EXPERIMENT ON CREEP OF BOND BETWEEN CORRODED STEEL BAR AND CONCRETE

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ABSTRACT: Effect of reinforcement corrosion on bond creep was studied experimentally by pullout test. Concrete prism specimens (150x150x400 mm) made of concrete mix of 60% water-cement ratio were provided with two deformed reinforced steel bars of 16 mm in diameter. The two steel bars were aligned concentrically along the axis of the specimen. In each specimen, one steel bar with shorter embedded length of 64 mm was corroded electrolytically. Based on the effect of different corrosion degrees on bond characteristics under short-term pullout test, corrosion degree of 5.5% of mass loss was chosen, where it was the lowest percentage of mass loss at which bond strength dropped dramatically to about 41% of that of the non-corroded one. Applied sustained bond stresses ranged from 52% to 95% of the residual bond strength after corrosion. The results of this study show that bond creep failure takes place under stress level of 34% for non-corroded specimens, if it corroded to 5.5% of mass loss, where bond stress level increased to 81%. Bond creep failure occurs when creep slip reaches a certain creep slip value, which depends on the initial corrosion crack width resulted from corrosion before applying the sustained load. Moreover, Load history has only effect on the time elapsed up to failure, and has no such effect on the value of creep slip gained at failure.

KEYWORDS: Corrosion, bond, slip, creep failure, bond stress level.

1. INTRODUCTION

Bond strength decreases due to corrosion resulting in cracks along the reinforcing steel bar (Abdullah 1996), thus, bond stress level, which is the ratio between the applied bond stress and the residual bond strength, increases significantly and may exceed the limit that causes failure in creep under service bond stresses that are less than the deteriorated residual bond strength. This limit was reported as 67% for bond of sound steel bar in concrete (Rostasy 1982). Therefore, corrosion of reinforcement would lead to bond creep failure within unexpected time. This become very serious in the circumstances in which bond is a substantial requirement for structure safety, such as, in anchorage and splices zone as well as reinforcing with large diameter of steel bar. Consequently, designers should consider a suitable safety factor not only to cover the applied stress on short-term but also to prevent creep failure due to corrosion. Therefore data of time dependence of bond is needed to prevent concrete structures from failure under service load conditions. However, few studies have been carried out on corrosion impact on the time-dependent bond behavior. Based on this situation, the present study investigates the effect of corrosion on bond behaviour under sustained load using pullout test specimens, considering various bond stress levels associated to the lowest degree of corrosion at which bond strength dropped dramatically due to the presence of corrosion induced cracks.

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2. OUTLINE OF EXPERIMENT

2.1. Materials and concrete mix

Ordinary Portland cement was used to make concrete of 60% water-cement ratio (W/C), which has been used widely. The coarse aggregate was a crushed stone with maximum nominal size of 20mm, specific gravity of 2.74 and fineness modulus of 6.35. The fine aggregate was crushed sand with specific gravity of 2.66 and fineness modulus of 2.88. The unit content of each concrete material was 180, 300, 790, 1015 and 0.075 kg/m³ of water, cement, sand, coarse aggregate and AE agent, respectively. The concrete compression, splitting tension strength and modulus of elasticity at age of 28 days were 36.0, 3.29 N/mm² and 30.0 kN/mm², respectively.

The used reinforcement was of deformed steel bar of 16 mm in nominal diameter and 295 N/mm² in nominal yield strength. The chemical composition percentages of the used steel were 0.19%, 0.12%, 0.52%, 0.028% and 0.039% in mass of Carbon, Silicon, Manganese, Phosphorus and Sulfur, respectively.

2.2. Test specimens

As shown in Figure 1, the specimens were reinforced concrete prism of dimensions 150x150x400 mm provided with two separate steel bars along their longitudinal axes. One steel bar with short embedded length equal to four times the nominal diameter (D) was to be corroded and the other one was with longer embedded of 9D in length was not corroded. The dimensions of the concrete cross section were chosen to prevent the axial tension failure of concrete. Unbonded portion near the loaded end was installed equal to nominal diameter of the steel bar (16 mm) to prevent the premature cracking at low levels of loading.

