Studies on the pull-out strength of ribbed bars in high-strength concrete

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ABSTRACT: The transfer of forces from reinforcing bars to surrounding concrete in reinforced concrete (RC) is influenced by many parameters. Several efforts were made to understand the influence of bond on global behaviour of RC members. However, the information on bond strength of high strength concrete (HSC) is lacking. An attempt was made to study the influence of various parameters on bond such as bar diameter, strength of concrete, lateral confinement and embedment length. The bond lengths were 50mm and 150mm with different bar diameters, strength of concrete and type of confinement. The bar diameters were 16mm and 20mm. The bars were embedded in concrete without confinement and with confinement using spirals and ties. The casting was done keeping the bars in the horizontal position. The anchorage bond specimens were tested using displacement control system and the slip of the bars was controlled at a rate of 1.51mm/minute (0.025mm/second). The bond stress-slip response was studied by varying the variables. As the strength of concrete increases the slip at failure decreases in the descending branch. With smaller bond length, the bond stress was found to be higher. The bond strength was found to decrease as the bar diameter increased. Splitting failure was observed in unconfined specimens, whereas pullout failure in confined specimens. The ultimate bond strength ranges between 10.8 MPa and 19 MPa with spiral confinement, whereas it ranges between 9.2 to 16 MPa with tied reinforcement. The ductility was found to increase with spiral reinforcement.

1 INTRODUCTION

Bond in reinforced concrete (RC) refers to the resistance of surrounding concrete against pulling out of reinforcing bars. Anchorage bond is developed parallel to the direction of force over a contact surface in order to induce stress in rebars at critical sections. The bond resisting mechanisms in RC members are understood well in normal strength concrete (NSC) after the numerous studies performed in the last thirty years. If the bond resistance is inadequate, slipping of reinforcing bar occurs destroying composite action. In RC members sudden loss of bond between rebars and concrete in anchorage zones causes brittle failure. However, the information on bond strength of high strength concrete (HSC) is scanty (FIB 2000).

Bond is necessary not only to ensure adequate level of safety allowing composite action of steel and concrete, but also to control structural behavior along with sufficient ductility. The bond in RC members depends on a number of factors such as reinforcing unit (bar or multi wire) and stress state in both reinforcing unit and surrounding concrete. Other parameters such as concrete cover, space between rebars, number of layers and bundled bars, casting direction and bar position play important role. Several research studies have been reported on the influence of deformation patterns and rib geometry on bond *(Rehm, 1961; Goto, 1971)*. For bars with rib face angles, bond behaviour is influenced by the rib face angle. However, when the rib face angle is less than 30 degrees, the bond behaviour is different. In bars with small rib spacing and small rib height the bond strength is reduced.

Mathey and Watstein (1961) reported that the bond strength decreases as the embedment length increases, and decreases as the bar diameter increases. *Hansen and Liepins (1962)* reported an increase in the bond strength under dynamic loading over static loading. Also progressive bond failure and large slip were expected from large repeated loading. *Ferguson and Thomson (1962)* reported on development length of rebars and effect of confinement. Bond stress varies as a function of development length rather than bar diameter. Ultimate bond stress varies as a function of $\sqrt{f_c'}$, with other factors being constant, since the bond strength is related to concrete tensile strength. The nature of bond failure and factors influencing splitting, importance of bar spacing and beam width, end anchorage, flexural bond and anchorage bond were reported by *Ferguson et al. (1966)*.

Lutz and Gergely (1967) studied the action of bond forces and the associated slip and cracking using rebars with different surface properties. The slip was found to be due primarily to the relative movement between concrete and steel along the surface of the ribs and also due to crushing of mortar. *Goto (1971)* studied the primary and secondary cracking by injecting ink around the deformed rebars in axially loaded tests. *Nilson (1972)* estimated the bond stress from the slope of the steel strain curve. The strain in concrete and steel was measured internally and the bond slip was calculated from the displacement functions obtained by numerical integration of strains. *Jiang et al. (1984)* developed new test method by cutting the reinforcing bars into two halves and placing in two opposite sides of the cross section to study the local slip, secondary cracking and strain distribution in concrete surrounding the interface. A simple one-dimensional analysis predicts the stresses in steel and concrete, local bond-slip, tensile stiffening and total elongation of the reinforcing bar. *Ueda et al. (1988)* studied the beam bar anchorage in exterior beam-column joints. A model has been proposed to predict the load-lead end deformation and anchorage length of rebars extended from beams into exterior columns and subjected to large inelastic loadings.

