論文 Effect of Bond on Shear Behavior of RC and PC Beams: Experiments and FEM Analysis

Keerthi RANASINGHE [*1], Hiroshi MUTSUYOSHI [*2], Muhammad ASHRAF [*3]

ABSTRACT: This paper describes the effect of bond between reinforcement and concrete on the shear behavior of reinforced and prestressed concrete beams. Seven beams with different bond conditions were tested till failure, while stress-slip relationships for these specimens were obtained from a parallel series of simple pullout tests. A numerical analysis was also conducted to simulate the beams tested. It was found that bond condition of steel bars and prestressing bars highly influences the shear strength and failure mode of RC and PC beams. A reasonably good correlation was observed between the experimental and analytical results.

KEYWORDS: Reinforced concrete, Prestressed concrete, Flexural capacity, Shear capacity, Bond characteristics of reinforcement, Numerical analysis

1. INTRODUCTION

Bond condition between reinforcement and adjoining concrete influences the ultimate failure mode and capacity of structures. It was reported by Kani [1] that with weaker bond higher load carrying capacities could be obtained for RC beams. He observed increased ultimate capacities of more than 31% for RC beams with weaker bond, compared to those with perfect bond. However, the discussion therein was mainly focused on the broader topic of shear mechanisms and change of bond was thus limited to the two cases of deformed and round bars. Ikeda and Uji [2] clarified that the failure mode of RC beams changed depending on the bond condition of steel bars and this shear mechanism could be made clear by a finite element analysis. However, it has hardly been investigated that the influence of various levels of bond condition has on shear mechanism of RC and PC beams. In this study, to clarify the effect of various levels of bond condition on shear mechanism of RC and PC beams, a series of RC and PC beams having various degrees of bond was tested. Furthermore, pullout tests of steel and prestressing bars changing their bond condition were also carried out.

All beams tested were simply supported and designed to fail in shear. Ten simple pullout specimens representing bond conditions that were maintained in beams, were also tested to measure the bond stress-slip characteristics of the above beams. The results of the pullout tests were then used to simulate the beams in a numerical analysis based on the finite element method (FEM).

2. EXPERIMENTAL PROGRAM

Four RC beams, three PC beams and ten pullout specimens were tested. Deformed steel bars (yield strength: 400MPa, modulus of elasticity 200GPa) were used for main reinforcements, while round bars with same characteristics as deformed bars were used for beam R3.

*1 Graduate School of Science and Engineering, Saitama University, Member of JCI
*2 Department of Civil and Env. Engineering, Saitama University, Member of JCI
*3 Graduate School of Science and Engineering, Saitama University

Different bond conditions were obtained in the span by changing the surface conditions of the main reinforcement. To prevent splitting failure in anchorage zones of specimens, sufficient stirrups were provided, while complete pulling out was prevented by having hooks at the ends of reinforcement. Details of the beams and the reinforcements are given in Table 1. Fig. 1 shows the details of test beams. In pullout specimens, concrete was well confined using transverse reinforcement of 6mm diameter to resist expected severe lateral stresses. Fig, 2 shows the details of the pullout specimens.

Table 1. Details of Beams

Type	Number	Main Reinforcement		Bond Condition	Prestressing Tendon	
		Qty.	Bond Modification Region		Type	Effective Prestress. Type & Value MPa
RC	R1	3 D19	----	Perfect Bond	----	----
	R2	3 D19	Between supports	Medium Bond	----	----
	R3	3 ϕ19	----	Small Bond	----	----
	R4	3 D19	Between supports	No Bond	----	----
PC	P1	2 D10	----	Perfect Bond	Deformed 13mm	Pre-tension / 746
	P2	2 D10	----	Medium Bond	Round 13mm	Pre-tension / 730
	P3	2 D10	----	No Bond	Unbond 13mm	Post-tension / 829

