Study on the Corrosion Length of Steel Bars in Concrete with Transverse Cracks Under the Dry-wet Circulation Environment

Rongzhen Dong, Jiaopei Liu, Jun Wei, Yunxuan Qi and You Liu

ABSTRACT

In the paper, the effect of transverse cracks on the corrosion length of steel bars in concrete under the dry-wet circulation environment has been studied. Specimens of reinforced concrete with different width of transverse cracks were used in the dry-wet circulation environment test. After a certain number of cycles, carry out the study on the state of reinforcement corrosion in concrete. Main results are as follows: the steel corrosion length in the specimens soaked in chloride solution was much longer than the steel corrosion length of those specimens soaked in water. Besides, the corrosion length of steel bars increased along with the increase of crack width. When the crack width was more than 0.3mm, the reinforced steel showed the sustained corrosion mechanism; but when the crack width was less than 0.3mm, the reinforced steel showed the crack sealing mechanism. The phenomenon illustrated that the corrosion rate was fast at the early stage, and slowed down or even stopped later. The relationship between steel corrosion length and the period of dry-wet circulation applied to the linear relationship. In the paper, the prediction model of steel corrosion length has been built after the relationship between steel bars corrosion length and the dry-wet cycles has been analyzed.\(^1\)

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INTRODUCTION

According to statistics, the corrosion of steel in concrete has become one of the most important factors affecting the durability of concrete structure[1]. If the corrosion medium eat off reinforced concrete structure through cracks, the corrosion rate of steel and the deterioration of the component[2] will be accelerated. Scholars from China and other countries have done a lot of experiments and researches on the corrosion of steel bars in concrete with transverse cracks, including accelerated tests[3-5] and long-term field exposure tests[6-8], which led to fruitful results. Scholar Beeby[9] suggested the existence of cracks do not have a huge impact on the steel corrosion, and it is the thickness of protective layer and the density of concrete who play the key role to the steel corrosion; however, some scholars believed that the crack width has a great influence on the corrosion of steel[10-11]; with further research carried out, LiK[12] put forward the sustained corrosion mechanism, crack sealing mechanism and the conclusion that reinforced concrete constructs with cracks shows different mechanism under different crack conditions or indifferent environments. At present, conclusions about the conditions for the occurrence of the two mechanisms are still not a unified. Francois, Vidal and other scholars[13] thought that the cracks under the width of 0.5mm almost do not affect the corrosion of steel in concrete. Scholar Pettersson[14] brought out the theory that the corrosion resistance of concrete with transverse cracks can be evaluated by the ratio of transverse crack width $\omega$ and thickness of protective layer $C$. Chinese scholar Lu Chunhua[15] studied on the cracked reinforced concrete beam member in bending conditions. He concluded that when the ratio of the average crack width and protection layer thickness is less than 0.002 (the maximum crack width is less than 0.0033C), the cracks do not have a significant impact on steel corrosion, and the corrosion rate of steel is the same as the corrosion rate of intact beam under the dry-wet circulation environment. Although there are a large number of research and achievements in this field, scholars cannot reach a unified conclusion accurately about the transverse cracks’ influence on corrosion of steel bars because the methods of detection, ways of experiment, various influencing factors in the experiments and accidental factors can lead to different results.

The paper focuses on the research of steel corrosion length in the concrete specimens, which were broken after the dry-wet cycle cycles. Compared to electrochemical detection and chloride ion analysis, the method we chose could detect the corrosion of steel in concrete more accurately to avoid the accidental and discrete results in experiments. In this experiment, the wetting-drying cycles tests were carried out on concrete specimens with transverse cracks in chloride solution and clear water respectively. Researchers focused on the relationship among crack widths, cycle period and the steel corrosion length, and then gave the prediction model of steel corrosion length in the crack area.
DESIGN OF EXPERIMENTS

