Effect of Rebar Cover and Development Length on Bond and Slip in High Strength Concrete

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Abstract

Composite behavior of reinforced concrete requires adequate bond between concrete and steel reinforcement that can transfer stresses between them. The bond strength is influenced by cover to the reinforcement and development length. Experimental investigation was carried out and twisted steel bars conforming to BS 4461 were used in high strength concrete to study bond strength characteristics. The post peak bond behavior was studied by using displacement controlled universal testing machine. The results of this experimentation confirmed that by increasing the cover/bar diameter ratio, bond strength increased and slip decreased for both small and large diameter twisted steel bars. This increased confinement reduced the uneven bond stress distribution along the development length. Stress concentration on the front key (concrete between two ribs) was reduced due to its continuity along the twisted steel bar. Hence it offered maximum possible resistance to bond failure and the bond strength increased. Similarly by increasing the development length, bond strength and corresponding slip both increased. Another fact visible from all figures and observed in all samples, is that as the first concrete key failed there was a sudden drop in bond strength due to the formation of longitudinal splitting cracks. These cracks are visible from the surface of the cylinder. Once a key is failed, failure propagated immediately.

Keywords: Concrete key; skewed action; interfacial transition zone; fracture process zone; embedment length

1. Introduction

High strength concrete is a suitable material for the construction industry of the developed world due to its high strength and durability. Optimized packing density, highly reduced water cement ratio and use of superplasticisers are responsible for high strength and durability of this material. It is a suitable choice for challenging locations like off shore construction, saline soils or parts of hydraulic structures. Similarly the bond between concrete and embedded reinforcing steel is essential for composite action in reinforced concrete construction [1,2].

This is only possible if there exists adequate bond between steel reinforcing bar and concrete that can transfer the stress among them. In high strength concrete the boundary between steel and concrete is highly improved. At interfacial transition zone "ITZ" pozzolanic effect reduces the concentration of $Ca(OH)_2$ crystals and secondary silicate hydrates are formed [3,4,5]. This phenomenon is responsible for very dense structure of concrete along the reinforcement due to which frictional component of bond strength "U" is significantly improved. The composite action of reinforced concrete is produced by the bond stress at this interface of the two materials [6]. This bond behavior is decisively determined by the behavior of concrete close to the rib [7]. Increasing the concrete compressive strength can improve bond performance. In other words, higher adhesion and friction force between concrete and rebar can be expected for concrete with higher compressive strength [8]. The bearing resistance of concrete keys is also increased due to high strength of concrete [9]. Ultimately bond strength is increased and embedment length can be decreased as compared to normal strength concrete. Nowadays research is going on to determine and improve different properties of high strength concrete. During the twisting operation to manufacture cold twisted bars, pattern of ribs are disturbed and well defined concrete keys that form in hot rolled deformed steel bars are not present in twisted steel bar. Instead there is a continuous concrete key that spirals around the steel as shown in Figure 1. Locally a skewed key can be considered for bond action. Stress concentration on the front keys is reduced. High strength concrete is more brittle as compared to normal strength concrete as cracking starts at almost 70% of ultimate load [10]. Since twisted steel bar is also used in high strength concrete, there was a need to determine its bond behavior with a particular emphasis on post peak