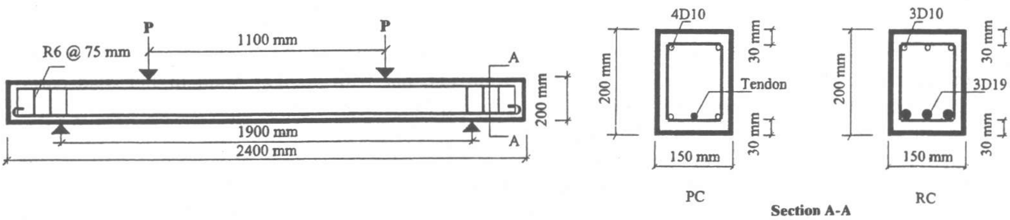


Fig. 1 Dimensions of Test Specimens

To change the bond condition of bars in beam R2, epoxy was coated on the surface of the bars two weeks before casting, to make sure it was well hardened to prevent proper bonding with concrete. Surfaces of the round bars in beam R3 were smoothened just before concreting. In beam R4, to achieve no bond condition of deformed bars, sheaths were provided on the loading span and then deformed bars were arranged. For pre-tensioned beams, a prestressing force of 100kN was introduced and this was released two weeks after casting. The same force of prestressing was applied to the post-tensioned beam one day before testing. Shear span to depth ratio of all beams was maintained at 2.4. Strain measurements were taken on the reinforcements and on the concrete at re-bar level and in the shear spans. Longitudinal displacement measurements were also taken at different heights at the mid section. The average compressive strength of concrete was 41MPa. Pullout specimen length was taken to represent the anchorage length of unbonded beam specimens. For pullout specimens, pullout load, strains along the length of the bar and the slip at the unloaded end were measured and specimens corresponding to each type of bond condition were tested on the same day as the beam was tested.

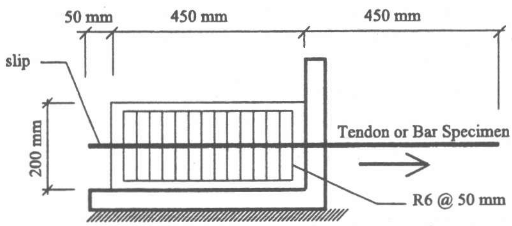


Fig. 2 Details of Specimens for Pullout Test

3. TEST RESULTS AND DISCUSSION

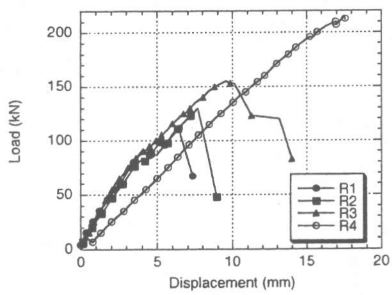
3.1 OBSERVATIONS

All RC beams failed in shear as expected. An increased load capacity of more than 90 % was observed for beam R4 compared to the control beam R1. For PC beams however, only pre-tensioned beams (P1 and P2) failed in shear, while post-tensioned beam (P3) failed in flexure. The test results are summarized in Table 2. Load displacement relationships are given in Fig, 3. Fig, 4 give the observed crack patterns.

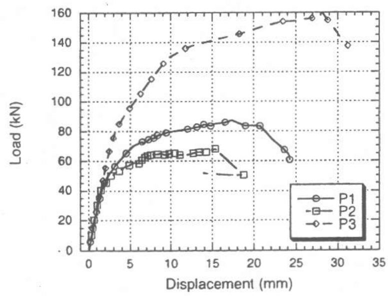
Table 2. Summary of Test Results

Beam	Failure Load (kN)	Increase of Failure Load	Load at diagonal shear Crack (kN)	Central Deflection / Maximum (mm)	Failure Mode
R1	111.3	-----	90	0.37	Shear
R2	130.0	16 %	75	0.44	Shear
R3	155.0	39 %	70	0.54	Shear
R4	215.0	93 %	190	1.00	Shear
P1	87.60	-----	75	0.62	Shear
P2	68.10	- 22 %	55	0.54	Shear
P3	159.8	82 %	-----	1.00	Flexure

For beam R1, flexural cracks appeared at a load of 45kN. On the other hand, cracking loads were 30kN, 20kN and 10kN for beams R2, R3 and R4 respectively. For R1 and R2, flexural cracks extended only up to the center of the section. Next two beams had flexural cracks well extended into the upper half of the sections. In R1, R2 and R3 shear cracks were developed out of existing flexural cracks. In R4, flexural cracks were observed only in the mid-span. Therefore, a delay in appearance of a noticeable diagonal crack was observed for R4 compared to R1.



A:- RC Specimens



B:- PC Specimens

Fig. 3 Load Displacement Relationships

For P1, first flexural cracks were observed at 65kN and this was reduced to 30kN in P2, and 20kN in P3. Load capacity of beam P2 did not increase compared to beam P1 although the bond condition in P2 was weaker. Beam P3 with no bond, however, achieved its full flexural capacity. Extension of flexural cracks into the compression region was observed in all three beams.

It was evident from the longitudinal displacement measurements made on concrete at different heights at the mid span section, that the strain distribution across the section was nonlinear for all beams, except for R1 and P1 where it was linear. Design of all these beams was based on the beam theory, and the above observation suggests a better design method, which could take the modified bond conditions into account, would have been more appropriate.

Bond stress and slip calculations were done according to Okamura and Maekawa [3] and Yankelevsky [4] and the stress-slip curves thus obtained from the pullout specimens are presented in Fig. 5.