Mix Proportion and Preparation of Specimens

In the experiment, the size of specimen was 100mm*100mm*400mm; the design grade of concrete was C40 and the proportion of cement, sand, aggregate, and water was 1:1.63:2.9:0.5. The cement adopted was “Hunan South” PO.42.5ordinary Portland cement, whose apparent density was 3.14g/m³; The sand adopted was “Xiangjiang” river sand (medium sand, fineness modulus is 2.4 and the largest diameter is 3mm); the aggregate adopted was “Hunan province Changsha suburban” middle gravel (the largest diameter is 15mm and the continuous-gradation ranges from 5~10mm); the water used is tap water; the reinforcements were HRB335 steel bars. The test specimens were made by the standard prism mold. And under the mould, there was a perforated plate by which we could fix the steel bars, besides, the contact surfaces of reinforcing steel bar and positioning steel plate were separated by epoxy resin. Before the production of specimens, steel corrosion was removed by the grinding machine and 0.1mm thick steel sheets were inserted into 2mm deep in the crack location which was designed. The position of steel sheet was expected to be the position of the crack in the specimen, where the certain crack width we need can be obtained by loading afterwards.

Methods to Induce Cracks in Concrete

When producing a crack, the formed test specimens were arranged in the clamp which is shown in Figure 1, so the reinforcing steel bar at the bottom of the specimen could be positioned at the center of the bottom of the specimen. After the bearing plate was fastened, the fastening nuts were tightened in turn (Screwing nut in inward rotation can reduce the cracks width, otherwise cracks can be expanded). In the process of producing crack, the crack width was measured by the crack width gauge, and the specimens were loaded until the design widths of cracks reached (The crack widths of this experiment were 0.1mm, 0.2mm, 0.3mm, 0.4mm, 0.5mm). After the specimens were unloaded, the steel sheet could be pulled out. In the latter part of the experiment, it was necessary to check the width of the cracks by crack width gauge.

Chloride Dry-wet Cycles

When the reinforced concrete specimen was formed, it should be cured standardly for 28 days in the curing room. The dry-wet cycle system is as follows: as is shown in Figure 2, it should be dried in an oven for 24 hours at 750C, and then soaked in 5%NaCl solution (C group) or water (Q group) for 48 hours.
Data of Steel Corrosion Length

After the fifth, twelfth, or twentieth cycle of chloride dry-wet cycles, the specimens of chloride group and clear water group were taken out and broke. Then the steel bars could be taken out and the steel corrosion lengths were measured. As is shown in Figure 3, specimens were broken at the area 50mm away from the left of the crack and 50mm away from the right of the crack, until the depth of the sample was 50mm. And then the length of corrosion could be measured by vernier caliper.
RESULTS AND DISCUSSION

The influence of transverse cracks on the reinforcement corrosion was reflected by the length of the steel corrosion in the crack area, the longer the steel corrosion length was, the larger influence area the crack was. By analyzing every factors that may influence the result in the experiment, the similarities and differences of the steel corrosion under different widths of cracks could be studied, as well as the development of the corrosion length under the dry-wet cycles.

Influence of Different Crack Width on Steel Corrosion Length

According to the data from the experiment, the length of steel corrosion in chloride ion group was significantly more severe than that in the water group. The average length of steel corrosion in the chloride group was about 1.6 times of that in the water group. Except the specimen of fifth cycle in the water group which was not corroded, the maximum ratio of corrosion length between the two groups could be up to 2.5 (When crack width was 0.2mm in fifth cycle). The effect of chloride on the corrosion of steel in concrete was very significant, but the overall development trend of corrosion length was similar in the two groups. In the same cycle, the corrosion length of steel bars was related to the crack width of concrete specimens. Figure 4 shows that the length of the reinforcement corrosion grew steady with the crack width increasing in the fifth and twelfth cycles; however, in the twentieth cycle, when crack width reached 0.3mm, the corrosion rate of steel increased rapidly, the corrosion length increased rapidly from 43.24mm (when crack width was 0.3mm) to 118.49mm (when crack width was 0.5mm) in chloride group; besides, the corrosion length also increased from 33.36mm (when the crack width was 0.3mm) to 60.52mm (when the crack width was 0.5mm) in the water group. It could be concluded that under conditions of this experiment, the critical width of transverse cracks that affect the corrosion of reinforcing steel bar is 0.3mm. When the crack width is less than 0.3mm, the influence of the crack on the steel corrosion is maintained in a certain range, the performance is just like crack sealing mechanism which is mentioned before; when the width of the cracks is more than 0.3mm, the promoting effect on steel corrosion will be greatly enhanced, and the sustained corrosion mechanism will also appear. From the beginning of 90s, many countries take the maximum crack width up to 0.4mm for the concrete running in good order, while in the marine environment, the upper limit of crack width is 0.3mm in some foreign norms [16-19]. As is shown in TABLE I, compared with the foreign norms, the domestic norms [20-21] is relatively strict, the allowed crack width is less than 0.2mm. According to the corrosion condition of those specimens whose crack width is more than 0.3mm in experiment, it is concluded that the transverse crack width should be less than 0.3mm in the actual project, and that the maximum crack width should be limited to 0.2mm in the harsh environment, considering that the corrosion environment may be more severe in practical cases.
and that when the reinforcement is under the tensile stress, stress corrosion will be more serious than normal.

