Study on Corrosion-induced Crack Initiation and Propagation of Sustaining Loaded RCbeams

X P Zhong, Y Li, C B Yuan, Z Yang and Y Chen
College of Civil Science and Engineering, Yangzhou University, Yangzhou, Jiangsu, China

Corresponding author. Email: zhongxiaoping@zju.edu.cn

Abstract. For 13 pieces of reinforced concrete beams with HRB500 steel bars under long-term sustained loads, at time of corrosion-induced initial crack of concrete, and corrosion-induced crack widths of 0.3mm and 1mm, corrosion of steel bars and time-varying behavior of corrosion-induced crack width were studied by the ECWD (Electro-osmosis - constant Current – Wet and Dry cycles) accelerated corrosion method. The results show that when cover thickness was between 30 and 50mm, corrosion rates of steel bars were between 0.8% and 1.7% at time of corrosion-induced crack, and decreased with increasing concrete cover thickness; when corrosion-induced crack width was 0.3mm, the corrosion rate decreased with increasing steel bar diameter, and increased with increasing cover thickness; its corrosion rate varied between 0.98% and 4.54%; when corrosion-induced crack width reached 1mm, corrosion rate of steel bars was between 4% and 4.5%; when corrosion rate of steel bars was within 5%, the maximum and average corrosion-induced crack and corrosion rate of steel bars had a good linear relationship. The calculation model predicting the maximum and average width of corrosion-induced crack is given in this paper.

1. Introduction

Many researchers have studied corrosion-induced crack process of concrete cover. Most of these focused on two aspects: 1) corrosion amount of steel bars at time of corrosion-induced crack on the surface of concrete cover, or time of corrosion-induced crack on the surface of concrete cover; 2) development law of crack width on the surface of concrete after cracking. In regards to corrosion amount of steel bars at time of corrosion-induced crack on the surface of concrete cover, Andrade et al. [1] conducted accelerated corrosion experiments on 4 group different specimen of steel bars position, steel bars diameter and cover thickness, found that reinforcement corrosion depth of the first visible surface crack (crack width was 0.05~0.10mm) was usually 10~50μm; Oh et al. [3] judged the crack by strain value, thought when the monitored strain value reached concrete crack strain, cover surface appeared initial crack, thus the relationship between corrosion rate of steel bars at time of cover surface crack and cover thickness was established. For study of surface crack width, Vidal et al. [4] studied 2 pieces reinforced concrete beams exposed under chlorine salt environment for 14 years and 17 years respectively, measuring calculated reinforcement corrosion at different positions by weightlessness method, and measured surface crack width of the corresponding location, set up the relationship between crack width and corrosion cross-section loss area of reinforcement; Zhang et al. [6] also built relationship between the average cross-section loss area of reinforcement and corrosion-induced crack width by experimental study. However, the effect of long-term sustained load on
corrosion-induced crack and crack width of cover has not been considered in above experimental studies. In fact, the actual structure is working under load and environment interaction, so, studying corrosion-induced crack behavior of reinforced concrete members under load has very important practical value for durability design and service life prediction of structure.

2. Experimental investigation

2.1. Experimental material
Ordinary Portland cement 42.5MPa was used as concrete raw material, coarse aggregate particle size is 5~20mm of rubble; natural river sand was used as fine aggregate, fineness modulus is 2.5; II grade fly ash was used, its dosage is 15%; JM-B type naphthalene series water reducing agent was used as high efficiency water reducing agent. Concrete mix proportion is shown in table 1.

| w/c ratio | Water (kg/m³) | Cement (kg/m³) | Fine aggregate (kg/m³) | Coarse aggregate (kg/m³) | Fly ash (kg/m³) | Water reducing agent (kg/m³) |
|-----------|------------|---------------|----------------------|------------------------|----------------|-----------------------------|
| 0.44      | 215        | 416           | 573                  | 1217                   | 73             | 8.8                         |

2.2. Specimen design
Taking cover thickness, steel bar diameter as the main parameter, 13 pieces reinforced concrete beams were designed and made. Test beam parameters are shown in table 2, reinforcement is as shown in Figure 1. In order to make chloride ion electricity permeability to surface of longitudinal reinforcement, a piece of 30mm × 1300mm × 0.2mm stainless steel sheet was put in the middle layer of each test beam.

![Figure 1. Details of the tested specimens](image)

2.3. Load level
Considering the actual structure durability degradation is under the coupled action of load and environment, so the accelerated corrosion experiment under long-term sustained load was done for B1-B13 beams. Each two beams were anchored each other, force was pressed by tightening nuts. Load level is subject to member tensile surface crack width in 0.2~0.25mm as a control condition.

