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Bond Strength of Re-bars in Interior Beam-Column Joint Under Cyclic Loading

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Abstract. The inelastic deformation of RC beam-column connections is significantly increased by the re-bar bond-slip under cyclic loading. In the present study, analyzing existing beam-column joint test results, a bond strength model was developed to evaluate bond-slip of beam re-bars in the joint. For verification of the proposed model, the prediction of the proposed model was compared with the cyclic test results of bond-slip specimens. The result showed that the prediction agreed well the bond strength degradation and the bond-slip of re-bars.

Keywords: Bond-slip, Bond strength, Cyclic loading, RC beam-column interior joint

1. Introduction

In Reinforced Concrete beam-column joint subjected to earthquake load, seismic performance is significantly affected by the concrete diagonal cracking and bond-slip of beam flexural bars at the joint [1]-[3]. Fig. 1 shows the load transfer mechanism in interior beam-column joint subjected to seismic load. Under seismic load, two times bond strength is required in beam flexural bars at the joint. However, the limited column depth h_c causes difficulty to secure a sufficient development length of the beam flexural bars.

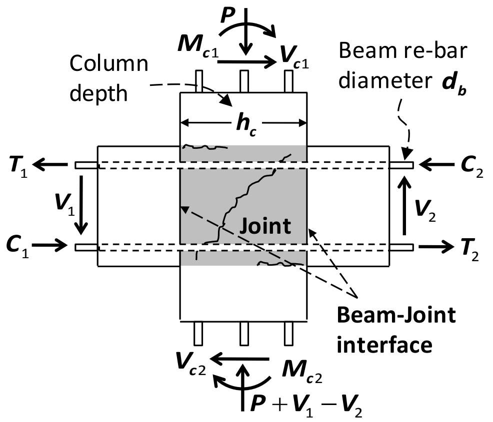

Fig. 1: Load-transfer of beam-column joint in interior connection

The existing studies developed the bond strength-slip relationship of re-bars, bond model for finite element analysis of reinforced concrete, and strain based bond model for beam-column joint [4]-[6]. In the existing test, concrete block tests were performed for a re-bar bond-slip. Because the component test cannot simulate the bond behavior of actual beam-column joint, however, bond strength can be accurately evaluated in only elastic range of re-bars. When the bond-slip of re-bars occurs in the concrete block, re-bar strain and yield strength are decreased. On the other hand, when a significant bond-slip of beam flexural bars occurs in

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interior beam-column joint, great inelastic strain of the re-bars are developed by the anchorage of re-bars at the opposite beam. Thus, the bond behaviors of re-bars including strain distribution, bond-stress, and bond strength in the actual joint can be different from those of the concrete block test.

In the present study, on the basis of the existing beam-column joint test, simplified bond model considering bond-slip of beam flexural bars at the joint was proposed. The existing bond model was improved by defining the new bond failure and bond stress at the joint. Compared to bond test result, the proposed bond model of re-bars was verified.

2. Bond Model of Re-bars at Joint

When an anchorage failure of deformed bars occurs in concrete, bond resistance is divided into bearing stress of ribs and surface friction of re-bars [4]. Before re-bar yielding, deformation between the re-bars and concrete is very small because of large elastic stiffness of the re-bars. Thus, concrete damage by bearing stress is not almost occurred. After re-bar yielding, on the other hand, the deformation is significantly increased. It induces the concrete cracking and bearing failure. That is, bond stress can be defined as a concrete bearing bond stress τ_e (= elastic bond stress) before re-bar yielding and a friction bond stress τ_u (= plastic bond stress) after re-bar yielding [3], [6]. Therefore, re-bar stress and bond-stress relationship is determined by equilibrium condition as follows.

