Bond of Deformed Bars to Concrete : Effects of Confinement and Strength of Concrete

철근 콘크리트 보-기둥 접합부의 부착거동에 대한 콘크리트 강도 및 보강철근의 효과

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Abstract

Slippage of beam longitudinal reinforcement at beam-column connections is an important cause of damage to reinforced concrete frames under static and dynamic loads. This paper summarizes the results of an experimental study on the effects of confinements and compressive strength of concrete on the local bond stress-slip characteristics of deformed bars. It is concluded from experimental results that, as far as the bond splitting cracks are restrained by the vertical column reinforcement, confinement of concrete by transverse reinforcement has insignigicant direct effect on the local bond behavior. The ultimate bond strength, however, increases proportionally with the square root of concrete compressive strength. An empirical model was developed for local bond stress-slip relationslip of deformed bars in confined concrete of different compressive strengths.

요 약

보-기둥 접합부에서 보의 축방향 철근의 슬립은 정하중 및 동하중 하에서 철근 콘크리트 골조를 손상시키는 중요한 요인중 하나이다. 이 논문은 이형철근의 국부 부착-슬립 특성에 관한 콘크리트강도 및 보강철근에 대해 실행된 실험결과를 요약하였다. 실험결과로 부터 부착할렬균열(bond splitting crack)이 기둥의 축방향 철근에 의해 제어되는 한 횡방향 보강철근이 국부부착거동에 직접적인 영향을 미치지 않으며 극한부착강도는 콘크리트강도의 제곱근에 비례해 증가함을 알 수 있었다. 이를 근거로 압축강도에 따른 보강철근 내부의 콘크리트와 이형철근의 국부 부착 응력-슬립 상관관계를 나타내는 실험모델을 유도하였다.

1. Introduction

In order to ensure the stability of reinforced concrete structural systems under severe loading conditions it is important to prevent slippage of reinforcing bars at such critical locations as beam-col-

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umn connections (see Fig. 1)[1]. Experimental characterization of bond performance within the confined core area of joints can thus be helpful in improving the design of anchored bars at beam-dolumn connections.[2,3,4]

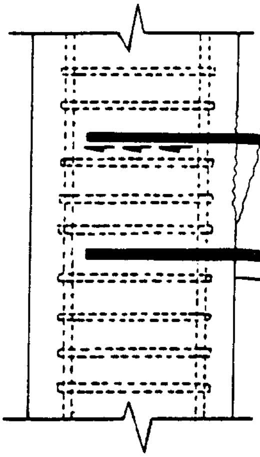


Figure 1. Anchorage of Beam Reinforcement at Exterior Joints

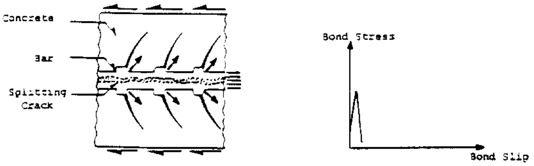
This study has been concerned with the effects of confinement and compressive strength of concrete on local bond characteristics of deformed bars in reinforced concrete joints. Confinement is achieved at joint regions through the use of transverse column reinforcement. The spacing of transverse steel was used in this study as the measure of confinement, the effects of which on local bond behavior was assessed. This experimental study was also concerned with the effects of concrete compressive strength on local bond behavior, noting that higher-strength concretes are finding increasing applications in the lower stories of highrise buildings.

2. Research Significance

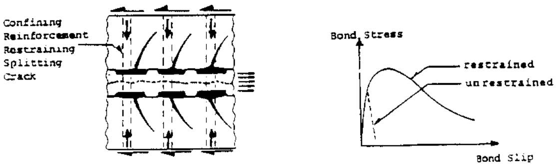
The slippage behavior of beam reinforcement anchored at beam-column connections plays an important role in deciding the rigidity and stability of reinforced concrete frames. The test data and the empirical model presented in this study can be helpful in developing more reliable design recommendations for anchorage of deformed bars at beam-column joints.

3. Background

The bond of deformed bars to concrete is provided mainly by mechanical interlocking between the bar lugs and surrounding concrete[4,5]. The action of lugs against concrete produces inclined cracks at relatively low bond stresses (Figure 2(a)). After inclined cracking, the steel stresses are transferred to concrete by inclined compression. The radial component of this force system simulates an internal pressure inside concrete, which causes a tendency toward failure by split cracking (Figure 2(a)). Confinement of concrete by steel bars crossing the potential splitting cracks can restrain the propagation and opening of these cracks, causing an ultimate failure by bar pul-out (Figure 2(b)).



