ISSN 1009－3095 *Journal of Zhejiang University*(*SCIENCE*) V.2, No.3, P.298－308, July－Sep., 2001
http://www.chinainfo.gov.cn/periodical; http://www.zju.edu.cn;
http://lib.zju.edu.cn/English; http://www.zjupress.com

EFFECT OF CORROSION ON BOND BEHAVIOR AND BENDING STRENGTH OF REINFORCED CONCRETE BEAMS*

JIN Wei-liang(金伟良), ZHAO Yu-xi(赵羽习)

(*Department of Civil Engineering, Zhejiang University, Hangzhou 310027, China*)

Received July 6, 2000; revision accepted Jan.2, 2001

Abstract: There is growing concern for corrosion damage in reinforced concrete structures with several decades' service. Pullout tests and beam tests were carried out to study the effect of reinforcement corrosion on the bond behavior and bending strength of reinforced concrete beams. The bond strength of plain bars and concrete initially increases with increasing corrosion, then declines. The turning point depends on the cracking of the concrete cover. The bond strength of deformed bars and concrete increases with corrosion up to a certain amount, but with progressive increase in corrosion, the bond strength decreases, and the cracking of the concrete cover seems to have no effect on the bond strength. On the basis of test data, the bond strength coefficient recommended here, which, together with the bond strength of uncorroded steel bars and concrete, can be used to easily calculate the bond strength of corroded steel bars and concrete. The bond strength coefficient proposed in this paper can be used to study the bond stress-slip relationship of corroded steel bars and concrete. The bending strength of corroded reinforced concrete beams declines with increasing reinforcement corrosion. Decreased bending strength of corroded RC beam is due to reduction in steel bar cross section, reduction of yield strength of steel bar, and reduction of bond capacity between steel bar and concrete.

Key words: reinforced concrete beam, corrosion, bond behavior, bond strength coefficient, bending strength, coordination coefficient
Document code: A **CLC number:** TU375.5

INTRODUCTION

There is growing concern for corrosion damage in reinforced concrete (RC) structures with several decades' service. The reinforcement corrosion of RC constructions probably is the most significant problem and outweighs other forms of deterioration.

Studies by Peattie et al. (1956) and Kemp et al. (1968) on how reinforcement corrosion affects the bond behavior between a steel bar and concrete suggested that reinforcement corrosion benefited the bond strength. Al-Sulaimani et al. (1990) and Yuan et al. (1999) indicated that the bond strength increased with corrosion increasing to about 1%, then declined with further increase in corrosion. All the above research related to deformed steel bars. The mechanics of bond strength of plain bars and deformed bars are quite different. The bond behavior of plain bars changes also, after its corrosion. The first part of this study investigates the effect of reinforcement corrosion on bond behavior by use of pullout tests.

The effect of reinforcement corrosion on the behavior of reinforced concrete beams is very important to the durability of RC structures. The second part contributes to an understanding of the effect of reinforcement corrosion on the bending strength of RC beams.

As for the research on durability of reinforced concrete structures, it is a problem that natural corrosion of steel bar takes very long time. Peattie and Pope (1956) put the specimens outside and let them be corroded naturally. This kind of experiment took a long time, while the corrosion of the steel bars was not severe enough. Some researchers used accelerated corrosion in their experiment in order to get the reinforcement corrosion data in a short period. Others studied RC members removed from real structures that had been in use for several years,

---

* Project supported by Cao Guanbiao Key Technology Development Founding of Zhejiang University and Construction Ministry of China.

while still others used the finite element method to analyze corroded reinforced beam. An electrochemical corrosion technique was used in this research to accelerate the reinforcement corrosion in the beams, on which bending experiments were carried out.

TEST PROGRAM

1. Specimens

The investigations on corrosion-bond behavior reported here were carried out under four series of tests. The mixture ratio of concrete of all specimens was the same as given below:

Cement: fine aggregate: coarse aggregate: water = 1:1.8:3.4:0.55, and its average cubic compressive strength of concrete $f_{cu} = 22.13$ MPa.

In series Ⅰ, pullout tests were conducted on 100 mm × 100 mm × 100 mm cubic concrete specimens with 12 mm diameter plain bars embedded 80 mm in them centrally. The yield strength of the plain bars was 389 MPa. This series was defined as P, where the percentage corrosion increased from P1 to P14.

The specimens in series Ⅱ were similar to those used in series Ⅰ, except that the steel bars were deformed, not plain. The yield strength of 12 mm diameter deformed bars was 428 MPa. This series was defined as D, where the reinforcement corrosion increased from D1 to D14. The specimens of series Ⅰ and Ⅱ are shown in Fig. 1.