$$\boldsymbol{d}\sigma\left(\frac{\pi \boldsymbol{d}_{\boldsymbol{b}}^2}{4}\right)=\tau_{\boldsymbol{e}}\left(\pi \boldsymbol{d}_{\boldsymbol{b}}\boldsymbol{dx}\right) \quad \text{or} \quad \frac{\boldsymbol{d}\varepsilon}{\boldsymbol{dx}}=\frac{4\tau_{\boldsymbol{e}}}{\boldsymbol{E}_{\boldsymbol{s}}\boldsymbol{d}_{\boldsymbol{b}}} \tag{1a}$$

$$\boldsymbol{d}\sigma\left(\frac{\pi \boldsymbol{d}_{\boldsymbol{b}}^2}{4}\right)=\tau_{\boldsymbol{u}}\left(\pi \boldsymbol{d}_{\boldsymbol{b}}\boldsymbol{dx}\right) \quad \text{or} \quad \frac{\boldsymbol{d}\varepsilon}{\boldsymbol{dx}}=\frac{4\tau_{\boldsymbol{u}}}{\boldsymbol{E}_{\boldsymbol{sh}}\boldsymbol{d}_{\boldsymbol{b}}} \tag{1b}$$

Where d_b= re-bar diameter, τ_e= elastic bond stress before re-bar yielding, and τ_u= plastic bond stress after re-bar yielding. Eqs. (1a) and (1b) were applied to re-bar stress $\sigma \leq f_y$ and $\sigma > f_y$ (f_y = re-bar yield stress), respectively.

Fig. 2 shows bond-stress and strain distribution according to bond-slip of beam flexural bars in interior beam-column joint. Fig. 2(a) presents the limited stage of bond-slip. Due to sufficient bond strength in the joint, compressive and tensile stress are applied to the beam flexural bars. Compressive and tensile friction bond stress τ_u are applied to the yielding length of re-bar at the joint interface. Bearing bond stress τ_e is applied to the elastic length of re-bar inside the joint. Fig. 2(b) presents the partial bond-slip stage that only tensile stress is applied to the beam flexural bars in the joint. That is, insufficient bond strength caused the tensile bond strength at total joint length. Plastic bond strength is defined at the both of joint interface by cyclic loading, and elastic bond strength is defined inside the joint. In this case, tension forces of re-bars are anchored at the compression zone of an opposite beam. Fig. 2(c) presents the complete bond-slip stage that the only plastic bond strength is applied to the total joint length.

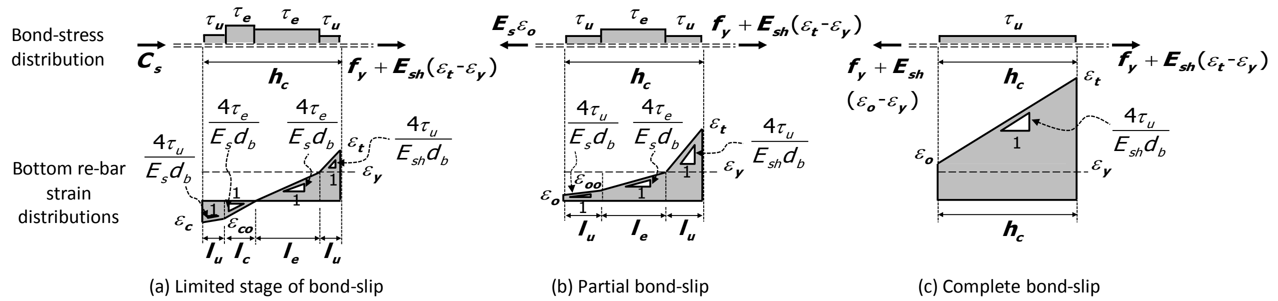


Fig. 2: Stress and strain distribution of beam re-bars in beam-column joint

In Fig. 2(a), when a re-bar strain ε_t is less than yield strain ε_y, bearing bond stress τ_e is applied to bearing bond length. The other region is defined as friction bond length l_u. Here, compressive bearing bond stress τ_e is greater than tensile bearing bond stress (see Eq. (3)). Therefore, tensile bond length l_e is longer than compressive bond length l_c. Under cyclic loading, because a yield penetration of re-bar occurs almost symmetrically, bond stress of beam flexural bars decreases at left and right joint interface. Furthermore, because the once degraded bond stress is not recovered, regardless of the beam flexural bars strength and direction, friction bond length l_u is same at the left and right interface, and same friction bond stress τ_u is applied. In Fig. 2(b), the friction bond length l_u is determined as the region that a tensile strain of re-bar ε_t is greater than yield strain ε_y. Due to cyclic loading in beam-column joint, equal friction bond length l_u is developed at the both of the joint interface. Tensile bearing bond length at the center of the joint is determined from $l_e = h_c - 2l_u$, and uniform tensile bearing bond stress τ_e is applied to the re-bar. As shown in Fig. 2(c), when friction bond length l_u is longer than half joint length $h_c/2$, the total joint length is defined as the friction bond length addressing cyclic loading, and uniform friction bond stress τ_u is applied.

