# Bond Characteristics between Low Strength Concrete and Plain Round Bar under Reversal Loading

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## Summary

In order to evaluate the seismic performance of existing RC buildings, pull-out tests were performed to obtain bond characteristics between low strength concrete and plain round bar under reversal loadings. From the test results of the specimen without strengthening, it was found that the maximum bond stresses were less than the allowable stress for the long term load, and that the degradations of bond stress were apparently influenced by the loading cycles. The fundamental bond-slip relationships were obtained in the tests. Additionally, the specimens repaired with epoxy resin injection showed a significant increase in bond stress. The analytical bond-slip hysteresis rule was derived from the test results. Comparisons between the observed hysteresis loops and the analytical loops were performed.

Keywords: bond hysteresis; low strength concrete; plain round bar; epoxy resin injection; bond-slip model

## 1. INTRODUCTION

After the Kobe Earthquake in 1995, seismic evaluations in Japan have found many existing RC buildings to have very low concrete strength (less than 13.5MPa). Due to this, the development of strengthening techniques for existing RC buildings has been carried out in Japan. Research projects concerning low strength concrete have been conducted, and according to several reports, the observed flexural strength of RC members with plain round bars have not reach the calculated flexural strength, despite the specimens being designed as the flexural failure type. It is estimated that the bond strength of plain bars deteriorated at an early stage of the loadings, and that bond slip failure occurred before the yielding of the main bars.

In previous tests by Hideo Araki [Hideo ARAKI (2010)], the conclusions of bond characteristics were summarized: 1) The maximum bond stress was less than the allowable bond strength in the RC Standard of Japan Architectural Institute in 1971, 2) The bond stress decreased rapidly after reaching the maximum bond strength, and the maximum bond strength was recorded in a very small displacement range (less than 0.2mm). From these results we can recognize that it is important to obtain more information of the bond-slip relationships.

Moreover, in order to clarify the seismic performance of those RC members, it is necessary to evaluate the bond characteristics of plain round bars in low strength concrete under reversal loading, and to develop a repair method to improve the bond characteristics of the plain bars. In this paper, an experimental investigation was performed with pull-out tests under three types of reversal loading. The restoring force characteristics of bond-slip were obtained. In addition, in order to improve the bond strength of plain round bars, the epoxy resin injection method was proposed. Finally, bond-slip envelopes and restoring force characteristics were proposed based on the experimental results of pull-out tests under reversal loading. These proposed hysteresis models were compared with the observed bond-slip hystersis. The validity of the proposed bond-slip model with a wide slip length range was comfirmed.



Figure 1. Details of Specimens

Table 1. List of Specimens

Series of Specimens	Specified Strength	Concrete	Embedment Length	Loading Series	Steel Bar	Retrofitting
RL-R13-N	Fc9		10d	1 2 3	13ф	_
RL-R13-R				1 2 3		Epoxy Injection
RL-R19-N				1 2 3	19ф	_
RL-R19-R				1 2 3		Epoxy Injection

## 2. EXPERIMENTAL PROCEDURE

## 2.1. Test Specimen

The specimens for the pull-out tests were prisms of low strength concrete with a plain round bar embedded axially. The prisms were 150mm×150mm in section and 200mm in length, with an embedment length of 10d (d: diameter of the bars). The specified concrete strength of 9MPa was constant. The variables considered in this test were the diameters of the bar  $(13\phi, 19\phi)$ . The prisms were cast with horizontal bars as the beams. A summary of specimens is listed in Table 1. The specimen with diameter of 13 $\phi$  is shown in Fig.1. Plural specimens for each series were arranged because the bond characteristics were usually scattered over a very wide range.

## 2.2. Material

The mix properties of the low strength concrete shown in Table 2 were based on the recommendation of the Practice of Mix Design of Concrete of the Architectural Institute of Japan(AIJ) [Architectural Institute of Japan,(1997)]. The water cement ratio was 110%, the maximum coarse aggregate size was 17.5mm, and the fine aggregate ratio for this concrete was 55%. All test specimens were made from one batch of concrete of the same strength. The mechanical characteristics of concrete from the compressive tests using three test cylinders are shown in Table 3, and the mechanical characteristics of steel from the tension tests are shown in Table 4.