The surface layer of the steel bar was removed by 10% HCl solution. In addition to the prism specimens, cylinders with a dimension 100x200 mm and that with 150x200 mm were cast to obtain compressive and tensile behavior of concrete. Twenty-four hours after casting, the specimens were demolded and immediately placed in curing water for one week. Hereafter, specimens were kept in the curing room (20 °C and 100% R.H.) up to age of 28 days old before starting of the electrolytic corrosion.

2.3. Accelerated corrosion

Electrolytic corrosion technique was used to accelerate corrosion of the shorter embedded reinforcement. Figure 2 shows a schematic accelerated corrosion setup.

The prism specimens for bond test were soaked in solution containing 3% Sodium Chloride (NaCl) by the weight of water. A constant electric potential of 72 volt was applied to each specimen for different controlled period to get various corrosion degrees in range of 0 to 10% of mass loss. Consequently, the imposed electric current intensity changed from 9.4 to 5.0 mA/cm² due to the variation of the electric resistance of the concrete cover and corrosion products during growing of corrosion. The direction of the current was arranged so that the reinforcing bar served as the anode where mass reduction takes
place, while a metallic ring adjusted faced to the embedded reinforcement bar to be corroded acted as cathode. After the power supply was turned on, the anodic current (corrosion current) flowing through each specimen was recorded every one minutes using data logger. The amount of corrosion was calculated according to Faraday’s law given by Equation (1).

\[
\Delta \omega = \frac{A \cdot I \cdot t}{Z \cdot F} = \frac{A}{Z \cdot F} \int I \, dt
\]

(1)

Where: \(\Delta \omega\) is metal weight loss due to corrosion (g), \(A\) is atomic weight of iron (55.847g), \(I\) is corrosion current (amp), \(t\) is time elapsed (sec), \(Z\) is valence of the reacting electrode of iron (2) and \(F\) is Faraday’s constant (96487 amp sec).

Preliminary test was carried out to confirm the reliability of using Faraday’s law, in the used galvanic corrosion arrangements and conditions, to get accurately predefined percentage degree of corrosion. The actual mass losses that measured by gravimetric method were always larger than the computed values with differences less than 5% of the measured ones; thus, the correlation between actual and predicted mass loss was almost perfect. Consequently, in this study, the reported degrees of corrosion were only based on that predicted by Faraday’s law.

2.4. Loading test

Figure 3 shows the arrangement of the specimen in loading apparatus for tension creep frame with capacity of 80kN. In the shown creep frame, the load was kept constant throughout the creep experiment period. Short-term tests were performed in the same creep frame by controlling the tension displacement along the specimen length. Load was measured by means of tension load cells. The bond slip response between the concrete and the reinforcing bars was measured at two points at distance of 5.0 mm from the steel bar surface using two electrical displacement transducers (EDT) (of 1/1000mm accuracy) mounted to a reference steel plate fixed on the external extension of the steel having the tested bond zone. Slip was computed by subtracting the elongation of the bar from the displacement measured between the concrete surface and the reference plate.

Bond stress of the short embedded length was computed using the equation \(\tau = \frac{P}{(u \cdot l)}\) where: \(\tau\) is the bond stress, \(P\) is the applied pullout load, \(u\) is the nominal perimeter of the steel bar and \(l\) is the length of the bond. Based on the effect of corrosion on bond strength resulted from the instantaneous pullout test, the degree of corrosion and bond creep stress levels were determined.
3. RESULTS AND DISCUSSIONS

3.1. Effect of corrosion on bond strength

Figure 4 shows the effect of corrosion on the bond strength resulted from instantaneous pull out test. As shown in the figure, in the absence of corrosion cracks before loading, for corrosion degrees less than 5.5%, bond strength increased slightly with increasing corrosion degree. This can be attributed to an increase in the reactionary confinement and the mechanical interlock of concrete around bar against axial direction. Failure occurred due to sudden splitting of the concrete cover followed by tension concrete failure.