Effects of anchored bar diameter, confinement of joint and compressive strength of concrete on the hook behaviour in exterior beam-column joints have been studied (*Soroushian, 1988)*). An analytical model has been developed for predicting the overall pullout behaviour of rebars, which has been recognised by *ACI–318-83* for development of standard hooks in tension. *Soroushian and Choi (1989)* reported on local bond strength of deformed bars with different diameters in confined concrete. The bond strength decreases as the bar diameter increases. *Soroushian et al. (1991)* studied the influence of strength of concrete with different confinements. Confinement influences local bond of deformed bars. The ultimate bond strength increases as square root of concrete compressive strength.

Abrishami and Mitchell (1992) formulated a new testing technique to simulate uniform bond stress distribution along a rebar to determine bond stress-slip response. *Malvar (1992)* tested specimens with varying confining pressure using confining rings with rebar ribs normal and inclined to the surface and obtained consistent bond-slip response over a short embedded length. Mathematical model for bond-slip behaviour of a reinforcing steel bar embedded in concrete subjected to cyclic loading was reported by *Yankelevsky et al. (1992). Bortolotti (2003)* proposed models to predict the tensile strength of concrete from pullout load.

The confinement improved the bond strength slightly but ductility was improved significantly (*Harajli et al. 2004). Somyaji et al. (1981) and Jiang et al. (1984)* conducted several experimental and theoretical studies on bond in NSC. The secondary cracks as well as the distribution of strain in concrete in the vicinity of rebar have been studied. *Darwin et al. (1996)* reported development length criteria for conventional and high relative rib area of reinforcement. On the basis of a statistically based expression, the development length of reinforcement and splice strength in concrete for compressive strength varying between 17 and 110MPa with and without confinement have been investigated. The effects of cover, spacing, development/spliced reinforcement were incorporated in design equation.

The effects of concrete compressive strength, splice length and casting position on the bond strength of rebars have been studied (*Azizinamini et al. 1993; 1999a))*. Increasing the development length in HSC in tension does not seem to increase the bond strength of deformed rebars, when concrete cover is small. Concrete crushing occurred in front of the ribs in NSC, whereas there was no indication of concrete crushing in front of the ribs in HSC with the first few ribs being more active. In HSC with small cover, failure occurred due to splitting of concrete prior to achieving uniform load distribution *Azizinamini et al. (1993). Azizinamini et al. (1999b)* in another study reported that when calculating the development length in HSC for tension splice, a minimum number of stirrups should be provided over the splice region. Statically based on the experimental data an expression has been proposed to calculate the extra number of stirrups required.

Eligehausen et al. (1983) reported comprehensive study on the effect of bar diameter embedded in NSC. The maximum bond capacity decreases slightly with increasing bar diameter. The frictional bond resistance was not influenced by the bar diameter, lug spacing or relative rib area. *Larrard et al. (1993)* investigated the effect of bar diameter on bond strength. The bond strength increases with tensile strength of concrete at a higher rate with smaller bar diameters. A parameter which accounts for the ratios of side cover and bottom faces, and spacing of the spliced bars was introduced. CEB-FIB report *(2000)* presented a general description of the local bond law for tensile forces. Six main stages have been recognized in local bond stress-slip response.

Goto (1971) carried out tests to clarify the propagation of different types of cracks around the tensile reinforcing bars. The internal cracks develop around the reinforcing bars in concrete cylinders as shown in Figure 1. The inclination of internal cracks and the direction of compressive forces on the bar ribs vary between 45 and 80^0.

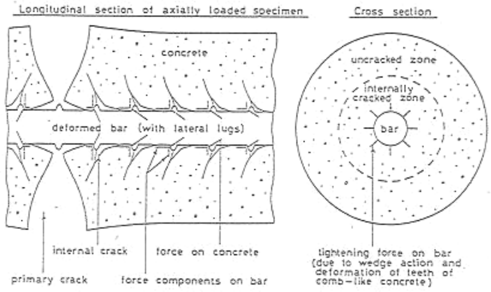

Figure 1. Internal cracks around the reinforcing bar embedded in concrete (Goto, 1971).