Stress and strain distributions of re-bars can be defined by using Eq. (1). Bond strength can be determined from sum of the bond stress along beam flexural bar. An elongation e_b of beam flexural bar at the joint interface can be calculated by integration of tensile strain ε (> 0).

$$e_b = \int_0^{h_c} \varepsilon \, dx \quad \text{for } \varepsilon \geq 0 \tag{2}$$

The re-bar bond model was developed on the basis of the methods by Hong et al. [3] and Lowes and Altoontash [6]. In the proposed model, cyclic loading effect was more accurately considered. That is, in the proposed model, friction bond stress τ_u is defined from the test results of the existing beam-column joint. As shown in Fig. 2, to consider the bond damage behavior under cyclic loading, bond damage was defined symmetrically at the both of the joint interface.

3. Bond Strength of Re-bars

Before re-bar yielding, the difference of bond property between cyclic loading and monotonic loading is not critical [4]. Thus, elastic bond stress τ_e of re-bars was used as a concrete strength function [4], [6].

$$\tau_e = 1.8\sqrt{f_c'} \quad \text{for tension (in MPa)} \tag{3a}$$

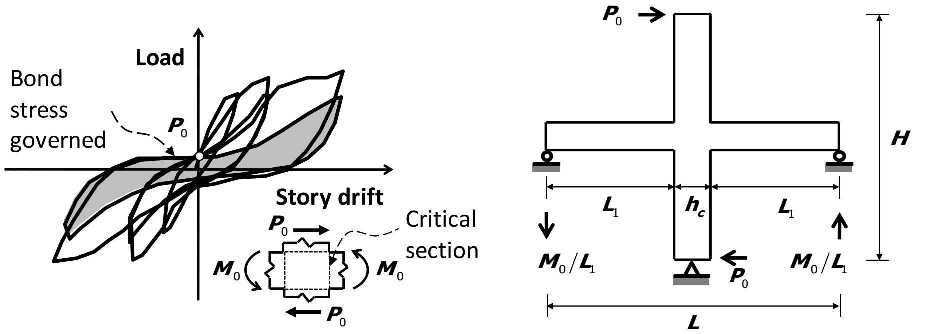
$$= 2.2\sqrt{f_c'} \quad \text{for compression (in MPa)} \tag{3b}$$

On the other hand, plastic bond stress τ_u of re-bar is significantly decreased by yield penetration. The existing researches proposed τ_u on the basis of the component bond tests [4], [6], [7].

$$0.05\sqrt{f_c'} \leq \tau_u \leq 0.4\sqrt{f_c'} \quad \text{(in MPa)} \tag{4}$$

Because the loading and boundary conditions in actual beam-column joint differ from those in component test, it is difficult to accurately evaluate the plastic bond stress τ_u. In the present study, plastic bond stress τ_u was proposed on the basis of the existing beam-column joint tests.

Fig 3(a) shows the load-drift relationship in beam-column joint with significant pinching under cyclic loading. In pinching region, bond-slip of beam re-bars is occurred by almost uniform frictional resistance. Thus, as shown in Fig. 2(c), bond stress of beam flexural bars is assumed to be the uniform bond stress τ_u in the total joint length. Because the bond-slip direction of the beam flexural bar is reversed in pinching region, load carrying capacity P_0 (see Fig. 3(a)) should be developed by only friction bond stress τ_u in the joint.



(a) Joint behavior with bond-slip (b) Configuration of beam-column joint

Fig. 3: Cyclic response of beam-column joint

During the bond-slip of beam flexural bars, beam flexural moments at left and right joint interface can be calculated by the friction bond stress τ_u. Load carrying capacity P_0 by flexural beam moments M_0 at left and right joint interface can be calculated by the moment equilibrium condition as follows (see Fig. 3(b)).

$$M_0 = \tau_u \left(\sum_{i=1}^{n} \pi d_{bi} h_c \right) h_s \tag{5}$$

$$P_0 = \frac{M_0 \left(h_c / L_1 + 2 \right)}{H} \tag{6}$$

Where n= the number of either top re-bars or bottom flexural bars at a beam section, d_{bi}= diameter of each beam flexural bars, h_s= distance between top and bottom flexural bars, L_1= shear span of the both beams, and H= effective column height.