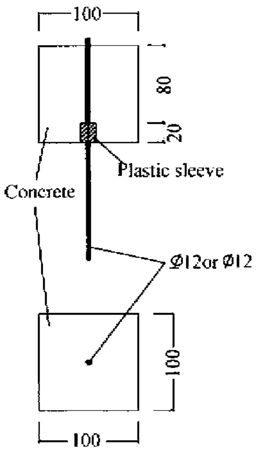

Fig. 1 Pullout specimens (mm)

In series Ⅲ, bending tests were carried out on beam specimens which were 150 mm × 150 mm in cross section and 1140 mm in length. Each beam was reinforced with two 12 mm bottom bars, two 6 mm top bars and 6 mm closed stirrups at 100 mm. These beam specimens defined as BD totalling 14 and had sufficient anchor length of 360 mm (BD). The reinforcement corrosion was increased from BD1 to BD14 to study bending strength of corroded PC beams. Insulating rubberized fabrics and epoxy resin were used to isolate the 12 mm bottom bars from the rest of the reinforcement cage, so that 12 mm bottom bars underwent independent corrosion induced through the electrochemical corrosion technique.

The beam specimens used in series Ⅳ were similar to those used in series Ⅲ, but the 12 mm bottom bars, totalling 3, had an anchor length of 100 mm, compared with the required anchor length of 360 mm. This series was defined as BDU. The size and reinforcement of beam specimens are shown in Fig. 2.

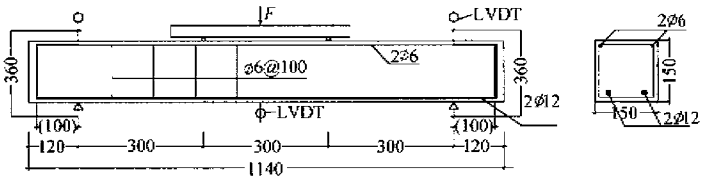

Fig. 2 Beam specimens BD(BDU) (mm)

2. Application of load

For pullout tests, the specimens were conducted in a 50 kN capacity universal testing machine. Slips of loaded-end and free-end were recorded for each load, as shown in Fig. 3.

The beam specimens were tested as simple support beams under a two-point load with a total span of 900 mm and shear span of 300 mm, using the hydraulic system shown in Fig. 2 and Fig. 4. Linear variable displacement transducers (LVDT) were used at the beam specimens' support ends and center to measure the deflection of the beams.

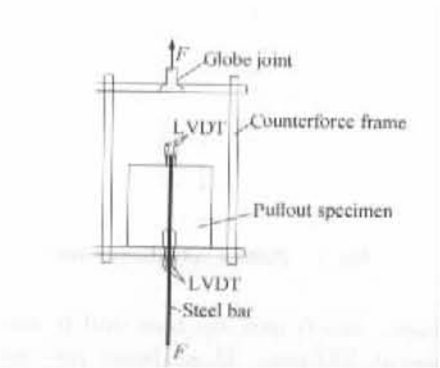

Fig.3 Application of pullout load

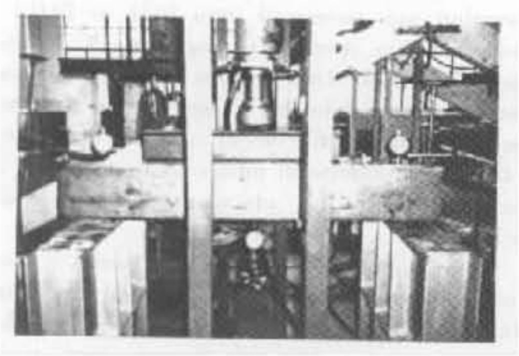

Fig.4 Application of bending load

3. Accelerated corrosion technique

This test used the electrochemical corrosion technique to accelerate the corrosion of steel bars embedded in the specimens. To simulate the corrosion process, direct current was impressed on the bar embedded in the specimens using an integrated system incorporating a small direct current power supply with an in-built ammeter to monitor the current. After specimens were immersed in a 5% NaCl solution for several days, the direction of current was arranged so that the steel bars in the specimens served as the anode, while a piece of stainless steel positioned in the solution served as cathode. To obtain the desired levels of reinforcement corrosion, the current intensity and the electrifying time had to be controlled.

RESULTS AND DISCUSSION

1. Effect of corrosion on the bond strength of two kinds of steel bars and concrete

The mechanics of the bond strength between the two kinds of steel bars (plain and deformed bars) and concrete are different. Chemical adhesion, friction and the pressure of the bar deformations against the concrete are factors contributing to the bond strength between Deformed bars and Concrete (D&C). The contribution of each of these components of bond resistance varies with the level of stress in the reinforcement. When members of bond resistance are lightly stressed, bond resistance is due primarily to chemical adhesion. After the adhesion is broken and some slight movement between the steel bars and concrete occurs, the bond strength is supplied by friction and the bar deformations bearing against the concrete. Of these two sources of resistance to further slipping, the bearing stress is the more significant. While three factors contributing to the bond strength between Plain bar and Concrete (P&C) are chemical adhesion, friction and bearing of the bar surface defects against the concrete, the ultimate bond strength mainly depended on the later two components.