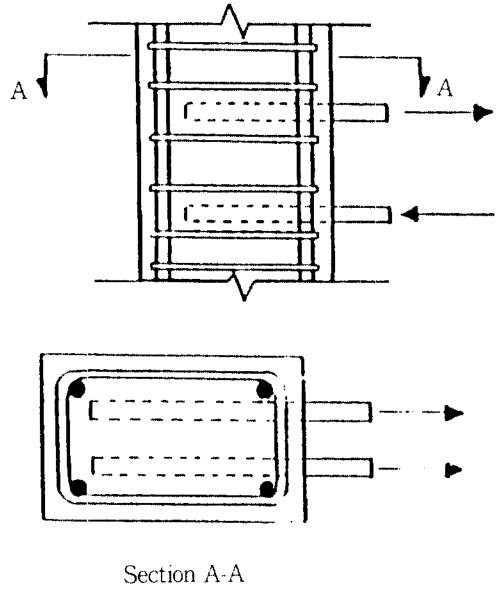
(a) Split Cracking



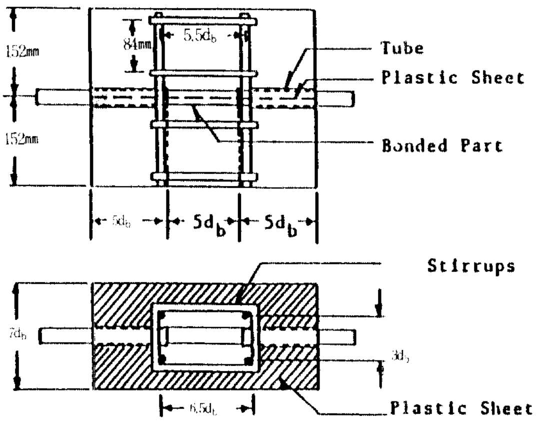
(b) Pull-Out

Figure 2. Bond Failure by Split Cracking in Unconfined Concrete, and Pull-Out in Confined Concrete[2]

In beam-column connections, the steel bars which arrest the splitting cracks are the column vertical and transverse reinforcement (see Figure 3 (a)). In order to simulate the local bond conditions at beam column joints, Ref. 5 has used a confined



(a) Confining Reinforcement at Joint

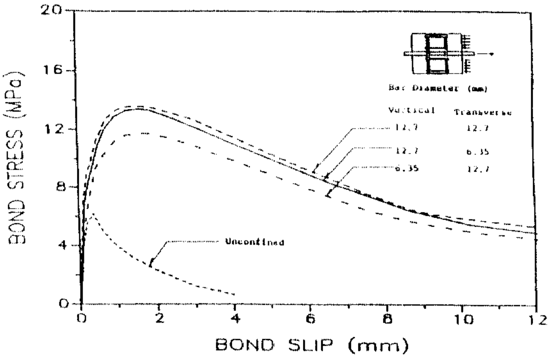


(b) Experimental Model for Local Bond Studies

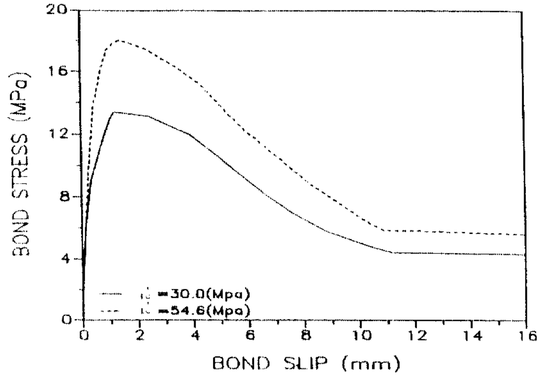
Figure 3. The Actual Joint Condition and the Experimental Model of Ref. 2

concrete block containing a partially bonded deformed bar (Figure 3(b)). Test data on these specimens (Figure 4(a)) have indicated that the behavior of local bond in confined specimens is dominated by bar pull-out, and is quite different from failure by split cracking in unconfined specimens. The increase in confinement steel area above a minimum value required for restraining the widening of splitting cracks, however, did not significantly improve the local bond stress-slip characteristics (see Figure 4(a)). Test results presented in Ref. 5 have covered only the effects of transverse steel area (not spacing) on local bond behavior. Considering the significance of transverse bar spacing in deciding the concrete confinement conditions, it is important to evaluate the behavior of local bond in concretes confined with transverse bars at different spacings.