Substituting Eq. (5) into Eq. (6), friction bond stress τ_u at the joint is as follows.

$$\tau_u = \frac{P_0 H}{h_s \left(\sum_{i=1}^{n} \pi d_{bi} h_c \right) \left(h_c / L_1 + 2 \right)} \tag{7}$$

To clearly consider plastic bond stress distribution such as Fig. 2(b), beam-column joints with significant pinching including Fig. 3(a) are analyzed. The principal test parameters are f_c'= 20.8 ~ 79.0 MPa, f_y= 336 ~ 858 MPa, d_b= 9.5 ~ 25.4 mm, and h_c= 240 ~ 550 mm [1], [8]-[18] (see Table 1).

Table 1: Test parameters of existing test specimens (MPa)

Speciemns		$A_h f_{yh}/V_u$	f_c'	τ_u	Speciemns		$A_h f_{yh}/V_u$	f_c'	τ_u	Speciemns		$A_h f_{yh}/V_u$	f_c'	τ_u
Hwang et al. [8]	S1	0.58	32.0	0.72	Yoshino et al. [11]	No1	0.39	28.6	0.63	Joh et al. [15]	B1	0.22	21.3	0.36
	S2	0.59	32.0	0.69		No3	0.34	28.6	0.70		B2	0.22	20.8	0.36
	S3	0.59	32.0	0.76		No4	0.51	28.6	0.74		LH	0.25	26.9	0.51
Asou et al. [9]	No1	0.64	67.1	1.31	Tateishi and Ishibashi [12]	AIJ	0.57	23.5	0.68		MH	0.50	28.1	0.61
Lee et al. [1]	BJ1	0.60	40.0	0.88		HBS	0.48	23.5	0.75	Kawai et al. [16]	I6C	0.28	66.1	0.75
	BJ2	0.54	40.0	0.72	Leon [13]	BCJ2	0.35	30.2	0.65	Hayashi et al. [17]	NO46	0.31	49.1	0.85
	BJ3	0.67	40.0	0.92		BCJ3	0.35	30.2	0.59		NO47	0.23	49.1	0.62
	B1	0.89	40.0	0.86		BCJ4	0.36	30.2	0.75	Shiohara [18]	B04	0.16	29.0	0.40
Xian et al. [10]	U1	0.86	30.9	0.72	Oda et al. [14]	BN1	0.50	79.0	1.05		B06	0.13	29.0	0.43
	U2	0.83	40.8	0.67		BN2	0.37	79.0	0.94		D03	0.12	32.4	0.37
	U4	1.02	47.2	0.93		BN3	0.43	79.0	1.02		D07	0.08	32.4	0.38
	U5	0.72	60.7	1.25		BN4	0.43	79.0	1.09		D11	0.12	32.9	0.41
	U6	0.65	59.3	1.02		BN5	0.55	51.3	0.93		E03	0.07	61.4	0.61

As joint shear strength increases, bond strength can be decreased by a significant concrete cracking. On the other hand, joint hoop bars decreased the width of shear cracking at the joint, and the bond strength can be increased. Fig. 4 shows the relationship between the ratio of joint hoop bars strength to joint shear demand and the ratio of $\tau_u/\sqrt{f_c'}$. The relationship can be approximately defined as follows.

$$\tau_u / \sqrt{f_c'} = 0.08 \left[A_h f_{yh} / V_u + 1 \right] \tag{8}$$

Where A_h= sum of joint hoop area parallel to beam flexural bars, f_{yh}= yield strength of hoop bars, V_u= $(\sum A_s f_y)$-P_u, $\sum A_s$= sum of top and bottom flexural bars of a beam, f_y= yield strength of beam flexural bars, and P_u= the maximum column shear force at the yielded joint by lateral load.