The bond strength between P&C relates to the surface conditions of the steel bars. After corrosion, the variation of bond strength is mainly due to the significant changes at the steel-concrete interface. The changes in interface conditions are characterized by initial changes in the surface roughness, then the development of an adhering interstitial layer of corrosion products between the steel bars and the concrete. As to an index reflecting the effect of corrosion on the bond strength between P&C, the Corrosion Layer Depth (CLD) is more appropriate than percentage corrosion, since the CLD varies with the different steel bars' diameter at the same percentage corrosion.

The bond strength between D&C depends on the bearing of the bar deformation against the concrete. After corrosion, change of bond strength is initially due to the changes in the roughness of the steel-concrete interface, then the reduction in the profile of the bar ribs, which relates more to corrosion layer depth than to percentage corrosion. Therefore CLD is regarded as a suitable index reflecting the effect of corrosion on the bond strength.

Briefly speaking, CLD is a factor directly affecting the bond strength, and is taken as an index reflecting the effect of corrosion on bond strength. CLD has relation to percentage corrosion, so the effect of the familiar percentage corrosion on bond strength can be obtained indirectly.

2. Pullout tests of plain bars

Bond stress versus slip relationship for various degree of corrosion

Fig.5 shows the typical bond stress loaded-end slip relationship for pullout specimens of plain steel bars. The reported bond stress was calculated from the external load on the steel bar and the total surface of the embedded portion of bars, thereby representing an average value of stress along the bonded length of steel bar. Fig. 5 indicates clearly that with increase of corrosion levels , the bond strength and the bond rigidity initially increase, then decrease.

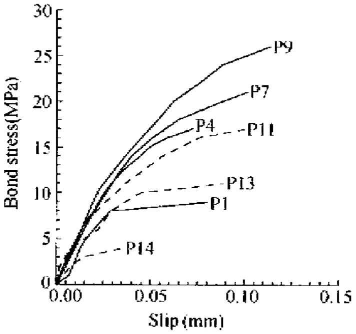

Fig.5 Bond stress versus slip relationship of P&C

Test data:

Data on the effect of corrosion on the bond strength between P&C are given in Table 1, listing the ratio of tested bond strength to theoretical bond strength of uncorroded steel bars and concrete, which can be expressed as bond strength coefficient η, the corresponding percentage corrosion and transformed CLD.

Table 1 Test data for the series I specimens

Specimens	Bond strength (MPa)	Ratio of bond stress	Percentage corrosion	CLD* (mm)
P1	2.65	1.22	0.27	0.0162
P2	3.23	1.01	0.29	0.0174
P3	5.97	2.27	0.92	0.0549
P4	5.83	2.17	1.13	0.0674
P5	7.41	2.81	0.78	0.0466
P6	8.62	3.27	1.47	0.0876
P7	7.29	2.77	1.85	0.1100
P8	7.96	3.02	1.50	0.0893
P9	9.28	3.53	1.99	0.1182
P10	10.25	3.90	1.04	0.1212
P11	5.97	2.27	2.75	0.1628
P12	4.84	1.84	2.43	0.2024
P13	3.74	1.42	4.77	0.2797
P14	1.62	0.61	5.01	0.2934

* Note: calculated by Eq.(4)

Fig.6 shows the test data and its optimized regressive line, with CLD as the abscissa and the ratio of test bond strength to theoretical bond strength of uncorroded steel bars and concrete η as the ordinate. Fig. 6 indicates that the bond strength initially increases with the increasing amount of corrosion, however, once a crack occurs, the bond strength decreases. The bond strength reaches the maximum value before corrosion expansion crack appears, and the maximum bond strength of P&C is three times that of uncorroded plain steel bars and concrete, which agrees with the viewpoint of Wang and Teng (1985).

If the bond strength coefficient η_p is given, together with the bond strength of uncorroded steel bars and concrete τ_{u0}, the P&C bond strength at various corrosion levels can be ex-

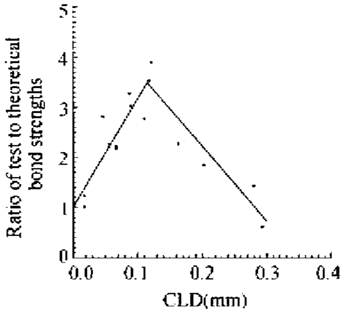

Fig.6 **Effect of reinforcement corrosion on the bond strength of P&C**

pressed as follows:

$$\tau_u = \eta \cdot \tau_{u0} \qquad (1)$$

where τ_u is the bond strength at various corrosion levels, τ_{u0} is the bond strength of uncorroded steel bar and concrete, η is the bond strength coefficient, η_p for plain steel bars in Eq. (3) and η_D for deformed steel bars in Eq.(6).

The test data based optimized regressive line shown in Fig.6, showing the bond strength coefficient of the pullout test of plain bars, can be expressed as follows:

$$\eta_1 = \begin{cases} 0.97 + 22.05\delta, & \delta \leqslant 0.115 \\ 5.25 - 15.28\delta, & \delta > 0.115 \end{cases} \qquad (2)$$

where η_1 is the bond strength coefficient and δ is the corrosion layer depth.