Tepfers (1973) showed the radial components of bond forces balanced against tensile rings in concrete in Figure 2, using a two dimensional finite element analysis (FEA). The angle "α" is 45 degrees along a perimeter touching the ribs of reinforcing bars independent of rib face angle.

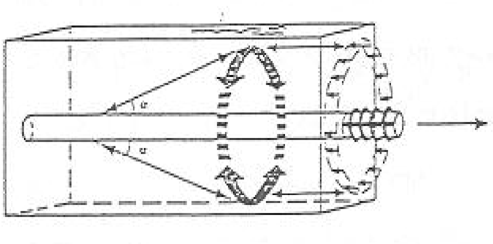

Figure 2. View of tensile ring (Tepfers, 1973).

Three mechanisms for bond resistance i.e. (i) chemical adhesion, (ii) friction, and (iii) mechanical interaction between concrete and deformed bars are responsible (*Lutz and Gergely, 1967)*. According to *Rehm (1961)***,** and *Lutz and Gergely (1967)*, slip of deformed bars occurs due to (i) splitting of concrete by wedging action, and (ii) crushing of concrete in front of the ribs. For the face angles between 40 and 105 degrees, the slip seems to be not influenced. However, the slip is mostly due to crushing of concrete in front of the ribs. This in effect produces a rib with face angles of 30 to 40 degrees *(Lutz and Gergely, 1967)*.

2 EXPERIMENTAL PROGRAMME

2.1 *Materials*

A 43 grade Portland Pozzolanic Cement (PPC) was used. Specific gravity of cement was 3.12. The fineness of cement was 5.6 %. The initial and final setting times were 124 and 300 minutes respectively. Fe 415 grade high strength deformed bars of diameters 16mm and 20mm as main reinforcement and 6mm mild steel (MS) bars for stirrup/spirals as confinement reinforcement were used. Concrete was made from normal weight black granite aggregate. Specific gravity of cement was 3.12. Specific gravity of coarse aggregate was 2.6. Specific gravity of fine aggregate was 2.6. Two concrete mixes were adopted. In 30 MPa concrete; weight of cement was 300 kg/m^3 and water-cement ratio was 0.45. The concrete mix proportions were 1: 2.30: 4.27: 0.45. In 60 MPa concrete; weight of cement was 400 kg/m^3 and water cement ratio was 0.35. Mix proportions were : 1: 1.64: 3.02: 0.35. Three standard cubes of size 150mmx150mmx150mm were used to determine the compressive strength of concrete.

2.2 *Test specimen*

Main bar was embedded in each cube with different confinements such as spirals, ties and without confinement. The test specimen was basically a concrete cube 150mmx150mmx150mm with a bar embedded coaxially (IS: 2770-1997). One end of the rebar was projected about 15mm to measure the free end slip, while the loaded end was jutted out about 750mm in order to grip the rebar for applying the tensile force. The specimens were cast using 16 and 20mm diameter rebars in two different concretes with different embedment lengths. By using PVC tubes the required embedment length was achieved. To achieve 50mm embedment length at the centre of the specimen, PVC tubes were used to unbond the bars from concrete over 100mm length. The PVC tube neither restrains the slip of the bar nor affects the transfer of bar forces to concrete. The slip was recorded at both loaded and unloaded ends of the bar. The bars were placed in the middle of the specimen horizontally.

2.3 *Test programme*

Tests were carried out on pullout specimen with four different parameters. In a set there were three specimens with different confinements. Only two specimens were tested without confinement. In this study, two concretes of strength 40 and 50MPa, embedment lengths of 150 and 50mm, bar diameters 16 and 20 mm and three confinements (spirals, ties and no confinement) were adopted. Typical reinforcements are shown in Figure 3

Figure 3. Confining reinforcement in pull-out specimens.

2.4 *Fabrication of test specimen*

Well seasoned wooden moulds were fabricated to cast 10 specimens in a single batch. Provisions were made at appropriate locations in the moulds to accommodate 3-16mm, 3-20mm and 4-25mm diameter bars. The bars were placed horizontally and concrete was poured vertically. The moulds had provision for fixing the reinforcement cage. Lubricating oil was applied on all sides of the moulds for easy removal of specimens. Concrete was poured carefully from the top and segregation was avoided. Needle vibrator was used to compact the concrete. After twenty four hours the specimens were demolded and cured up to 28 days till testing.