2.4. Accelerated corrosion method
The accelerated corrosion can be divided into two phases:

1) In the electro-migration phase, the embedded stainless steel sheet in the concrete was connected with the positive of direct current dc power source by wire, external stainless steel net was connected with the cathode of power by wire, opening the dc power supply, maintaining a constant voltage of 30v, the chloride ion was migrated to the surface of the corroded reinforcement. The electro-migration time calculation of each beam is shown in Table 2.

2) The wet-dry cycle phase, constant current power phase. After the electro-migration experiment, a current density of 0.2mA/cm² was applied through the flexural tensile reinforcing steel in concrete.
beams (acting as the anode) and the stainless steel net (acting as the cathode) to accelerating corrosion. Taking surface area of corroded reinforcement as combined surface area of reinforcement within flexural tensile area 1m length, the required corrosion current sizes of each beam can be obtained by calculation, as shown in Table 2. A wet-dry cycle was used during accelerated corrosion, each dry-wet cycle is for 14 days, the ratio of dry and wet is 1:1. The preset corrosion degree of each beam was subject to corrosion-induced crack width on concrete surface as control condition, as shown in Table 2. The accelerated corrosion experiment ended after the preset corrosion-induced crack width was achieved.

Table 2. Test beam sizes, corrosion parameters and practically measured corrosion-induced cracking widths

| Beam designation | l x b x h (mm) | d (mm) | c (mm) | d (mm) | t (mm) | f (mm) | wc,de (mm) | wc,ex (mm) | ρ (%) | te (s) |
|------------------|----------------|--------|--------|--------|--------|--------|------------|------------|-------|--------|
| B1               | 1500 x 168 x 180 | 16     | 30     | 5.32   | 0.38   | 0.05-0.08 | 1.67       | 0.07      |
| B2               | 1500 x 168 x 180 | 16     | 30     | 5.32   | 0.38   | 0.3      | 4.50       | 1.0       |
| B3               | 1500 x 168 x 180 | 16     | 30     | 5.32   | 0.38   | 0.3      | 2.0        | 0.3       |
| B4               | 1500 x 180 x 180 | 20     | 30     | 5.32   | 0.47   | 0.3      | 2.38       | 0.35      |
| B5               | 1500 x 186 x 180 | 22     | 30     | 5.32   | 0.5    | 0.3      | 1.07       | 0.35      |
| B6               | 1500 x 195 x 180 | 25     | 30     | 5.32   | 0.57   | 0.3      | 0.98       | 0.31      |
| B7               | 1500 x 188 x 180 | 16     | 40     | 7.1    | 0.38   | 0.05-0.08 | 1.25       | 0.07      |
| B8               | 1500 x 188 x 180 | 16     | 40     | 7.1    | 0.38   | 1.0      | 4.05       | 1.05      |
| B9               | 1500 x 188 x 180 | 16     | 40     | 7.1    | 0.38   | 0.3      | 2.04       | 0.3       |
| B10              | 1500 x 208 x 180 | 16     | 50     | 8.87   | 0.38   | 1.0      | 4.11       | 1.1       |
| B11              | 1500 x 208 x 180 | 16     | 50     | 8.87   | 0.38   | 0.05-0.08 | 0.82       | 0.08      |
| B12              | 1500 x 208 x 180 | 16     | 50     | 8.87   | 0.38   | 0.3      | 2.65       | 0.34      |
| B13              | 1500 x 228 x 180 | 16     | 60     | 10.65  | 0.38   | 0.3      | 4.54       | 0.35      |

t is corrosion current.

\( w_{c,de} \) is predetermined corrosion-induced cracking width.

\( w_{c,ex} \) is practically measured corrosion-induced cracking width.

\( \rho \) is corrosion rate of reinforcement average section.

\( te \) is electro-migration time.

3. Experimental result and analysis

3.1. The feature points of corrosion-induced crack and reinforcement corrosion rate

This paper chose corrosion-induced cracks beginning to appear and crack width reaching 0.3mm and 1mm as feature point, and analyzes the influence factors and reinforcement corrosion rate.