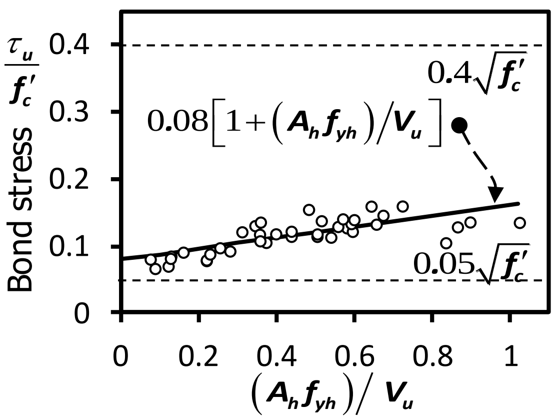


Fig. 4: Residual bond stress according to design parameters

For a verification of component bond model, test results by Viwathanatepa et al. [5] were compared. Fig. 5 shows a bond test results. Test parameters are re-bar diameter d_b(= 19.1~25.4 mm) and development length h_c(= 381~635 mm). Fig. 5 shows the load-elongation (F_b-e_b) relationship of the specimens.

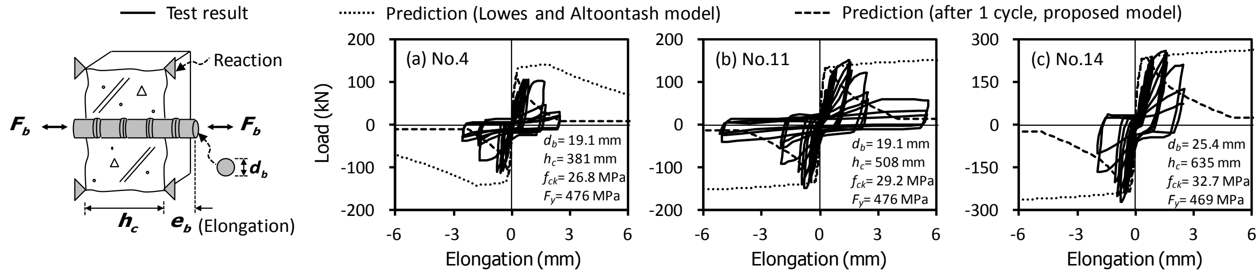


Fig. 5: Comparison between cyclic test and bond stress model

Using the proposed bond model, the prediction of F_b-e_b relationship was compared as thick dotted line in Fig. 5. The proposed values in Eqs. (3) and (8) was used as the elastic bond strength τ_e and plastic bond strength τ_u, respectively. The prediction by the existing bond model [6] was compared as thin dotted line in Fig. 5. In the existing model, τ_u= $0.23\sqrt{f_c'}$ was used as the average value. Elastic modulus and hardening modulus of re-bars were E_s= 200 GPa, and E_{sh}= 0.01Es, respectively. As shown in Fig. 5, the proposed model underestimated the bond strength for 1st cyclic loading, but agreed well with the 2nd and 3rd cyclic loadings. This is because the plastic bond stress τ_u in the proposed model was evaluated from the large inelastic re-bar subjected to cyclic loading. On the other hand, the existing model [6] using τ_u= $0.23\sqrt{f_c'}$ overestimated the bond strength. Particularly, as shown in Fig. 5(a), test result was overestimated for specimen No.4 with short development length. This is because the existing model [6] does not consider the symmetric damage of plastic bond stress τ_u and bond stress degraded length l_u under cyclic loading.

4. Conclusion

In the present study, simplified bond strength model and bond-slip relationship of re-bar addressing cyclic loading in interior beam-column joint were studied. The primary results are as follows.

1) To consider a bond-slip of beam flexural bar in RC beam-column joint subjected to cyclic loading, strain based bond model of re-bars by yield penetration was proposed. In the proposed model, bond strength at the both sides of the joint was decreased equally by cyclic loading.

2) For RC beam-column joint with complete bond failure, bond slip is occurred without the load increment at unloading/reloading, and constant load is maintained by the friction bond stress τ_u. τ_u was determined from the hysteresis curves of RC beam-column joint with complete bond failure.

3) The bond-slip relationship of re-bar predicted by the proposed model was compared with the bond test results. The predictions agreed well with the test results.

5. Acknowledgements

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