3.2 DISCUSSION OF RC BEAMS

It could be noted from the test results that initiation and propagation of shear cracks were dependant on the degree of bond in each beam. A noticeable reduction of stiffness resulting from the no bond condition, was observed in R4 compared to the other beams (ref. Fig 3). Thus, among specimens R1 to R4, it was clear that R4 had a relatively larger central deflection compared to the other three beams (ref. Table 2). Flexural cracks for this beam therefore, were mainly concentrated near the mid span region during most part of the loading period. This contributed to delay the appearance of a diagonal crack. Enhanced shear capacity observed for beam R4 compared to R1 could be directly attributed to this reason. Beams R2 and R3 had cracks evenly distributed between the supports. Stress due to bond at any particular crack tip was not high because of this distribution. On the other hand, these stresses are comparatively low because of the poor bond conditions compared to R1. Hence, even though cracks appeared at lower loads, the propagation was delayed. Therefore, increments in shear strength were observed for these two beams. Although sudden increments in reinforcement strains were noticed with the opening of shear cracks, none of the four beams exhibited yielding of longitudinal reinforcement. Provision of reinforcement for the anchorage region was similar for all beams with hooks provided at the ends of main reinforcement for additional support. This prevented a complete pulling out of bars although extremely high strains were noticed in concrete in the anchorage region.

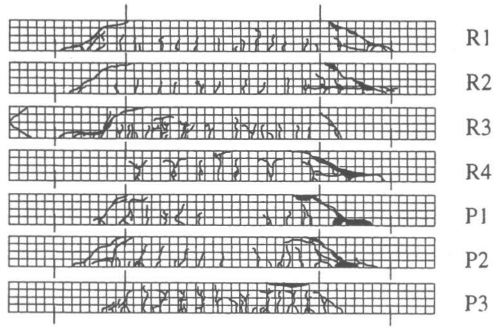
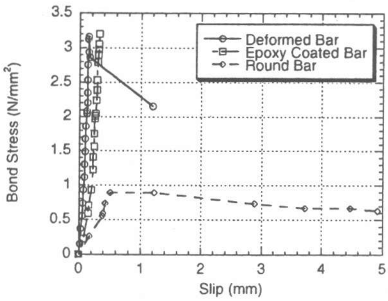
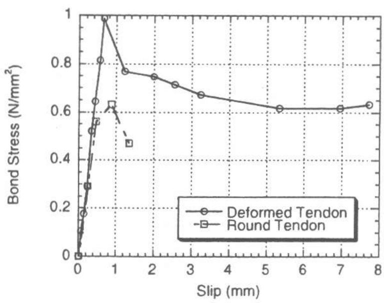


Fig.4 Crack Patterns



A:- RC Specimens



B:- PC Specimens

Fig. 5 Bond Stress-Slip Relationships (pullout test)

3.3 DISCUSSION OF PC BEAMS

The maximum strength of beam P2 that had round bars with small bond was lower than that of beam P1. With increase in loading, the weaker bond in P2 was destroyed at a lower load compared to P1, releasing the prestress. Strain measurements on the tendon showed that at higher loads even the bond in P1 to be non-existent. However, at loads in the range of 50kN to 70kN strain measurements were significantly different at locations along the tendon, proving the existence of bond. Shear cracking had therefore, probably already started within this load range. On subsequent loading, these cracks opened, thereby reducing the stiffness. For P3 however, cracking was delayed due to no bond condition, and therefore it achieved its full flexural capacity.

4. NUMERICAL ANALYSIS

4.1 MATERIAL MODELLING

A finite element analysis was performed to simulate the mechanical behavior of beams tested. Eight-noded reinforced concrete plate element model based on a smeared crack model, proposed by Okamura and Maekawa [3] was used to model reinforced concrete. Two-noded truss elements were used for longitudinal tension reinforcement as well as for prestressing tendons. A two-noded bond link element was used to model the bond between reinforcement and concrete.

Three types of failures depending on the given material properties are specified in the original model. Tension failure is defined as strain in the reinforcing bars reaching its ultimate strain of 3%. In compression, when the analytical compressive strain parallel to cracks reaches its ultimate value of 1% a compression failure is deemed to have occurred. Shear failure occurs when the shear strain along any crack plane reaches it maximum value of 2%. Reinforcement truss elements were modeled as elasto-plastic materials. Constitutive relationships for bond link element were the bond-slip relationships that were experimentally recorded under pullout testing.

4.2 RESULTS

Load displacement curves obtained both from the analysis and tests are given in Fig, 6. Results of the preliminary analysis based on perfect bond assumption are also included in the figure.