Effect of corrosion on the bond strength of plain bars and concrete

In the pre-cracking corrosion stage, the bond strength increases with increasing corrosion. This could be explained on the basis of increased surface roughness of the plain steel bars with the growth of rust, which tends to enhance the holding capacity. Wang et al. (1985) and Xu (1990) indicated that with slight to severe corrosion, the friction coefficient of plain steel bars and concrete increases 2 – 3 times. Beginning corrosion of a steel bar gradually decreases its diameter and produces rust of higher volume than that of the steel bars. This increase in volume seems to increase the radial force, so-called corrosion expansion force between the steel bars and concrete. The higher radial force enhances the bond strength. Once a crack occurs, the confinement of the steel bars reduces, and the radial force changes suddenly because of energy release, then the bond strength begins to decline.

The bond strength coefficient of Eq. (2) is only suitable for the pullout specimens of plain steel bars. The extended equation for other situations of plain bars is discussed below. The index directly reflecting the effect of corrosion on bond strength is CLD, and was discussed before. At the same CLD, the bond strength of different cover-to-bar diameter ratio specimens can be considered to be identical. But it should be pointed out that the equation of bond strength coefficient still relates to cover-to-bar diameter ratio, as the cover-to-bar diameter ratio determines the cracking time of concrete cover, on which the turning point of bond strength of P&C depends.

According to the above analyses, the coefficient of bond strength between P&C is recommended as follows:

$$\eta_p = \begin{cases} 1 + 22\delta, & \delta \leqslant \delta^* \\ 1 - 15 + 37\delta^*, & \delta > \delta^* \end{cases} \qquad (3)$$

where δ^* is the CLD corresponding to the cracking time, which can be calculated from the relationship:

$$\delta^* = D_0\left(\sqrt{n\rho^* + 1 - \rho^*} - 1\right)/2 \qquad (4)$$

where D_0 is diameter of the steel bar, ρ^* is percentage reinforcement corrosion corresponding to the crack time, n is volume expansion ratio, usually 2 – 4 according to Han and Cai (1991). A ratio of $n = 3$ is assumed in the present work.

3. Pullout tests of deformed bars

Failure modes and bond stress versus slip relationship

All the pullout specimens of deformed bars failed in the split mode, except the specimens D1, where bond failure occurred by pullout of the bars rather than by splitting of the concrete. When reinforcement corrosion was slight, the specimens split at one lateral face or two opposite lateral faces, as shown in Fig. 7 (a). In the more corroded specimens, which already had the corrosion expansion cracks even before the pullout tests, the split occurred just at the existing crack, and was accompanied by some slight cracks nearby, as shown in Fig. 7 (b). The concrete cover over the severely corroded specimens almost flaked off when the specimens failed, and could even be taken off by hands easily, as shown in Fig.7 (c).

Fig.8 shows the typical bond stress versus loaded-end slip relationship for pullout specimens of deformed bars, and indicates that with increase of corrosion level, the bond strength and the bond rigidity initially increase a little, then decrease consistently.

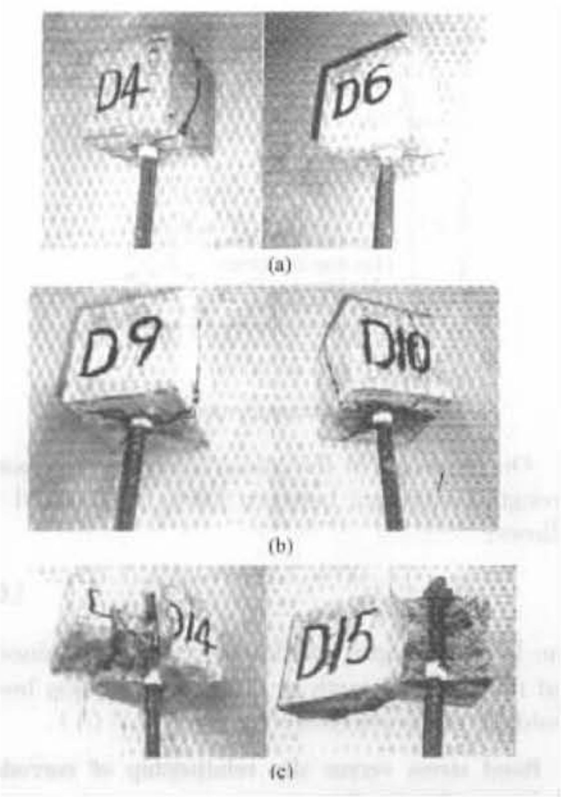

Fig.7 Failure mode of pullout tests of deformed bars
(a) D4, D6; (b) D9, D10; (c) D14, D15