The stress strain curve of compressive concrete strength is illustrated in Fig.2. The average concrete strength was 11.2MPa. Compressive stress gradually decreased after the maximum strength while strains increased to more than 20,000 $\mu$ . This ductile behavior was a distinguishing feature of the low strength concrete.



Figure 3. Test Apparatus

## **2.3. Testing Procedure**

Pull-out loading was subjected to the top end of the embedded bar with a 500kN capacity center hall jack as shown in Fig.3. The pull-out load was measured with two types of load cells of 50kN and 10kN capacity, in order to properly measure the pull-out force. Slip displacement at the free end of the bar was measured with a displacement transducer instrumented at the end of the prism. A spherical bearing was used between the top of the prism and the end of the jack. This was done to prevent the bending caused by the bar not being parallel to the axis of the prism. In addition, in order to subject the reversal loading in the positive-negative range, bar was connected to the external bar with a long nut as shown in Fig.3.

## 2.4. Loading Program

Three types of loading passes were subjected to the specimens. Series 1 was one cycle of loading with a large slip length range ( $\pm 20$ mm) to investigate the fundamental bond-slip mechanism. Series 2 was a reversal cycle of loading in a positive specified slip length range. The slip lengths were 0.2mm and 0.5mm, and it increased every 1mm from 1mm to 10mm. Series 3 was a reversal cycle of loading in a positive-negative specified slip length range to simulate the earthquake loading. The slip length of Series 3 altered in the same way as Series 2.

#### 2.5. Epoxy Resin Injection

Considering existing buildings that have been damaged in minor or moderate earthquakes, epoxy resin was injected at a slip length of 0.2mm. This slip displacement was less than the 0.01inch (0.254mm) that was described as the slip displacement at the maximum bond strength after the adhesion was



Figure 5. The Maximum Bond Strength

Figure 6. Effect of Epoxy Injection

broken[D. A. Abrams (1913)]. However, the strength degradation of all the specimens was observed at a slip length before 0.2mm in this study. Low viscous epoxy resin of 100~ 200mPa.s was injected at a very low pressure of 0.06N/mm<sup>2</sup>. Epoxy resin injection points are shown in Fig.4.

## 3. RESULTS AND DISCUSSION

#### 3.1. Bond Strength

Fig.5 shows the maximum bond strength of plain bars without epoxy resin injection. The allowable bond strengths in the RC Codes of Japan Architectural Institute in 1971 have been inserted into Fig.5. The bond strength for 13 $\phi$  and 19 $\phi$  bar scattered in the range of 0.19 to 0.51MPa, and all of the values were less than the allowable stress for the long-term load. The average value was 0.33MPa and 0.32MPa for 13 $\phi$  and 19 $\phi$  respectively. There was no difference regarding the bar diameter. Fig.6 shows the comparison of the maximum bond strength before and after epoxy resin injection. The bond strength of specimens with epoxy resin injection for 13 $\phi$ and 19 $\phi$  bar scattered in the ranges of 4.1MPa to 5.6MPa and 2.2MPa to 3.5MPa, and the average values were 4.88MPa and 2.91MPa respectively. The specimens repaired with epoxy resin injection showed a significant increase in the maximum bond stress, because the volume of air spaces under the 13 $\phi$  bar was relatively larger than that of 19 $\phi$ . Therefore, a larger amount of epoxy resin might be injected around bars of 13 $\phi$  than 19 $\phi$ . These test results agree with the previous test [Hideo ARAKI (2010)].

## 3.2. Bond-Slip Relationship without Epoxy Resin Injection

Fig.7 shows the bond-slip relationships of the specimens without epoxy resin injection of  $13\phi$  bar. The bond-slip relationships of  $19\phi$  were almost the same as  $13\phi$ , and no bond splitting failure was observed



Figure 7. Bond-Slip Relationships (Without Epoxy Resin Injection)



Figure 8. Bond-Slip Relationships (With Epoxy Resin Injection)

throughout the tests.

Fig.7 (a) shows the bond-slip relationship for Series 1. Slip displacement at the free end of the bar was not observed in the early stages even though pull-out force increased. Afterwards, the slip displacement began to increase when the pull-out force reached a certain value. The maximum bond strength was recorded by the displacement of 0.2mm. The bond stress decreased rapidly after the maximum bond strength. The slope of the bond-slip relationship became constant until the slip displacement reached about 5mm. When force was unloaded and reloaded on the opposite side, the slip displacement did not change until bond stress reached the value that was minus the bond stress of the unloading.

