- Technical paper -

# BOND FAILURE OF CORRODED REINFORCEMENT IN CONCRETE UNDER SUSTAINED LOAD

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**ABSTRACT**: The effect of reinforcement corrosion on bond creep characteristics is investigated experimentally through pull out test in long-term under corrosion degree in range of 0.5 to 0.7% of measured mass loss that corresponds to average corrosion crack widths, before loading, in range of 0.2 to 0.3mm. As a result, bond stress/strength ratio larger than or equal to 60% would cause creep failure, when corrosion degree is less than 0.7% and corrosion crack width is wider than or equal to 0.2 mm, after a loading period that depends on the applied bond stress/strength ratio with negligible effect of load history.

KEYWORDS: Bond, Slip, Creep, Corrosion, Bond stress level, Creep Failure.

## **1. INTRODUCTION**

Bond strength decreases due to corrosion induced cracks along the reinforcing steel bar[1], thus, bond stress level (applied stress/strength ratio) increases significantly and may exceed the limit that causes creep failure under service bond stresses less than the instantaneous bond strength under the same deterioration conditions. This limit was reported as 67% for bond of sound steel bar in concrete [2]. Therefore, corrosion of reinforcement would lead to bond creep failure within unexpected time. This become very serious, particularly, in the circumstances in which bond is a substantial requirement for structural safety, such as, in anchorage and splices zone as well as when reinforcing with large diameter of steel bars. 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 the degradation of the bond strength 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, In this study, which is the extension of previous studies [3 to 5], the effect of reinforcement corrosion on bond creep characteristics is investigated experimentally through pull out test in long-term under corrosion degree in range of 0.5 to 0.7% of measured mass loss that corresponds to average corrosion crack widths, before loading, in range of 0.2 to 0.3mm. As a result, bond stress/strength ratio larger than or equal to 60% would cause creep failure, when corrosion degree is less than 0.7% and corrosion crack width is wider than or equal to 0.2 mm, after a loading period that depends on the applied bond stress/strength ratio with negligible effect of load history.

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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 /m<sup>3</sup> 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,  $3.29 \text{ N/mm}^2$  and  $30.0 \text{ kN/mm}^2$ , respectively.

The used reinforcement was of deformed steel bar of 16 mm in nominal diameter and 295 N/mm<sup>2</sup> 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 **Fig.1**, the specimens were reinforced concrete prism of dimensions 150x150x400 mm provided with two separate steel bars aligned 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.

In addition to the prism specimens, cylinders with a dimension 100x200 mm and others 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 weak. 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. The prism specimens for bond test were soaked in solution containing 3% Sodium Chloride (NaCl) by the weight of water, as shown in **Fig.2**. A constant electric potential of 72 volt was applied to each specimen for different controlled period to get various corrosion degrees of mass loss. The average imposed electric current intensity was 4.0 mA/cm<sup>2</sup>. 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. The amount of corrosion was calculated by measuring the weight loss after failure in pull out test.



Fig.2 A schematic accelerated corrosion setup

#### 2.4 LOADING TEST

Fig. 3 shows the arrangement of the specimen in loading apparatus for tension creep frame with capacity of 80kN. In the shown creep frame, Applying the load during either short-term or long-term tests were performed by controlling the tension displacement along the specimen length, then load was kept constant throughout the creep experiment period. Load was measured by means of tension load cells. The bond slip measuring 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. Nominal bond stress was computed with dividing the applied load by the total interfacial area between the concrete and corroded length of the reinforcement bar (4.0D, D: diameter of RB) and the concrete.

## **3. RESULTS AND DISCUSSIONS**

#### 3.1 EFFECT OF CORROSION ON BOND STRENGTH

**Fig. 4** shows the effect of corrosion degree (m) on both the bond strength  $(f_b)$  resulted from instantaneous pullout test and the corrosion crack width  $(w_{cor})$  resulted before loading. As shown in the Figure, in the absence of the external corrosion cracks before loading, for corrosion degrees less than 0.4%, bond strength increased slightly with increasing the corrosion degree. With propagation of corrosion, the corrosion cracks that initiate internally around the steel bar develop to the outer concrete surface with widening of both the internal and external crack widths. Therefore bond strength decrease significantly to 1.0 N/mm<sup>2</sup> at 3.0% corrosion degree.