In Table 2 B1、B7、B11 beams are used to analyze the effect of different cover thickness on corrosion rate of reinforcement at time of corrosion-induced cracking under long-term sustained loads; B3、B4、B5、B6 beams and B3、B9、B12、B13 beams are used respectively to analyze when the expected corrosion-induced crack width reaches 0.3mm, the effect of steel bar diameter and cover thickness on corrosion rate of reinforcement; While B2、B8、B10 beams are used to analyze when the expected corrosion-induced crack width reaches 1mm, the effect of cover thickness on corrosion rate of reinforcement. When constant current is adapted to accelerate corrosion, assume that reinforcement is uniform corrosion, the corrosion rate of reinforcement average cross section in Table 2 can be calculated and obtained from equation (1) - (2):

\[
\Delta d_s = \frac{t_s M_{Fe} i}{\gamma_s Z_{Fe} F}(1)
\]
rate of steel bar. Considering the influence of cover thickness on corrosion, the maximum width and average width of each beam have a good linear relationship with the corrosive rate of steel bar.

From the results of experiment and analysis for B3, B5, B7, B9, B11 beam it appears that when corrosive rate of steel bar was within 5%, the corrosion induced crack width reaches 1 mm, the required corrosion rate of steel bar decreases with increasing of steel bar diameter, and increases with increasing of cover thickness, the change of its corrosive rate is between 0.98% and 4.54%; When cover thickness is between 30 mm and 50 mm, and corrosion-induced crack width reaches 1 mm, the corrosive rate of steel bar is between 4% and 4.5% (B2, B8, B10 beam).

3.2. Time-varying analysis of corrosion-induced crack width

After each dry-wet circulation time on B2, B8, B10 beam respectively, corrosion-induced crack width was measured, corresponding corrosive rate of steel bar was calculated, the relationship of corrosion-induced crack changing with corrosive rate of steel bar was obtained as shown in Figure 2.

From Figure 2 when corrosive rate of steel bar was within 5%, the corrosion-induced crack maximum width and average width of each beam have a good linear relationship with the corrosive rate of steel bar. Considering the influence of cover thickness on corrosion-induced crack width on the
surface of members, the development of corrosion-induced cracks can be predicted according to the following equation:

\[ w_{c,\text{max}} = A \rho - B \leq 5\% \quad (3) \]

\[ w_{c,\text{average}} = C \rho - D \leq 5\% \quad (4) \]

Where, \( w_{c,\text{max}}, w_{c,\text{average}} \) are the maximum value and average value of corrosion-induced crack width respectively; \( \rho \) is the corrosive rate of reinforcement average cross section; \( A, B, C, D \) stand for coefficient, for the different cover thickness, the coefficient is given in this paper, as shown in Table 3.

| Cover thickness (mm) | \( A \) | \( B \) | \( C \) | \( D \) |
|----------------------|--------|--------|--------|--------|
| 30                   | 0.2047 | 0.0174 | 0.0699 | 0.0251 |
| 40                   | 0.2501 | 0.0069 | 0.1445 | 0.0179 |
| 50                   | 0.3146 | 0.1829 | 0.1537 | 0.0893 |

The relationship of corrosion-induced crack maximum width and average width changing with time can be obtained by equation (1)–(2) formula.

4. Conclusion

1) Under long-term sustained load, when cover thickness is between 30mm and 50mm, the corrosive rate of reinforcement at time of corrosion-induced crack is between 0.8% and 1.7%, and decreases with increasing of concrete cover thickness; When corrosion-induced crack width is between 0.3mm and 0.35mm, the required corrosive rate of steel bar decreases with increasing of steel bar diameter, and increases with increasing of cover thickness, the change of its corrosive rate is between 0.98% and 4.54%; When corrosion-induced crack width reaches 1mm, the corrosive rate of steel bar is between 4% and 4.5%. When the corrosive rate of steel bar is predicted through corrosion-induced crack width, such influence factors as the diameter of steel bar and cover thickness of concrete should be considered comprehensively.

2) When corrosive rate of steel bar is within 5%, the maximum width and average width of the corrosion-induced crack have a good linear relationship with the corrosive rate of steel bar.

Acknowledgements

This work was supported by the National Natural Science Fundation of China through Projects (Project code: 51678513 and 51278444).

References

[1] AndradeC, AlonsoC and MolinaFJ 1993 Cover cracking as a function of bar corrosion: part 1—experimental test. Materials and Structures 26 453-464.

[2] OhBH, KimKH and JangBS 2009 Critical corrosion amount to cause cracking of reinforced concrete structures. ACI Materials Journal 106 333-339.

[3] VidalT, CastelA and Francois R 2004 Analyzing crack width to predict corrosion in reinforced concrete. Cement and Concrete Research 34 165-174.

[4] ZhangR, CastelA and Francois R 2010 Concrete cover cracking with reinforcement corrosion of RC beam during chloride-induced corrosion process. Cement and Concrete Research 40 415-425.