Ref. 5 has also presented the results of a limited number of tests on the effects of concrete compressive strength on local bond behavior in confined concrete. The results (Figure 4(b)) indicated that at higher concrete compressive strengths the bond stiffness, strength and post-peak resistance tend to be higher. These conclusions, however,



(a) Confining Steel Area



(b) Concrete Compressive Strength

Figure 4. Effects of the Confining Reinforcement Area and Concrete Compressive Strength on the Local Bond Behavior.

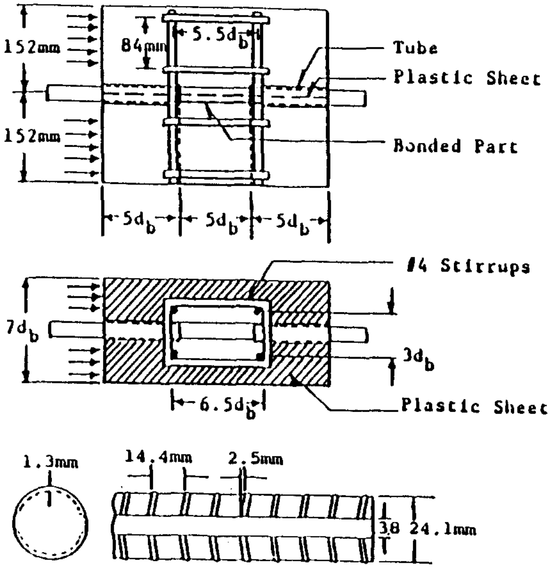
have been based on tests with only two different levels of compressive strength. More test data on local bond behavior in concretes of different compressive strengths are needed in order to quantify the effects of concrete strength on bond characteristics.

The research reported herein has been concerned with generating experimental data and empirical formulations on the effects of confinement and compressive strength of concrete on local bond behavior of deformed bars in conditions of beam-column joints.

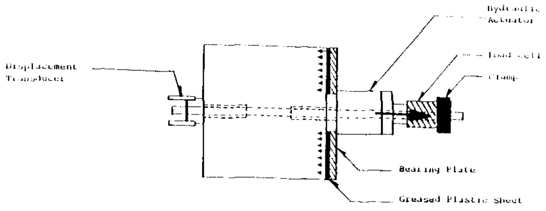
4. Experimental Program

The test specimens used in this study were similar to those of Ref. 5, with a #8 deformed bar partially bonded (along 5 in., 127㎜, of its length) inside a concrete block (Figure 5(a)). The bonded length was, according to Ref. 5, long enough to reduce the scatter of test data, and short enough to produce a uniform bond stress and slip. The variables in this test program were the spacing of transverse reinforcement and the compressive strength of concrete. Table 1 presents the values of transverse bar spacing and concrete compressive strength used in this investigation. A plastic sheet was placed inside concrete at the level of embedded bar in order to create an artificial splitting crack (which could be caused by bond stresses of the adjacent bars) outside the confined core area. With the arrangement shown in Fig. 5a, test conditions simulate the local bond behavior of deformed bars with a clear spacing of four times the bar diameter in confined concrete.

The reinforcing bars used in this study had a yield strength of 60Ksi (414 MPa). The deformation pattern of the embedded #8 bar is shown in Figure 5(a). The maximum aggregate size in concrete was 0.75 in. (19㎜), and the concrete was cast perpendicular to the bonded bar axis. The specimens were moist-cured inside their wood forms for seven days before being demolded and exposed to the regular lab environment. They were tested at the age of 28 days.



(a) Test Specimen



(b) Test Set-up

Figure 5. The Test Specimen and Experimental Set-up

Table 1. Test Program

Variable	No. of Specimen	Transverse Reinforcement	Concrete Compressive Strength Mpa(Psi)
Transverse	2	2#4	27 (3950)
Reinforcement	2	6#4	27 (3950)
Spacing	2	Vertical Bars	27 (3950)
	2	Plain	27 (3950)
Concrete	2	4#4	24 (3500)
Compressive	2	4#4	29 (4220)
Strength	2	4#4	34 (4950)
	2	4#4	54 (7850)

The test set-up and instrumentation are shown in Figure 5(b). The pull-out load was spplied at one end of the deformed bar with a hydraulic actuator. A load cell with a maximum error of 1% was used to measure the applied load. Loading was quasi-static and displacement-controlled. Local bond stress was derived by dividing the measured pull-out force by interfacial area along the bonded length (assuming a uniform bond stress distribution)[5]. Two electrical displacement transducers were used at the free end of anchored bar to measure pull-out displacements. Assuming a uniform slippage along the embedment length, this pull-out displacement is equal to the local bond slip.[5]

5. Experimental Results

Bond stress-slip relationships for specimens with different transverse (confining) reinforcement spacings are shown is Figure 6. Each curve in this figure is the average of two test results, which wre performed on two identical specimens and showed similar trends.