Fig.3 Loading setup



Fig.4 Corrosion degree versus both bond strength and corrosion crack width

#### **3.2 SPECIMENS FOR SUSTAINED LOAD TEST**

For sustained load specimens, corrosion degree in range of 0.5 to 0.7% was adopted, that was corresponding to average crack width in range of 0.2 to 0.3 mm, and instantaneous bond strength in range of 6.3 to 4.3 N/mm<sup>2</sup>, which act as percentage of the average bond strength of the intact specimen (11.37 N/mm<sup>2</sup>) in range of 55% to 38%, respectively. Corrosion degrees of 0.5 and 0.7% have penetration corrosion depth (in steel bar) of 0.020 and 0.028 mm, respectively, that equal to 1.8 and 2.5% of the lug height (1.1 mm for the used steel bar of D16). Therefore the range difference, which is 0.7% of the lug height, has a negligible effect on bond strength, compared with the change in the related average corrosion crack width from 0.2 to 0.3 mm, respectively.

In order to assess the bond strength  $f_b$  of the corroded specimens for the sustained load test, the relationship between average corrosion crack width  $w_{cor}$  and bond strength was established as shown in **Fig.5**. Bond strength was computed using Eq. 1 obtained from the regression

$$f_b = e^{(2.24 - 2.7w_{corr})} \tag{1}$$

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 instantaneous bond strength associated to the pre-loading average corrosion crack width. 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 (two loading steps). In stage one, sustained loads were applied for a period of 3.5 months, when the creep slips of SA4982 and SC4160 became nearly constant. Thereafter, in stage two, for all the specimens except SB7070 and SA8888, the loads were increased instantaneously then kept constant throughout the rest of the experiment period.



Fig.5 Effect of corrosion crack width on bond strength

	Measured			Loading periods			
Symbol	corrosion	$W_{\rm cor}^{(*)}$	$f_b^{(\mathrm{x})}$	Stage one (from 0 to 105 days)		Stage two (after 105 days)	
	degree	(mm)	$(N/mm^2)$	Bond stress	Bond stress	Bond stress	Bond
	(%)			$(N/mm^2)$	level	$(N/mm^2)$	stress level
R02432 <sup>(+)</sup>	0.00	0.000	11.37	2.69	24%	3.67	32%
SA4982	0.71	0.297	4.00	2.07	49%	3.48	82%
SC4160	0.56	0.183	4.31	2.40	41%	3.49	60%
SA6387	0.65	0.293	3.94	2.69	63%	3.76	87%
SB7070	0.65	0.230	4.22	3.58	70%	3.58	70%
SA8888	0.68	0.289	4.03	3.81	88%	3.81	88%

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<sup>(\*)</sup>  $w_{cor}$  is the average corrosion crack width induced before loading. <sup>(x)</sup>  $f_b$  is the instantaneous bond strength computed using Eq. 1.

<sup>(+)</sup>Reference beam: zero corrosion

#### **3.3 SUSTAINED PULL OUT TEST**

Fig.6 represents the creep slip for the sustained load specimens. The Figure shows the increase in slip due to creep only, and no slip increase due to instantaneous loading is represented.

(1) Stage one of sustained loading

As shown in Fig.6, during the first 105 days, non-corroded specimen R02432 and the corroded one SA6387 were applied to the same applied bond stress of 2.69 N/mm<sup>2</sup>, However, they exhibited creep slip of 0.06 and 0.25mm, respectively. This implies that creep slip increased to four times under the same applied bond stress due to corrosion.