Fig.7 (b) shows the bond-slip relationship of specimens for Series 2. When force was again unloaded and reloaded, slip displacement did not change until bond stress reached the value that was approximately 0.9 times of the bond stress of the unloading. The bond-slip relationship became constant when slip length exceeded 3mm.

Fig.7 (c) shows the bond-slip relationship of specimens for Series 3. The envelop of bond-slip was approximately the same as the other series. The restoring force characteristics were evaluated with the results of Series 2.



Figure 9. The Relationship of Bond Strength Reduction Ratio and Slip Length

#### 3.3. Bond-Slip Relationship with Epoxy Resin Injection

Fig.8 shows the bond-slip relationship of the  $13\phi$  specimens with epoxy resin injection. The bond strength significantly increased in comparison with the results of the specimen without epoxy injection. It is noted that the vertical scale of bond stress of in Fig.8 was 16 times that of Fig.7. Bond splitting failure was not observed although very high bond strength was measured.

After the maximum bond strength of the specimens in each series of loading was reached, bond stress decreased more slowly than those of the specimen without epoxy injection. From the above results, not only the adhesion bond strength but friction bond strength also increased substantially due to the epoxy resin injected into the air pocket between the bar and concrete. The area of enveloped loops of specimens for Series 2 and Series 3 were greater than those of the specimen without epoxy resin injection. Reductions in the responses of a building during an earthquake are expected because of the large energy absorption capacity due to the bond characteristics.

#### 3.4. Characteristics of Post Peak Bond Strength

The comparisons of the post-peak bond strength of each loading series are shown in Fig.9. The vertical axis has been normalized by dividing the maximum bond strength and the origin of the horizontal axis corresponding to the slip displacement when the maximum bond strength was recorded. It was found that reduction ratios of bond strength were apparently influenced by the reversal cycles. Degradation of bond strength after maximum bond of the specimen with epoxy injection was much less than that of the specimen without repairs.

#### 4. ANALYSIS OF BOND-SLIP RELATIONSHIP

Research concerning a bond-slip model for deformed bar has previously been performed [Shiro MORITA (1975)]. However, the bond-slip model for plain round bar was not analyzed. To clarify the seismic performance of the members with plain round bar in existing low strength concrete buildings, it is necessary to build a fundamental bond stress-slip model.

#### 4.1. Monotonic Loading Envelope

Fig.10 shows the analytical rule of the bond-slip relationship. In this study, basic points in the restoring force characteristics were derived from the regression analysis using the experimental data. Each point value in the monotonic loading envelope was obtained from the experimental data from specimens of series 1. In Fig.10, the maximum bond strength was the basic point B ( $\tau_{Max}$ ,  $S_{Max}$ ) used to determine other points A C D. The monotonic loading envelope composed of the increasing zone shows as route A-B, the decreasing zone as route B-C, and the stability zone as route C-D. Bond-slip relationships of each point are shown as the following by Eqn.( 4.1).



Figure 10. Bond-Slip Basic Model

$$\begin{array}{l} A(0.79\tau_{\text{Max}},0\text{mm}), B(\tau_{\text{Max}},S_{\text{Max}}) \\ C(0.21\tau_{\text{Max}},5\text{mm}), D(0.21\tau_{\text{Max}},S>5\text{mm}) \end{array}$$

$$(4.1)$$

In addition, in the third quadrant illustrated the envelope is symmetrical.

#### **4.2. Reversal Loading Envelope**

The envelope under reversal load is proposed as shown in Fig.10. The unloading point is point O' between B and C and the returning point is point E after one cycle reversal loading. The relationship between point E and O' is shown by Eqn. (4.2), where  $\alpha(\text{Eqn.}(4.3))$  is the bond strength reduction ratio to the bond strength of the previous loading.

$$E(\tau_{E}=\alpha\tau_{O'}, S_{E}=S_{O'})$$

$$(4.2)$$

$$\alpha = \frac{\tau_{\rm E}}{\tau_{\rm O'}} = 0.52 \tag{4.3}$$

Bond stress is assumed to decrease from point F when the bond stress increases from point E. The relationship between point F and O' is shown by Eqn.(4.4).