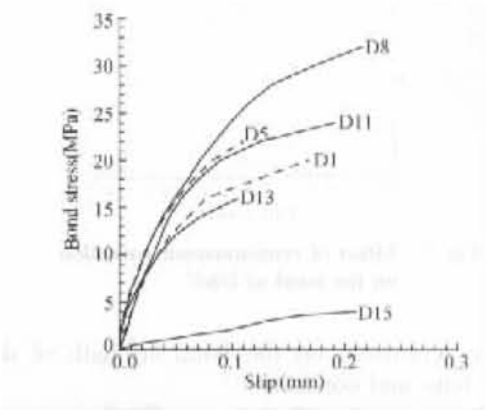

Fig.8 Bond stress versus slip relationship of D&C

Test data:

Data on the effect of corrosion on the bond strength between D&C are listed in Table 2, with the item values not the same as those of Table 1. Fig.9's test data based optimized regressive line indicates that the bond strength initially increases a little with increasing reinforcement corrosion, then declines consistently, and that cracking of concrete seems to have no effect on the bond strength.

Table 2 Test data for the series II specimens

specimens	Bond strength (MPa)	Ratio of bond stress	Percentage corrosion	CLD* (mm)
D1	8.92	1.07	0.12	0.0072
D2	9.48	1.12	0.16	0.0092
D3	7.36	0.87	0.24	0.0144
D4	8.45	1.00	0.32	0.0192
D5	8.39	0.88	0.43	0.0257
D6	10.61	1.25	0.62	0.0371
D7	11.34	1.34	0.81	0.0484
D8	9.72	1.18	1.66	0.0834
D9	7.50	1.78	4.64	0.1505
D10	5.68	1.02	5.97	0.2209
D11	4.45	1.06	8.70	0.2613
D12	3.75	0.35	8.60	0.3316
D13	2.54	0.67	9.95	0.4343
D14	1.40	0.20	9.99	0.5177

* Note: calculated by Eq.(3)

According to the test data, the bond strength coefficient of the pullout specimens of deformed steel bars can be expressed as follows:

$$\eta_2 = \begin{cases} 0.92 + 7.6\delta, & \delta \leqslant 0.05 \\ 1.46 - 2.3\delta, & \delta > 0.05 \end{cases} \quad (5)$$

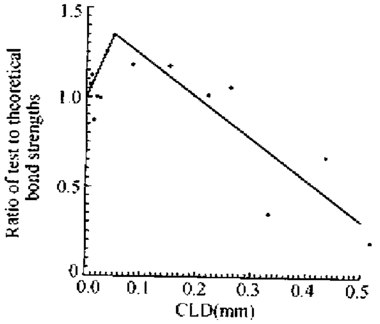

Fig.9 **Effect of reinforcement corrosion on the bond of D&C**

Effect of corrosion on the bond strength of deformed bars and concrete

The bond strength between D&C increases initially with increasing corrosion. This can be explained on the basis of the surface roughness of steel bars or similar in the situation of plain steel bars. However, the ultimate bond strength between D&C is mainly contributed by the pressure of the bar deformation against the concrete, so the change at the interaction face of concrete and steel ribs affects the bond resistance. The later decline of the bond strength can be explained on the basis of the degradation in the profile of the bar ribs. And the interaction face of the concrete and steel ribs does not change abruptly at the cracking time of concrete cover, so cracking has no effect on the bond strength.

Al-Sulaimani et al. (1990) and Yuan et al. (1999) considered that the bond strength between D&C related to the concrete cover and the bar diameter on the basis of their pullout test of different diameter deformed bars. The bond strength coefficient recommended here had no relation with the above two factors. The effect of these factors had been taken consideration in the bond strength calculation of uncorroded bars and concrete. In Fig.6 and Fig.9, the ratio of test to theoretical bond strength is taken as the ordinate to filter the influence of concrete cover and bar diameter, CLD is taken as the abscissa to filter the influence of the bar diameter. Fig. 10 is based on Al-Sulaimani's (1990) pullout different diameter test data with some transformation. The solid line in Fig. 10 was constructed by using the average value of test data, and the dashed lines by average test value ± 10%. The influence of concrete cover and the bar diameter need not be considered in calculating the bond strength coefficient η, according to Fig.10.

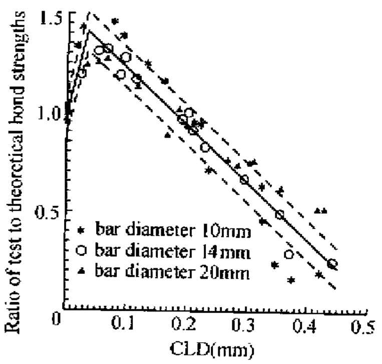

Fig.10 **The transformed test data**

On the basis of the above analysis, the bond strength coefficient between D&C is proposed as follows:

$$\eta_D = \begin{cases} 1.00 + 7.0\delta, & \delta \leqslant 0.05 \\ 1.46 - 2.3\delta, & \delta > 0.05 \end{cases} \qquad (6)$$

The bond strength coefficient η_D was obtained, and the bond strength at different corrosion level could be obtained easily by using Eq.(1).