The scholar Suzuki Kazuo[22] and others studied the bent beams, and found that the damage slip length between reinforced surface and concrete is proportional to the width of the transverse crack in the transverse crack area; the effect of steel bar corrosion and outside force causes the separation of steel bar surface and concrete, then the steel bar in the damage area between reinforced surface and concrete is directly exposed in the atmosphere or the erosion solution through the cracks. Chloride ion, water, water vapor of atmospheric and oxygen can reach the surface of the steel bar, and corrode it. Therefore, the damage separation length is related to the steel corrosion length. In the same way, it is assumed that the length of reinforcement corrosion is proportional to the width of the transverse crack.

The data of the steel corrosion lengths and the crack widths is linear fitted in Figure 5, it can be found that the length of corrosion in chloride group is not only far longer than those in the water group, but the corrosion length growth rate is also faster than those in the water group with the increase of crack width. Besides, the difference of growth rates in the two groups increases gradually with the development of dry-wet cycles.

The data of the linear slope $K$ and the dry-wet cycles is linear fitted. And then the relationship between linear slope $K$ and dry-wet cycles can be found.

$$K = \begin{cases} 
9.22t, & R^2 = 0.9837, \text{Chloride group} \\
6.19t, & R^2 = 0.9304, \text{Clear water group} 
\end{cases}$$

(1)

<table>
<thead>
<tr>
<th>Standard</th>
<th>ACI224</th>
<th>EN1992-1</th>
<th>BS8110</th>
<th>CEB-FIP</th>
<th>GB/T50746</th>
<th>JTGD62</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega_{\text{max}}$</td>
<td>0.4</td>
<td>0.3</td>
<td>0.3</td>
<td>0.1-0.3</td>
<td>0.2</td>
<td>0.15</td>
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</table>

Figure 4. Steel corrosion lengths with different crack widths in the fifth, twelfth and twentieth cycles.

Figure 5. Steel corrosion lengths with different crack widths in the fifth, twelfth and twentieth cycles.
The Variation of The Steel Corrosion Length Under The Same Crack Width of Concrete With The Development of Dry-wet Cycle and The Prediction Model of It

According to the steel corrosion length data in TABLE II, the relationship between the length of reinforcement corrosion and the times of wet-dry cycles is applied to the linear relationship. In Figure 6, the linear trend line is made to obtain the prediction model of steel corrosion length approximately. According to Figure 6, the slope of the trend line has a faster growth when the width of the crack is more than 0.3mm (It is more obvious in the water group). Thus, the critical crack width (0.3mm) which is concluded previously can be further verified.

Figure 5. The trend line about the relationship between corrosion length and crack width.

Figure 6. The trend line about the relationship between the length of reinforcement corrosion and dry-wet cycles.
The data of the the steel corrosion lengths and the dry-wet cycles is linear fitted, as shown in Figure 6. The fitting function are shown in TABLE III.

According to the relationship between the slope k and the transverse crack width \( \omega \) of each function in TABLE III, the prediction model of steel corrosion length can be obtained by calculating and analyzing:

\[
L_{corr} = \begin{cases} 
0.59te^{3.38\omega}, & \text{Clear water group} \\
1.25te^{2.71\omega}, & \text{Chloride group} 
\end{cases}
\]  

(2)

In the formula:

- \( L_{corr} \)—The length of reinforcement corrosion in the crack area;
- \( t \)—The times dry-wet cycles, from 0 to 20T;
- \( \omega \)—Transverse crack width of concrete surface, from 0.1mm to 0.5mm.

Considering the situation that the prediction model of corrosion length is obtained under the condition of limited experimental period and small crack width, the range of the T and \( \omega \) are limited.