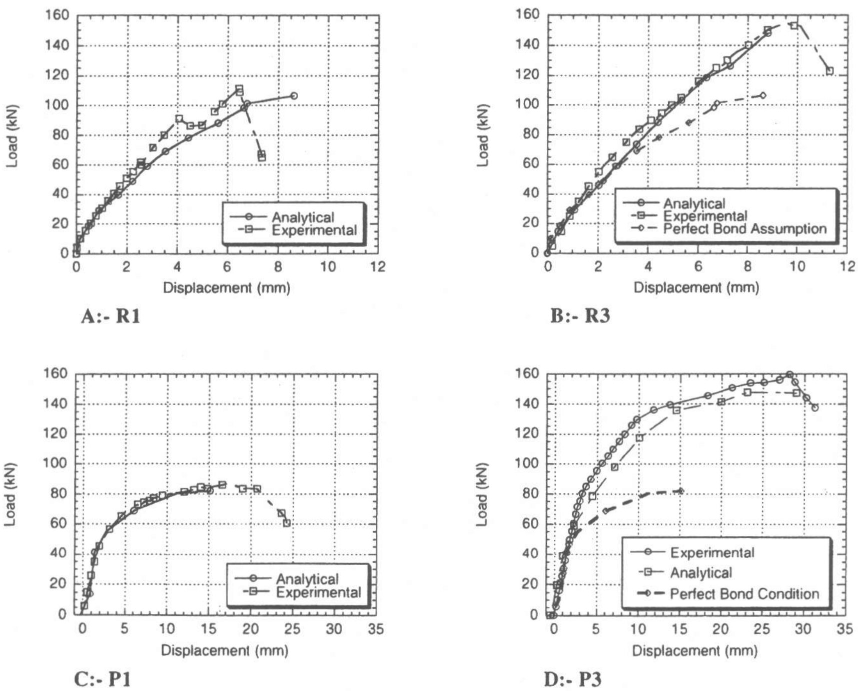


Fig. 6 Load Displacement Relationships for Analysis

Table 3 shows a comparison of ultimate capacities between the experiment and analysis. The difference between experimental values and analytical ones was noted to be within 10% for all beams. Failure modes predicted by the analysis agreed well with that of experimental results.

Table 3. Comparison of Ultimate Failure Load

Beam	Experimental Load (kN) / Mode	Analytical Load (kN) / Mode	Exp/Ana. Ratio
R1	111.3 / Shear	106.5 / Shear	1.05
R2	130.0 / Shear	124.6 / Shear	1.04
R3	155.0 / Shear	148.0 / Shear	1.05
R4	215.0 / Shear	216.6 / Shear	0.99
P1	87.6 / Shear	82.3 / Shear	1.06
P2	68.1 / Shear	65.1 / Shear	1.06
P3	159.8 / Flexural	147.7 / Shear	1.08

5. CONCLUSIONS

An experimental investigation was carried out to study the effect of bond on the shear behavior of RC and PC beams. Results obtained further established the fact that with weaker bond higher shear capacities could be obtained. Based on the experimental and analytical results, the following can be concluded. Further studies are underway to investigate the applicability of using controlled unbonding as a possible method of enhancing mechanical behavior of RC structures.

1. For RC beams, a significant improvement in shear strength could be obtained by weakening the bond. A reduction in stiffness and subsequent large flexural cracks were noted. Although a delay in appearance of shear crack was noticed for the beam with completely unbonded reinforcement, the amount of load carried between shear cracking and final failure did not show improvement compared to the other beams.
2. For PC beams, the gain of strength depended on the method of prestressing. In pre-tensioning, an increase in load capacity could not be obtained due to release of prestress resulting from bond failure.
3. A noticeable deviation from the beam theory was observed for beams with poor bonding. It suggests that refined design methods taking this phenomenon into consideration should have been more appropriate where unbonding needs to be implemented.
4. The finite element analysis was able to simulate the behavior of the present series of experiments with reasonable accuracy.

ACKNOWLEDGEMENTS

Authors' sincere gratitude is hereby expressed to all members of the structural materials laboratory of Saitama University for their innumerous assistance provided during the experiments. Dr. Bimal Adhikary and Dr. Wael Zatar of the same laboratory needs special mention for their invaluable suggestions given throughout the experiments

REFERENCES

1. Kani, G.N.J. "The Riddle of Shear Failure and Its Solution", Journal of ACI, April 1964, pp. 441-467
2. Ikeda, S. and Uji, K. "Studies on the Effect of Bond on the Shear Behavior of Reinforced Concrete Beams", Proceedings of JSCE, January 1980, pp. 101-109 (In Japanese)
3. Okamura, H. and Maekawa, K. "Nonlinear Analysis and Constitutive Models of Reinforced Concrete", Gihodo Press, Tokyo, 1991.
4. Yankelevsky, D.Z. "New Finite Element For Bond Slip Analysis", Journal of Structural Engineering, ASCE, Vol. 111, No. 7, July 1985, pp. 1533-154