Failure of plain specimens was by split cracking, and it cccurred in a brittle manner. The presence of vertical steel bars restrained the widening of splitting cracks, and changed the failure mode to a pull-out one. The differenced in bond stress-slip characteristics of specimens with vertical bars and with or without transverse reinforcement at different spacings were practically insignificant. Noting that split cracking in these specimens occurs parallel to the plane of transverse steel bars (as is also the case in actual beam-column connections), the insignificant effects of transverse reinforcement on local bond behavior may be attributed to their ineffectiveness in restraining the widening of splitting cracks which run parallel to them. It is also worth mentioning that in actual joint conditions the transverse reinforcement is effective in reducing the extent of concrete cracking. As a result, the increase in transverse reinforcement ratio may provide a better environment for bond in stress conditions of actual joints, which could lead to enhanced bond stress-slip characteristics.

The effects of concrete compressive strength on local bond stress-slip relationship in confined specimens are shown in Figure 7. Each curve in this figure is again the average of two similar curves obtained in tests on identical specimens. The test results shown in Figure 7 indicated that ultimate bond strength increases with increasing compressive strength of concrete. The other characteristic stess and slip values in bond stressslip relationships are, however, not consistently influenced by the variations in concrete strength.

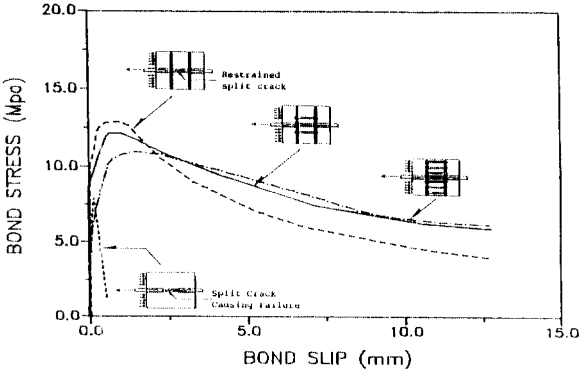


Figure 6. Effects of Confining Reinforcement on the Local Bond Stress-slip Relationship of Deformed Bars

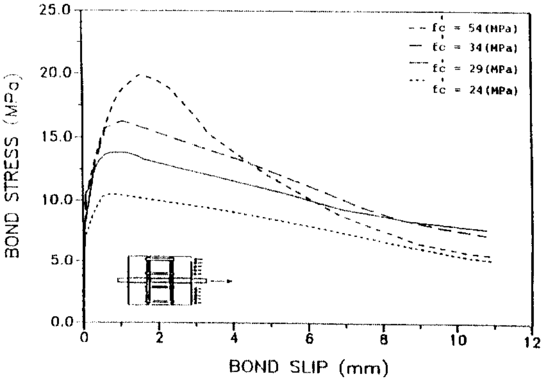


Figure 7. Effects of Concrete Compressive Strength on the Local Bond Stress-Slip Characteristics of Deformed Bars in Confined Concrete

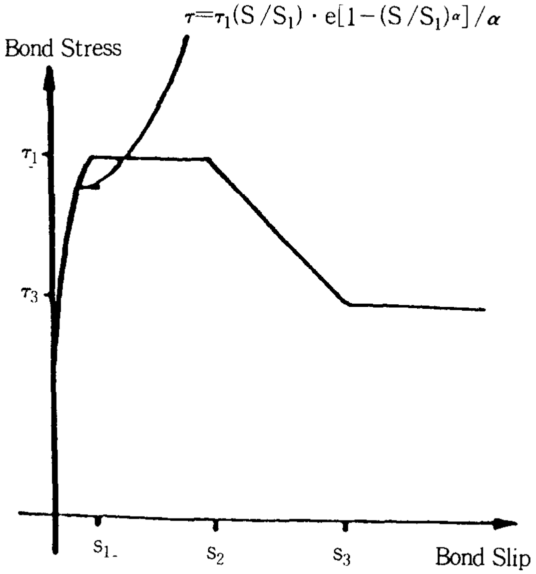


Figure 8. General Shape of the Local Bond Stress-Slip Model

6. Empirical Modeling

The general shape of local bond stress-slip relationship for deformed bars embedded in confined concrete can be simulated by the model shown in Figure 8[6]. This model consists of a curvilinear ascending branch, a flat segment at the peak bond stress, a linear descending branch, and a flat tail. It includes 5 parameters (characteristic bond stresses τ_1 and τ_3, and slips s_1, s_2 and s_3), to be derived empirically. Test results presented here and also those given in Ref. 6 indicate that the characteristic values s_1, s_2, s_3 and τ_3 are largely independent of concrete strength, confinement by transverse reinforcement and bonded bar diameter. Test resuls presented in this paper and Ref. 6 indicate that the compressive strength of concrete has a definite influence on peak bond stress, τ_1. Figure 9 shows that the peak bond stress tends to increase proportionally with the square root of concrete compressive strength. Ref. 6 also provided experimental evidence on the dependence of peak bond stress on the bonded diameter.