For the specimen having corrosion cracks before loading, bond strength decreased significantly. For corrosion degrees from 5.5% to 10.5%, the bond strength reduced from 41% to 11% of the bond strength (10.4 N/mm²) obtained from the intact specimen. This resulted from the absence of the hoop strength due to the presence of corrosion splitting cracks before loading.

3.2. Cracking and failure mechanism

As shown in Figure 5, before loading test, the internal pressures due to corrosion form longitudinal cracks that extend in the transverse direction and divide the concrete prism into segments. The transverse cracks extend in a direction perpendicular to the plane which having maximum principle tensile stress. Meanwhile, corrosion cracks widths grow.

By increasing the applied pull out load during loading test, each concrete segment moves away from the steel bar, thus, splitting cracks widths grow till a critical value of \(w_{cr}\) at which the interlocking action between the concrete keys and the lugs of the steel bar is almost vanished causing pull out failure. However, the concrete segment may be crushed before attaining \(w_{cr}\), where tensile stresses in the critical zones (Figure 5(b)) exceeded the concrete tension strength; therefore, pull out failure takes place.

By observing the experimented specimens, after pull out failure, no crushing in the concrete keys was found; therefore the shear failure of the concrete keys has no contribution in pull out failure.

Under sustained load, the rates of creep tensile strains in the critical zones at the tips of the transverse cracks control the growing of the splitting cracks till reaching the same critical width \(w_{cr}\) of that under instantaneous load. However, before reaching \(w_{cr}\), the tensile strains may exceed the tensile strain capacity resulting in extending of the transverse cracks, under constant load, and reducing the critical zone area, thus increasing the tension stresses that eventually may lead to rupture of the concrete segment and pull out failure.
3.2 Adopting of corrosion degree and bond stress levels

In Figure 4, corrosion degree of 5.5% mass loss was adopted for the sustained load test, where it was nearly the lowest corrosion degree at which bond strength decreased significantly to the range of 30 to 41% of that (10.4 N/mm²) for the intact specimen. The figure also illustrates the average corrosion crack widths resulted before loading test for the corroded specimens of the adopted corrosion degree only. Bond strengths for the sustained load specimens were predicted from the relationship between average corrosion crack width and bond strength as shown in Figure 6.

Table 1 represents the specimens’ specifications for the sustained load test. For each specimen, the bond stress level shown in the table is the ratio between the applied bond stress and the bond strength associated to the average corrosion crack width (Figure 6). In order to include the effect of the load history in this study, the total magnitudes of the sustained loads were divided into two stages. In stage one, the sustained loads were applied for a period of 3.5 months till the creep slips of SA5287 and SC5681 became nearly constant. In stage two, for all the specimens except SA9494, the loads were increased instantaneously then kept constant throughout the rest of the experiment period.

3.4. Sustained pull out test

Figure 7 represents the slip creep for the sustained load specimens. The figure shows the increase in slip due to creep only and no slip increase due to instantaneous loading represented in this figure.

3.4.1. Stage one of sustained loading

During the first 105 days, creep slip increased with the increase of load stress level, where specimens SA5287, SC5681, SA6895 and SA9494 under bond stress levels of 52, 56, 68 and 94%, respectively, exhibited creep slip of 0.07, 0.10, 0.25 and 0.36 at the age of 105 days after loading, respectively. Specimens SA6895 and SA9494 with bond stress levels equal to or more than 68% showed remarkable increase in slip compared with that of specimens SC5681, SA5287 of bond stress levels less than or equal 56%. This may imply that bond stress level of 56%, corresponding to 23% in absence of corrosion, could be considered as safety limit to prevent large bond creep in case of facing corrosion degree of 5.5% based on slip at 105 days after loading.