4. Bond stress versus slip relationship of corroded bars and concrete

The widely used finite element method to predict the behavior of reinforced concrete structural members is based on knowledge of properties of the concrete matrix, the reinforcement steel and the bond stress versus slip relationship at the concrete-steel interface. Many researches have been carried out on the bond stress versus slip relationship of uncorroded steel bars and concrete.

The following bond stress-slip relationship of corroded steel bars and concrete is based on that of uncorroded steel bars and concrete:

$$\tau(s) = \eta \cdot \tau_0(s) \qquad (7)$$

where $\tau(s)$ is the bond stress-slip relationship of corroded bars and concrete, $\tau_0(s)$ is the bond stress-slip relationship of uncorroded bars and concrete, η is the bond strength coefficient, η_P for plain bars in Eq.(3) and η_D for deformed bars in Eq.(6).

5. Beam tests

Failure modes and load versus mid-span deflec-

tion

All beam specimens（BD & BDU）failed in flexure， with cracks appearing almost simultaneously at the bottom of the beams， which means the reinforcement corrosion did not affect the cracking load of RC beams.

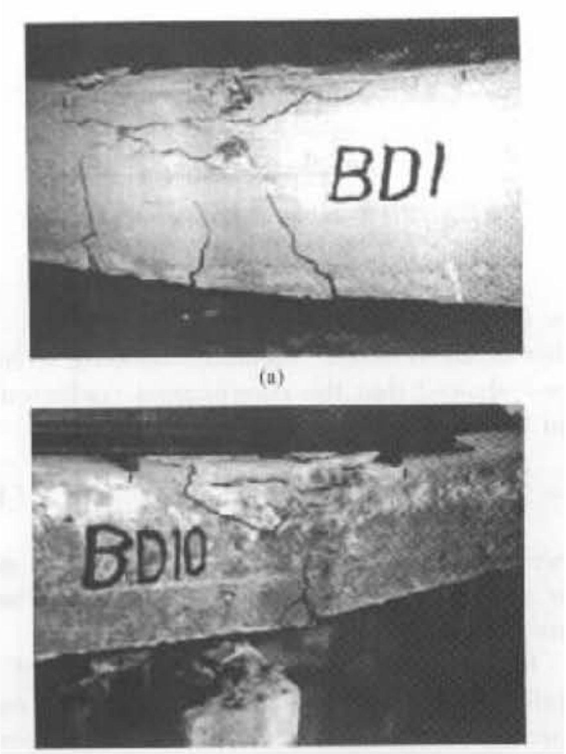

Fig. 11 **Different failure form of beam specimens**
（a）BDI；（b）BD10

With the increase of reinforcement corrosion， the failure mode would change from ductile mode to brittle mode， as in the case of underreinforced beams. Several main cracks indicative of obvious failure appeared at the bottom of slightly corroded beams when beyond cracking load was applied， while in the severely corroded RC beams， cracks appeared only at one place. BD1 and BD10 represent light and severe reinforcement corrosion respectively， as shown in Fig. 11.

Fig. 12 of the typical load versus mid-span deflection curves of BD beams shows clearly that the strength and rigidity of RC beams decrease with increase of reinforcement corrosion.

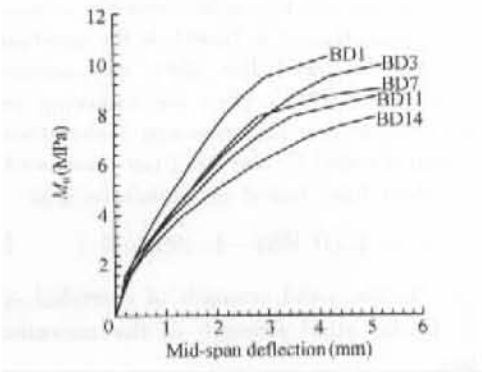

Fig. 12 **Load versus mid-span deflection of BD**

Decrease of bending strength

Bending strength of beam specimens and their corresponding corroded degree are listed in Table 3.

Table 3 **Test data for beam specimens**

Beams	Corrosion percent（%）	Bending strength（kN·m）	Anchor length（mm）	Failure mode
BD1	0.47	10.27	360	flexure
BD2	0.54	9.53	360	flexure
BD3	1.21	9.92	360	flexure
BD4	1.24	9.32	360	flexure
BD5	1.24	10.27	360	flexure
BD6	1.27	9.53	360	flexure
BD7	2.15	9.53	360	flexure
BD8	2.82	9.07	360	flexure
BD9	2.83	9.53	360	flexure
BD10	2.88	8.69	360	flexure
BD11	3.45	9.53	360	flexure
BD12	4.14	8.20	360	flexure
BD13	5.20	8.69	360	flexure
BD14	6.05	7.89	360	flexure
BDU1	0.47	9.91	100	flexure
BDU2	4.85	8.56	100	flexure
BDU3	5.58	8.32	100	flexure

Past studies indicated that the bending strength of RC beams decreased with increase of reinforcement corrosion. There were three main reasons: （1） Reduction in the steel bar cross-section，（2） Reduction of yield strength of steel bar，（3） Reduction of bond capacity between steel bar and concrete，which can be expressed by the coordinate coefficient β.