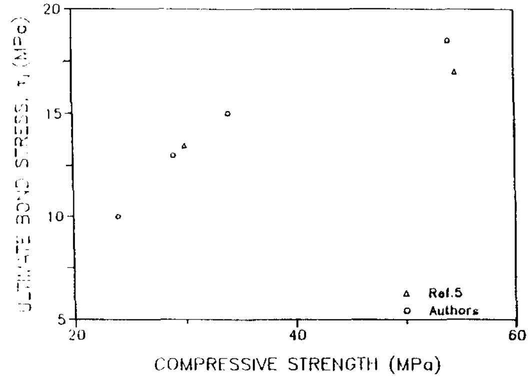


Figure 9. Effect of Concrete Compresssive Strength on Local Bond Strength (Bar Diameter—1 in., 25.4 mm)

Table 2. Empirical Values and Expressions for the Characteristic Local Bond Stress and Slip Values (units, mm, Mpa : 1mm—0.039 in., 1 Mpa—144 psi)

τ_1(MPa)	τ_3(MPa)	s_1(mm)	s_2(mm)	s_3(mm)
$(20-d_b/4)\cdot\sqrt{f'c}/30$	5.0	1.0	3.0	10.5

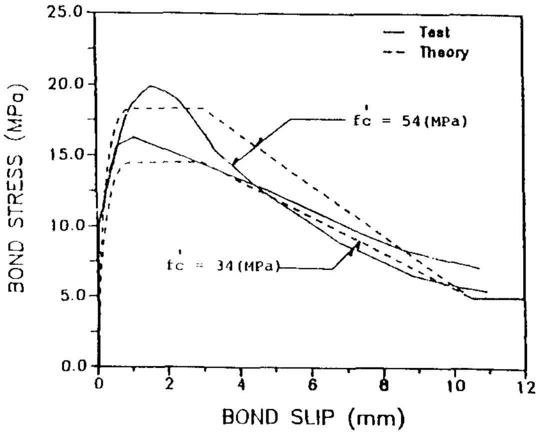


Figure 10. Comparison of the Experimental and Analytical Bond Stress-Slip Relationships (Bar Diameter-1 in., 25.4mm)

The average values of s_1, s_2, s_3 and τ_3, and the empirical expression (based on test results of this paper and Ref. 6) for τ_1 in terms of bar diameter (d_b) and concrete compressive strength (f'_c) are shown in Table 2. Typical experimental and analytical local bond stress-slip relationships for concretes of different strengths are compared in Figure 10. The developed model seems to provide a basic tool for future analytical studies on beam-column connections.

7. Summary and Conclusions

Effect of confinement by transverse reinforcement and compressive strength of concrete on local bond stress-slip characteristics of deformed bars were assessed experimentally through tests on specimens simulating the local bond condition of beam reinforcement in beam-column connections. The results indicated that :

(1) confinement of concrete by transverse reinforcement does not directly influence the local bond behavior of deformed bars in joints with vertical column bars sufficient to restrain the widening of bond splitting cracks.

(2) The ultimated bond strength increases almost proportionally with the square root of concrete compressive strength. The other characteristic values of bond stress and slip in local bond stress-slip relationships are not strongly influenced by variations in concrete compressive strenth.

An empirical model was developed for predicting the local bond stress-slip relationship of deformed bars with different diameters in confined concretes having different compressive strengths.

8. Acknowledgements

The financial support for this study was provided by the fund of Korea Science & Engineering Foundation. The encouragement of Dr. P. Soroushian of the Composite Material and Structures Center in Michigan State University is gratefully acknowledged.

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Notations

d_b	– Bar diameter
f'_c	– Concrete compressive strength
α	– Coefficient in local bond constitutive model (see Figure 9)
s	– Bond slip
s_1, s_2, s_3	– Characteristic bond slip values for local bond constitutive model(see Figure 9)
τ	– Bond stress
τ_1, τ_2, τ_3	– Characteristic bond stress values for local bond constitutive model

(접수일자 : 1991.4.15)