**Fig.7** represents the effect of bond stress level on creep slip gained at 105 days from loading time. From the figure, creep slip increased with the increase of load stress level. In addition, It is obviously shown that specimens SA6387, SB7070 and SA8888 with bond stress levels equal to or more than 63% showed remarkable increase in slip compared with that of specimens SC4160 and SA4982 of bond stress levels less than 50%. This may imply that bond stress level of 50%, corresponding to bond stress level of about 20% in case of intact specimen, could be considered as safety limit to prevent large bond creep in case of facing corrosion degree in range of 0.5 to 0.7% based on slip at 105 days after loading.

#### (2) Stage two of sustained loading

At 105 days after loading, sustained bond stresses for all specimens were increased except SB7070 and SA8888 as illustrated in **Table 1**.

As shown in **Fig.6**, for specimen SA8888, SA6387, and SA4982 that have similar 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. This implies that creep slip at failure depends on the pre-loading corrosion crack width, where specimens with similar crack widths of about 0.30 mm collapsed when they experienced creep slip of 0.55mm in average, regardless of the effect of load history.

**Fig.8** represents the final applied bond stress level versus the time elapsed under loading till creep failure. For the specimens SA8888 and SB7070 (one loading step), the elapsed time was measured from the loading time in loading stage one. On the other hand, for the other specimens, where sustained loads were divided into two loading steps (**Table 1**), the elapsed time was measured from the time of increasing the load to the



Fig.7 Effect of bond stress level on creep slip at 105 days after loading



## Fig.8 Effect of final bond stress level on elapsed time under loading up to bond creep failure

final stress level in loading stage two. The final applied bond stresses, as illustrated in **Table 1**, were in range of 3.48 to 3.81 N/mm<sup>2</sup>. If this range of stresses was applied to intact specimens, the load stress level would be in range of 31% to 34%, however due to the presence of corrosion induced cracks bond stress levels increased to become in range of 60 to 88% that eventually led to failure after a various time intervals depending on the bond stress level, as shown in the figure, where, elapsed time till creep failure increases with the decrease of bond stress level. Therefore, it could be deduced that bond stress/strength ratio of 60% would cause creep failure, when corrosion degree is less than 0.7% and corrosion crack width is wider than or equal to 0.2 mm. This stress/strength ratio is equivalent to that reported by Rostasty [2] as 67%, in the absence of corrosion. Moreover, From the figure, it could be said that load history has negligible effects, where creep slips of SA4982 and SC4160 became nearly constant at 105 days, where, for the all specimens, with/without load history, the relation between the bond stress level ( $\varphi$ ) and the elapsed time (t), could be expressed by Eq.2 (from regression) with correlation coefficient (|r|) of 92%.  $t = 567.04 - 5.54 \ \varphi$ 

Finally, according to the results obtained in this study, from the design point of view, it is recommended to keep the designed bond stress below 20% of the bond strength to avoid remarkable increase of creep slip, and below 30% of the bond strength to guarantee enduring the applied bond stress without bond creep failure, in case of attacking with corrosion with corrosion crack widths in range of 0.2 to 0.3 mm. 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 ...etc.

#### **4. CONCLUSIONS**

Within the limits of the results obtained in this study for specimens with corrosion crack widths (before loading) in range of 0.2 to 0.3 mm and corrosion degree of 0.5 to 0.7% of mass loss, the following points could be drawn:

- (1) Based on creep slip measured at 105 days from loading time, a remarkable increase in creep slip existed when stress level exceed 20% for non-corroded specimens, when the specimens experienced corrosion induced cracks of width in range of 0.2 to 0.3 mm existed, where bond stress level exceeded 50%.
- (2) Bond creep failure occurred for non-corroded specimen when bond stress/strength ratio exceed 30%, if it experienced corrosion crack width of 0.2 mm or wider, where bond stress/strength ratio increased beyond 60% due the deterioration of bond strength by corrosion.
- (3) Creep failure in bond occurred when creep slip reached 0.55, 0.52 and 0.72 mm for corroded specimens with average corrosion crack widths of 0.30, 0.23 and 0.18 mm, respectively.
- (4) Load history has negligible effect on time elapsed up to failure.

## ACKNOWLEDGMENTS

The authors gratefully acknowledge Electric Technology Research Foundation of Chugoku in Japan for its financial support to carry out the research in this study.

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