The first reason can be expressed by the following formula:

$$A'_s = A_s(1 - \rho\%) \tag{8}$$

where A'_s is steel bar cross section after its corrosion，A_s is the uncorroded steel bar cross section，$\rho\%$ is percentage reinforcement corrosion.

The second reason is based on the mechanics behavior of the steel bar after its corrosion. Zhang and Lu （1995） gave the following relationship of corrosion and nominal yield strength （yield load divided by the steel bar cross section area） of steel bar，based on numerous data:

$$f'_y = f_y(0.986 - 1.1992\rho\%) \tag{9}$$

where f'_y is the yield strength of corroded steel bar，f_y is the yield strength of the uncorroded steel bar.

As to the third reason，only its existence was pointed out or a constant smaller than 1 was given in former research reports as the reduction coefficient. Xi et al. （1997） and Tao et al. （1996） suggested the equations of coordination coefficient β，which is related to the corroded expansion crack width.

An equation of the coordination coefficient β related to the reinforcement corrosion percentage is given here on the basis of test data.

Fig. 13 shows the test data' s optimized regressive line，with the percentage corrosion of bar as abscissa and the ultimate bending strength as ordinate. Theoretical bending strength line here was calculated according to the size of RC beams and mechanics behavior of materials. Only the reductions of the cross section and yield strength of steel bars were considered in constructing Fig. 13 showing clearly that the slopes of the two descendent lines are different. The difference between the two slopes shows the effect of reinforcement corrosion on the coordination coefficient.

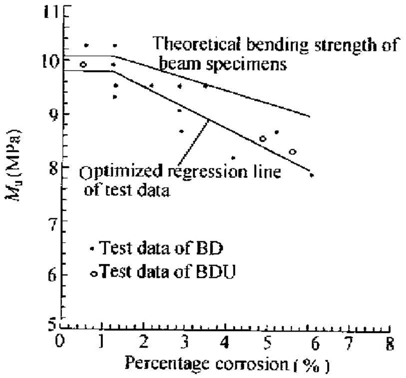

Fig. 13 **Relationship of the corrosion of bar and the bending strength**

Analysis of the two lines in Fig. 13 （one is the optimized regressive line of test data，the other is theoretically calculated bending strength line） showed that the coordination coefficient β can be expressed as follows:

$$\beta = \begin{cases} 1, & \rho > 1.2 \\ 1.0168 - 0.014 \times \rho, & 1.2 \leqslant \rho \leqslant 6 \end{cases} \tag{10}$$

where β is the coordination coefficient of steel bar and concrete，$\rho\%$ is the percentage reinforcement corrosion.

Eq. （10） show clearly that the effect of the reinforcement corrosion on the coordination coefficient can be neglected when the reinforcement corrosion is light，and that the effect of the reinforcement corrosion on the coordination coefficient can be expressed as a linear equation when the reinforcement corrosion is severe. When reinforcement corrosion is larger than 6%，which exceeded the range of application，the RC beams longitudinal cracks due to reinforcement corrosion appear. Xi et al. （1997）' s equations as given below can be used for calculating the corroded expansion crack width:

$$\beta = \begin{cases} 1, & \omega \leqslant 0.5\text{mm} \\ \left(\dfrac{1.1 - 0.09d}{10}\right)\left(1.12 - \dfrac{\omega}{9.4}\right), & \omega > 0.5\text{mm} \end{cases} \tag{11}$$

where β is the coordination coefficient of steel bar and concrete，ω is corroded expansion crack width.

Bending strength of corroded beams

Bending strength of the corroded beam can be expressed on the basis of the coordinate coefficient:

$$M_u = \beta M_{u1} \tag{12a}$$

where M_u is the bending strength of the corroded beam, M_{u1} is the bending strength of the corroded beam considering only the reduction of the cross section and yield and strength of steel bar, using the parameters A'_s and f'_y, β is the coordination coefficient of steel bar and concrete, in Eq.(10).

The following simple expression based on test data is recommended for use in practical engineering projects:

$$M_u = \beta' M_{u0} \tag{12b}$$

where M_{u0} is the bending strength of an uncorroded RC beam, β' is the comprehensive reduction coefficient considering the reinforcement corrosion:

$$\beta' = \begin{cases} 1, & \rho > 1.2 \\ 1.04514 - 0.03762 \times \rho, & 1.2 \leqslant \rho \leqslant 6 \end{cases} \tag{13}$$

To verify the recommended Eq.(13), it is necessary to compare it with other test data. Xi et al. (1997) and Niu et al. (1999) gave the relationship of reinforcement corrosions and bending strength of beams, which agreed with the optimized regression line of Fig.13. Al-Sulaimani et al. (1990) gave the test data in detail, Eq.(13) and their test data match very well.