3.4.2. Stage two of sustained loading

At 105 days after loading, sustained bond stresses for all specimens were increased except SA9494 as illustrated in Table 1. The applied bond stresses became in range of 3.48 to 3.81 N/mm². If this range

Table 1 Specifications of creep specimens

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Corrosion degree</th>
<th>Average corrosion crack width (mm)</th>
<th>Bond strength (N/mm²)</th>
<th>Loading periods</th>
</tr>
</thead>
<tbody>
<tr>
<td>RN2635</td>
<td>0.0%</td>
<td>0.000</td>
<td>10.40</td>
<td>Stage one From 0 to 105 days</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Bond stress (N/mm²)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.69</td>
<td>26%</td>
</tr>
<tr>
<td>SA5287</td>
<td>5.5%</td>
<td>0.297</td>
<td>4.00</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.07</td>
<td>52%</td>
</tr>
<tr>
<td>SC5681</td>
<td>5.5%</td>
<td>0.183</td>
<td>3.41</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.40</td>
<td>56%</td>
</tr>
<tr>
<td>SA6895</td>
<td>5.5%</td>
<td>0.293</td>
<td>3.94</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2.69</td>
<td>68%</td>
</tr>
<tr>
<td>SA9494</td>
<td>5.5%</td>
<td>0.289</td>
<td>4.03</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3.81</td>
<td>94%</td>
</tr>
</tbody>
</table>

(*) Estimated bond strength using Figure 6.
of stresses was applied to intact specimens, the load stress level would be in range of 34% to 38%, however due the presence of corrosion cracks bond stress levels increases to become in range of 81 to 95% that eventually led to failure after a various time intervals, as shown in Figure 7.

As shown in Figure 7, for specimen SA9494, SA6895, and SA5287 that have similar average corrosion crack widths of 0.289, 0.293 and 0.297 (about 0.30 mm), respectively, creep slips at creep failure were 0.53, 0.56 and 0.57 mm, respectively, with average of 0.55mm. On the other hand SC5681 with crack width of 0.183mm failed when creep slip increased with time, and reached 0.72mm. This implies that slip at failure depends on the initial corrosion crack width, where specimens with similar crack widths of about 0.30 mm collapsed when they experienced creep slip of 0.55mm in averaged, regardless of the effect of loading history. As a result, creep slip at bond failure decreases with increase the initial corrosion crack widths.

It is also shown that, for specimens SA9494, SA5287 and SC5681, creep slip rate increased more steeply toward failure when it reached 0.37, 0.38 and 0.40 mm, respectively, with average of 0.38 mm. This may imply that, for 5.5% corrosion degree and corrosion crack widths in range of 0.183 to 0.297 mm, creep slip of 0.38 mm was the creep slip limit at which creep slip rate began to increase till failure. This was not shown with SA6895 because this creep slip value of 0.38 has been reached during the first four days after increasing the load level to 95%, where creep rate is high during the first days after loading.

According to the mentioned above, from the design point of view, it is recommended to keep the designed bond stress below 23% of the bond strength to avoid large creep, and below 34% of the bond strength to guarantee enduring bond stress without failure, if the structure experiences corrosion induced crack. However, more experiments are needed to consider the different parameters that affecting the splitting cracks induced by corrosion, such as, concrete strength, concrete cover, steel bar diameter and corrosion rate, specially inducing corrosion under applied sustained load.

4. CONCLUSIONS

Within the limits of the results obtained in this study, for specimens with corrosion degree of 5.5%, the following points could be drawn:

(1) Bond creep failure takes place under stress level of 34% for non-corroded specimens, if it corroded to 5.5% of mass loss, where bond stress level increased to 81%

(2) For specimens with corrosion crack widths in range of 0.18 to 0.30 mm, rate of creep slip started to increase more steeply toward failure when the creep slip reached 0.38 mm.

(3) Creep failure in bond occurred when creep slip reached 0.55 mm and 0.72 mm for corroded specimens with average corrosion crack widths of 0.30 and 0.18 mm, respectively.
(4) Load history affect only the time elapsed up to failure, and has no such effect on the value of creep slip gained at failure.

5. ACKNOWLEDGEMENTS

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6. REFERENCES