2.5 *Experimental set-up and testing*

The test setup for testing pullout specimens under controlled displacements is shown in Figure 4. A 250 kN capacity actuator was hung from an existing A frame which could transmit 2000kN load. The specimen was kept in a frame which hanged from the actuator. To avoid the influence of lateral strains by friction at the bearing plates Teflon sheets were placed between the specimen and base plate of the frame. A steel plate of size 150 x 150 x 12mm with a central opening of 100 x 100 x 12mm was placed below Teflon sheet to allow free failure of concrete due to pullout.

Figure 4. Experimental Test set-up.

The loaded surface was leveled off using gypsum (POP) and a steel plate was placed on top of POP over which an LVDT was fixed to record displacement at unloaded end of the bar. At loaded end two LVDTs were placed to monitor the end displacement. A locking arrangement by means of steel wedges was used. Load cell, which was placed above the wedge along with LVDTs and strain gauges were connected to the data logger which continuously recorded the respective readings at a frequency of 0.5Hz. Monotonic load was applied by means of the actuator and the rate of stroke control was maintained at 1.51mm/min (i.e.0.025mm/sec). The total displacement of 60mm in the actuator was set as the end value or complete pullout of the bar whichever occurred first to end the test. Three identical tests were carried out to have a minimal statistical basis.

3 RESULTS AND DISCUSSIONS

Forty pull-out specimens were tested for anchorage bond strength and its variation. The bond stress-slip curves were drawn from the experimentally monitored load vs. slip (at the free and loaded ends) data. The actual materials properties and various parameters obtained from the observations were used. The bond stress (τ) was calculated as the stress developed over an equivalent surface area using the formula

$$\tau = \frac{P}{\pi \, d_b \, l_b} \tag{1}$$

"Where" P = load (N), l_b = embedment length (mm), and d_b = diameter of the rebar (mm)

3.1 *Modes of failure*

The unconfined concrete at the end of rebar in tension offers the least bond resistance because of early formation of radial splitting cracks caused by high tensile hoop stresses. The failure was caused by the formation of a concrete cone from the concrete block due to bond forces acting on the concrete in front of rebar lugs. Better bond performance was observed with confining reinforcement. Splitting cracks in the plane between bars was developed, but its growth was resisted by the confinement. The bond failure was probably due to shear failure in concrete between the lugs.

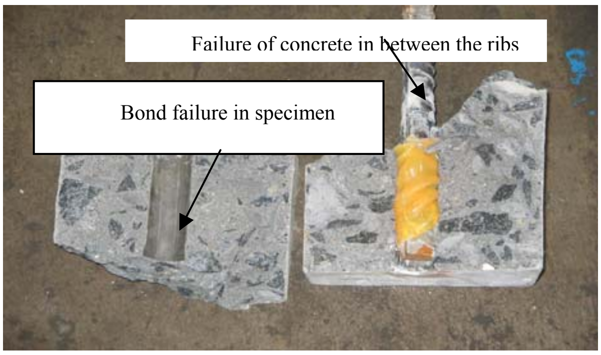

Figure 5. Splitting failure in unconfined specimen.

An ideal pull-out failure was occurred in all the tested specimens with confinement. However, splitting failure was encountered in the specimens without confinement. Wide longitudinal cracks were formed along the specimen surface. Eventually, the specimen was split into two halves in most of the test specimens as shown in Figure 5. In the tested specimens confined by ties or spirals the splitting cracks were effectively arrested by the confinement, due to which splitting failure was minimized or avoided altogether resulting only in pull-out of rebars from concrete as shown in Figure 6. This was clearly shown by the descending branch of the bond-slip curve which lost its bond stiffness gradually with load. The portion of concrete in between the ribs was sheared off in confined concrete specimens and the bar experienced with stresses much below the yield strength of rebar. The failure of concrete in between the ribs was clearly noticed by observing the tested specimens. The unconfined specimens failed due to splitting and the pulled out bar was intact showing that there was no crushing failure and the bar was pulled out from the concrete.

Figure 6. Pullout failure in confined concrete specimen.