Reinforced beams having insufficient anchor length

The bending strength of BDU should be considered at the same level as BD, as shown in Fig.13. Although BDU had insufficient anchor length, these beams did not fail due to shortage of anchor length, but failed in flexure. Therefore in the case of simple support beams, failure of the anchor can be avoided, if the steel bars are put along the bottom of the RC beam just like BDU.

CONCLUSIONS

1. The bond strength between plain bars and concrete initially increased with the increasing reinforcement corrosion. This can be explained on the basis of increased surface roughness of plain bars. Once the crack occurred, the bond strength began to decline because of energy release.

2. The bond strength between deformed bars and concrete at first increased a little with the increasing corrosion. This also can be explained on the basis of the surface roughness of steel bars. Then the bond strength declined consistently because of the reduction in the profile of the bar ribs. Cracking seemed to have no effect on the bond strength between D&C.

3. The bond strength coefficient obtained on the basis of test data, together with the bond strength of uncorroded steel bars and concrete, can be used to calculate the bond strength between corroded steel bars and concrete.

4. The bond stress-slip relationship of corroded steel bars and concrete presented in this paper is the base of the finite element method used to predict the behavior of reinforced concrete structural members.

5. With the increase of the bar corrosion, the failure mode of corroded RC beams changed from ductile mode to brittle mode similar to that of underreinforced beams, and the distribution of cracks of corroded RC beams became concentrated instead of scattered.

6. Three main factors that induce the decrease of bending strength of corroded RC beams are presented. Reduction of bond capacity between steel bar and concrete is discussed here and the coordination coefficient of concrete and steel bar is obtained on the basis of test data.

7. The formula for bending strength of corroded RC beams and its simplification are given in this paper.

References

Al-Sulaimani, G. J., Kaleemullah, M., Basunbul, I. A., et al., 1990. Influence of corrosion and cracking on bond behavior and strength of reinforced concrete members. *ACI, Structural Journal*. **87**:220 – 237.

Andrade, C., Alonse, C., Molina, F. J., 1993. Cover cracking as function of bar corrosion: Part Ⅰ-Experimental test. *Material and structures*, **26**:453 – 464.

Andrade, C., Alonse, C., Molina, F. J., 1993. Cover cracking as function of bar corrosion: Part Ⅱ-Numerical model. *Material and structures*, **26**:532 – 548.

Han, J. Y., Cai, L. S., 1991. Test study on reinforcement corrosion of reinforced concrete members. Test report of Chinese Structural Research Institute, Beijing(in Chinese).

Kemp, E. L., Brezny, F. S., Unterspan J. A., 1968. Effect of rust and scale on the bond characteristics of deformed reinforcing bars. *ACI Journal, proceedings*, **65**: 743 – 756.

Li, H. B., Yan, F., Zhao Y. X., et al., 2000. Model of corroded expansion force at cracking on reinforced concrete structures. *Journal of Zhejiang University*, **34**:415 – 422 (in Chinese, with English abstract).

Niu, D. T., Qu, S., Wang, L. K., et al., 1999. Analysis of the bearing capacity of corroded RC beams. *Building Structure*, **8**:23 – 25 (in Chinese, with English abstract).

Peattie, K. R., Pope, J. A. , 1956. Effect of age of concrete on bond resistance. *ACI Journal*, *proceedings*, **52**:661 – 672.

Quan, M. Y., 1990. The behavior of corroded reinforced concrete members. *Industrial Construction*, **20**: 15 – 19 (in Chinese, with English abstract).

Tao, F., Wang, L. K., Wang, Q. L., et al., 1996. Experiment study on the bearing capacity of exiting reinforced concrete members. *Industrial Construction*, **26**: 17 – 20 (in Chinese, with English abstract).

Wang, C. Z., Teng, Z. M., 1985. Theory of reinforcement concrete structural. Chinese construction industrial Publisher, Beijing (in Chinese).

Xi, W. L., Li, R., Lin, Z. S., et al., 1997. Experimental studies on the property before and after reinforcement corrosions in basic concrete members. *Industrial Construction*, **27**: 14 – 18 (in Chinese, with English abstract).

Xu, Y. L., 1990. Experimental study of anchorage properties for deformed bars in concrete. Ph.D. Thesis, Qinghua University, Beijing (in Chinese, with English abstract).

Yan, F., 1999. Studies on the durability of the RC structural members in atmosphere circumstance. Ph.D. Thesis, Zhejiang University, Hangzhou (in Chinese, with English abstract).

Yuan, Y. S., Yu, S., Jia, F. P., 1999. Deterioration of bond behavior of corroded reinforced concrete. *Industrial Construction*, **29**:47 – 50 (in Chinese, with English abstract).

Zhang, P. S., Lu, M., Li, X. Y., 1995. Mechanical property of rustiness reinforcement steel. *Industrial Construction*, **25**: 41 – 44 (in Chinese, with English abstract).

Zhao, Y. X., Jin, W. L., Yan, F., 2000. Corroded expansion force and its influence factors of reinforced concrete members. Proceedings of 6th national conference on theory and application of reinforced concrete structure, Shanghai. (in Chinese, with English abstract).