$$F(\tau_{F}=0.70\tau_{0'}, S_{F}=1.12S_{0'})$$
(4.4)

From point F bond stress decreases to point G. G is represented by the following Eqn.(4.5).

$$G(\tau_{G}=0.07\tau_{Max},S_{G}=3mm)$$

$$(4.5)$$

#### 4.3. Hysteresis Properties under Reversal loading

Fig.11 shows the bond-slip relationship model when unloading in route B-C. The relationship between point H and O' is shown by Eqn. (4.6).

$$H(\tau_{H} = -\beta \tau_{0'}, S_{H} = S_{0'}), \beta = \left| \frac{\tau_{H}}{\tau_{0'}} \right| = 0.54$$

$$(4.6)$$

Point I from H at the displacement 0 is shown in Eqn.(4.7). The relationship between point I and H is shown by Eq.(4.7).



Figure 11. Bond-Slip Basic Model (Unloaded at C-D)



Figure 12. Bond-Slip Basic Model (Unloaded at B-C)

$$I(\tau_{i}=\gamma\tau_{H},S_{i}=0),\gamma=\left|\frac{\tau_{i}}{\tau_{H}}\right|=0.37$$
(4.7)

Bond stress increases from point I and reaches point J. The relationship between Point J and F is shown by Eq.(4.7).

$$J(\tau_{j} = -\tau_{F}, S_{j} = -S_{F})$$

$$(4.8)$$

After point J, bond stress decreases when slip displacement increases in the negative range through the route J-M-N. The symmetrical side is F-G-Q.

In the case of route A'-R-E-F, Point R is shown in Eq.(4.9).

$$R(\tau_{R} = -\beta \tau_{A'}, S_{R} = S_{A'}), \beta = \left|\frac{\tau_{R}}{\tau_{A'}}\right| = 0.54$$
(4.9)

However, if  $\tau_R = \beta \tau_A \leq 0.07 \tau_{Max}$ , value of  $\tau_R$  is equal to  $0.07 \tau_B$ . In the case of route B'-K-L-E-F, point K and L are shown in Eq.(4.10).

$$K(\tau_{\kappa} = -\beta \tau_{B'}, S_{\kappa} = S_{B'}), \beta = \left| \frac{\tau_{\kappa}}{\tau_{B'}} \right| = 0.54$$

$$L(\tau_{L} = \gamma \tau_{\kappa}, S_{L} = 0), \gamma = \left| \frac{\tau_{L}}{\tau_{\kappa}} \right| = 0.37$$
(4.10)



Figure 13. Comparisons between Test Date and Proposed Model

However, if  $\tau_K = \beta \tau_B \leq 0.07 \tau_{Max}$ , value of  $\tau_K$  is equal to  $0.07 \tau_B$ . In the case of route C'-S-G, point S is shown in Eq.(4.11).

$$S(\tau_{s}=0.07\tau_{Max}, S_{s}=S_{C'})$$

$$(4.11)$$

Bond stress is assumed to be a constant of  $0.07\tau_{Max}$  when slip displacement is large. Fig.12 shows the bond stress-slip relationship model with unloading at C-D or G-Q in the large slip displacement.

#### 4.4. Comparison with Test Results and Proposed Model

Fig.13 shows comparisons between the test results and the proposed bond-slip model for series 3,  $13\phi$  and  $19\phi$  specimens, with a small slip displacement (0~1mm) and large slip displacement (0~5mm). The bond stress-slip model provided approximate agreement with the test results. However, some differences could be found, and as such more investigations are necessary for the bond stress-slip characteristics in future.

#### **5. CONCLUSIONS**

Based on the experimental and analytical investigations, the following conclusions can be made,

- The maximum bond strength for all specimens was less than the allowable stress for long-term load. Any difference of maximum bond strength for 13φ and 19φ bar were not observed.
- (2) The specimens repaired with epoxy resin injection showed a significant increase in the maximum bond stress. The effect of epoxy resin injection for 13φ bar was relatively higher than that of 19φ.
- (3) Bond strength reduction ratio is influenced by the reversal cycles.
- (4) The proposed bond-slip model provided an approximate agreement with the test results.

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