### TABLE II. THE DATA OF STEEL CORROSION LENGTHS.

<table>
<thead>
<tr>
<th>crack width</th>
<th>Steel corrosion length/(mm)</th>
<th>wetting-drying cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Clear water group</td>
<td>Chloride group</td>
</tr>
<tr>
<td>0.1</td>
<td>0</td>
<td>8.32</td>
</tr>
<tr>
<td>0.2</td>
<td>4.42</td>
<td>11.21</td>
</tr>
<tr>
<td>0.3</td>
<td>7.64</td>
<td>14.43</td>
</tr>
<tr>
<td>0.4</td>
<td>12.43</td>
<td>15.26</td>
</tr>
<tr>
<td>0.5</td>
<td>15.29</td>
<td>17.95</td>
</tr>
<tr>
<td>0.1</td>
<td>11.48</td>
<td>15.46</td>
</tr>
<tr>
<td>0.2</td>
<td>17.45</td>
<td>33.74</td>
</tr>
<tr>
<td>0.3</td>
<td>32.18</td>
<td>35.37</td>
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<td>0.4</td>
<td>31.64</td>
<td>38.67</td>
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<tr>
<td>0.5</td>
<td>40.72</td>
<td>41.62</td>
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<tr>
<td>0.1</td>
<td>13.92</td>
<td>32.24</td>
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<tr>
<td>0.2</td>
<td>25.26</td>
<td>39.57</td>
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<tr>
<td>0.3</td>
<td>33.36</td>
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</tr>
<tr>
<td>0.4</td>
<td>37.83</td>
<td>55.34</td>
</tr>
<tr>
<td>0.5</td>
<td>60.52</td>
<td>118.49</td>
</tr>
</tbody>
</table>

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TABLE III. THE FITTING FUNCTION BETWEEN THE LENGTH OF REINFORCEMENT CORROSION AND THE TIMES OF DRY- WET CYCLES.

<table>
<thead>
<tr>
<th>crack width ( \omega/(\text{mm}) )</th>
<th>Fitting function</th>
<th>( R^2 )</th>
<th>group</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>( L_{\text{corr}} = 0.7314t )</td>
<td>0.91325</td>
<td>Clear water group</td>
</tr>
<tr>
<td>0.2</td>
<td>( L_{\text{corr}} = 1.2947t )</td>
<td>0.98852</td>
<td></td>
</tr>
<tr>
<td>0.3</td>
<td>( L_{\text{corr}} = 1.9184t )</td>
<td>0.93186</td>
<td></td>
</tr>
<tr>
<td>0.4</td>
<td>( L_{\text{corr}} = 2.1062t )</td>
<td>0.96775</td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>( L_{\text{corr}} = 3.1204t )</td>
<td>0.99655</td>
<td></td>
</tr>
<tr>
<td>0.1</td>
<td>( L_{\text{corr}} = 1.5324t )</td>
<td>0.98858</td>
<td>Chloride group</td>
</tr>
<tr>
<td>0.2</td>
<td>( L_{\text{corr}} = 2.2009t )</td>
<td>0.96535</td>
<td></td>
</tr>
<tr>
<td>0.3</td>
<td>( L_{\text{corr}} = 2.3926t )</td>
<td>0.97128</td>
<td></td>
</tr>
<tr>
<td>0.4</td>
<td>( L_{\text{corr}} = 2.8948t )</td>
<td>0.99371</td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>( L_{\text{corr}} = 5.2003t )</td>
<td>0.94146</td>
<td></td>
</tr>
</tbody>
</table>

CONCLUSIONS

1. In the early stage of dry-wet cycle, with the increase of the crack width, the length of steel corrosion grew slowly; and then steel corrosion of different crack width specimens showed different corrosion mechanism, when the crack width was more than 0.3mm, the growth of the steel corrosion length would accelerate, which showed the sustained corrosion mechanism; and when the width of crack was less than 0.3mm, the growth of steel corrosion length tended to slow down, which showed the crack sealing mechanism.

2. The corrosion length of the steel bar in the chloride group was much larger than that in the water group, and the growth rate of the reinforcement corrosion length in the chloride group was much greater than that in the water group with the increase of the crack width and the times of dry-wet cycles.

3. In the experiment, the relationship between the length of reinforcement corrosion and the dry-wet cycle is applied to a linear relationship, by which the prediction model of the length of corrosion could be established.

REFERENCES