3.2 *Bond strength*

The maximum bond strength of unconfined concrete ranged between 50 and 60 % of that with confinement. The bond stress at the stage of longitudinal splitting was about 8.0 to 11.8 MPa in both 40MPa and 50MPa concretes. After attaining the peak value, a sudden drop in the load was observed. The descending branch did not reveal any resistance due to friction. The maximum bond stress in tested specimens with 16mm diameter bars with different confinements was observed when the slip was between 0.3 and 1.5mm. The slope of the ascending branch of bond stress-slip curve decreased gradually. It was relatively steeper than those with 20mm diameter rebars. A horizontal plateau was observed at a maximum bond stress, τ_{max} at a slip of around 0.3mm and the slip increased further at the same shear stress up to about 1.5 to 4.0mm. Subsequently the bond resistance dropped to τ_f called frictional bond resistance at a slip of about 10mm and then was remained constant thereafter up to failure. Coincidentally this value was equal to the clear spacing between the ribs in the bars. The slip continued to increase when the bond stress reached a constant value in the post-peak region of the bond stress-slip curve.

3.3 *Bond stress-slip response*

Slip is defined as the relative displacement of rebar with reference to the surrounding concrete. The relative displacement of the bar is always measured with reference to the undisturbed concrete and consists of relative slip at the interface and shear deformations in concrete. Therefore, displacement occurred due to localized strains in the interface even if there was no slip. Figure 7 shows a typical bond stress-slip response with 16mm bars at 150mm embedment length in 40 MPa concrete.

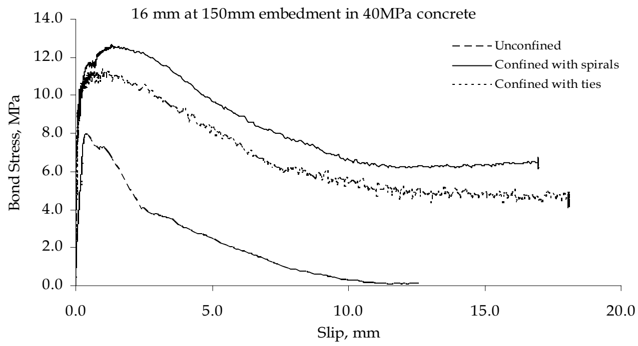

Figure 7. Bond stress vs. Slip with 16mm bars at 150mm embedment in 40 MPa concrete.

3.4 *Effect of various parameters*

The bond strength did not change much with diameter of bars. However, the resistance increased slightly with increase in bar diameter in certain cases. The variation in rebar diameter did not influence much the extent of the plateau. The post peak behaviour was better when large bar diameter was used. The maximum bond stress (τ_{max}) was relatively higher at small embedment length, at 50 mm and it was achieved at a slip varying between 0.3 and 1.5mm. There was no significant change of the slope of the ascending branch as well as the maximum bond stress plateau. But for specimen with 50mm embedment length, the descending branch was more ductile compared to that with 150mm embedment length. As the surface area of embedment increased, the maximum bond stress decreased. It shows, however, that there exists a size effect on bond strength of rebars. It has been proved that a splitting failure can be delayed or avoided altogether by providing confining reinforcement. Though the effects of the confining reinforcement (be it spiral or ties) was rather limited, however by providing spirals the bond strength was slightly increased. Usually, it is assumed that once a pull-out failure is initiated, providing a large concrete cover or a sufficiently strong restraining (confining) reinforcement, the value of τ_{max} can not be increased further. The extent of the post-peak curve was significantly increased by spirals showing increase of ductility with spiral reinforcement.

4. CONCLUSIONS

From the present study, the following conclusions can be drawn;

1. The maximum bond stress τ_{max} for unconfined specimens was about 50 to 60% of that of those confined with spirals.
2. The lateral confinement increased the bond strength significantly and the extension of the post-peak curve increased showing improved ductility.
3. The maximum bond stress τ_{max} for specimens confined with spirals was higher and showed significant improved ductility.
4. The influence of bar diameter on the local bond stress-slip relationship was rather small in the tested range (d_b = 16mm and 20mm).
5. The bond strength also decreased as the embedment length increased. The bond stress varies along the larger embedment lengths while it is more or less uniform in smaller lengths.

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