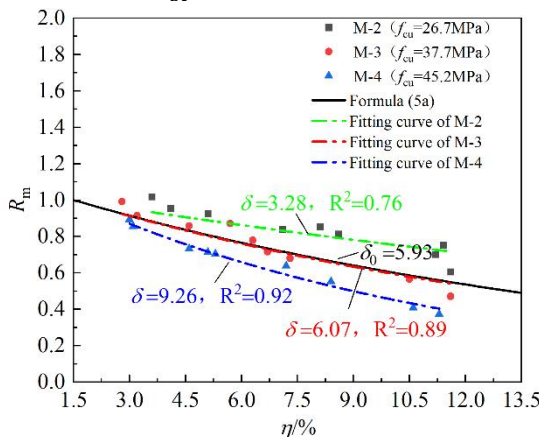


Fig. 6 Degradation of R_m with corrosion rate

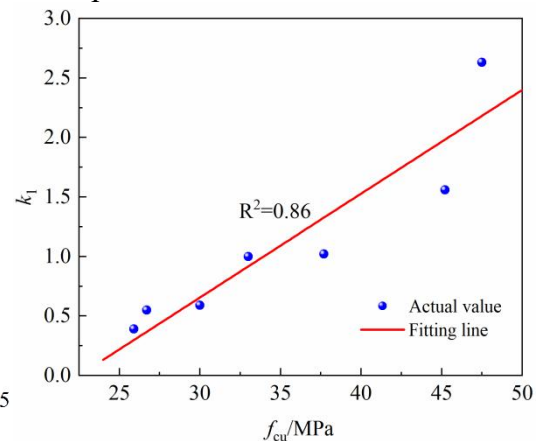


Fig. 7 Relationship between k_1 and f_{cu}

Table 2. Concrete correction coefficient k_1

Data source	Concrete strength/MPa	Predicted value of δ_0	Actual value of δ	k_1
Ref. [9]	25.9	12.60	4.87	0.39
Ref. [10]	30.0	14.49	8.61	0.59
Ref. [11]	47.5	4.99	12.98	2.60
M-2	26.7	5.93	3.28	0.55
M-3	37.7	5.93	6.07	1.02
M-4	45.2	5.93	9.26	1.56

4. Summary

Three reinforced concrete specimens with concrete strengths of 26.7 MPa, 37.7 MPa, and 45.2 MPa were tested, and the degradation of the bond-slip behaviour of corroded reinforced concrete were studied by conducting electrochemically accelerated corrosion tests and pull-out tests. The following conclusions were obtained:

(1) The corrosion appearance of steel bar under the half soaking method (HSM) is basically the same as that in the natural environment. With increasing corrosion time, different degrees of pitting and regional corrosion of the longitudinal bars are observed.

(2) Steel bar corrosion in a specimen will reduce the bonding strength of the specimen. The higher the concrete strength grade of the specimen, the faster the bonding strength deteriorates with increasing corrosion rate.

(3) Based on the experimental results and previous work, a relative bonding strength degradation model is established, accounting for many factors, such as concrete strength and longitudinal bar rust.

Acknowledgements

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