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behavior. Cover to the reinforcement and development/embedment length are important parameters that affect the bond strength and slip to a major extent. The simplest model representing the stress transfer between steel and concrete is so called "friction concept" whereby the shear stress that develops along the lateral surface(bond stress) is a function of normal confining pressure exerted by the surrounding concrete on the bar surface and concrete cover[11]. Therefore cover is an important parameter of force transfer between steel and concrete because the bond force spreads from steel rib to the outer side [7]. In high strength concrete using conventional steel with ordinary profile and ordinary concrete cover may cause premature longitudinal crack formation [12]. In order to study the bond behavior extensive experimental investigation was carried out using pull out samples. Data acquisition system was used with linear displacement transducers (LDTs) to determine the slip "δ" between steel reinforcement and concrete. Displacement controlled universal testing machine was used to study the highly precise post peak bond behavior. The data was recorded after every 50 millisecond. A specially designed assembly was used to grip the pull out samples. This assembly had a hinge at the bottom to eliminate any occasional eccentricity of steel reinforcement during casting of samples. In order to study the effect of confinement, c/d_b ratio was varied from 1.47 to 2.13 for 19mm twisted steel bar and 2.38 to 3.35 for 13 mm bar. The results showed that by increasing the confinement, bond strength increased and corresponding slip reduced for both 13mm and 19mm diameter bars as shown in Figures10 to 15. This extent of increase was more pronounced incase of 13mm bar where it increased by 130% as shown in Figure 12. However the extent of increase was small i.e 30% for 19mm bar as shown in Figure 15. For 13mm bar and 19mm bar slip reduced by 50%. By increasing the embedment length from $3.5d_b$ to $4.5\ d_b$ bond strength increased by about 90% as shown in Figure 18. This is true for short embedment lengths where bond stress distribution is almost even and stress concentration at front key is significantly reduced. As the length of the specimen decreases the bond stress becomes more uniform [13]. Higher the confining pressure higher the frictional force required for pull out and higher the strength reserves of splitting failure [11]. Another fact visible from all the figures and observed in almost all samples, was that as the first concrete key failed there was a sudden drop in bond strength due to the formation of longitudinal splitting cracks even visible from the surface of the cylinder. Therefore if there is adequate confinement available, the tension stiffening effect reduces the sudden drop in bond strength as it is visible in all the figures.

2. Fracture Mechanics Approach

It has been pointed out earlier that bond strength increases by increasing the embedment length and the relationship is nonlinear for normal strength concrete. This may be due to strain softening and stress redistribution in concrete adjoining the reinforcing steel bar. The fracture process zone in front of primary and longitudinal splitting cracks would be large and zone of perfect plasticity would be small which is a typical quasi brittle material behavior. During the stress redistribution, energy is consumed in this zone of perfect plasticity. As a crack initiates the flux of energy is released into it where it is dissipated in the form of surface energy [14]. However in high strength concrete the fracture process zone in front of primary and longitudinal splitting cracks would be small as shown in Figure 2. According to David and Broek this behavior of all high strength materials can be described by linear elastic fracture mechanics. In high strength concrete stored strain energy is quite large and very little softening occurs therefore whole energy is used in immediate crack propagation in highly abrupt manner.

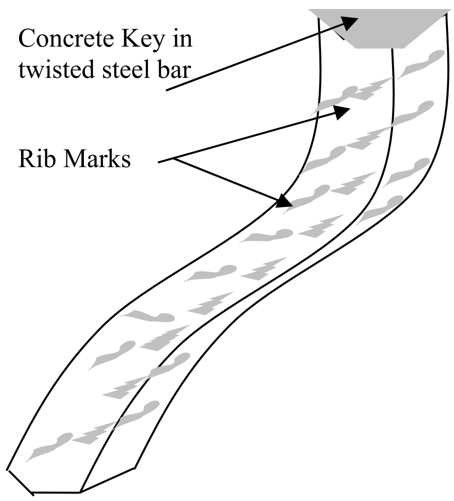

Figure 1: Concrete Key in twisted steel bar [2]

Therefore bond stress and slip relationship exhibited by high strength concrete samples showed an initial stiff linear response and then failure was quite sudden due to the formation of longitudinal splitting cracks. The failure mechanism was splitting and in some cases it was pull out. Cracks in high strength concrete initiate at much higher load level, typically 70 to 80% of the ultimate load. Same behavior was observed in high strength concrete pull out sample where the interface debonding cracks and longitudinal splitting cracks initiated at much higher bond stress. This resulted in accumulation of strain energy in the material. Once a crack was formed at the interface due to slip between steel and concrete, all the accumulated strain energy was poured in for the propagation of the crack. As this energy was much more than the fracture energy required to create new surface, the crack propagated in unstable manner and led to longitudinal splitting crack resulting the failure of the sample. That is why stress redistribution and strain softening do not occur in high strength concrete [14]. The transferable tensile strength decreases essentially faster with increasing crack width by using high strength concrete compared with normal strength concrete [7].

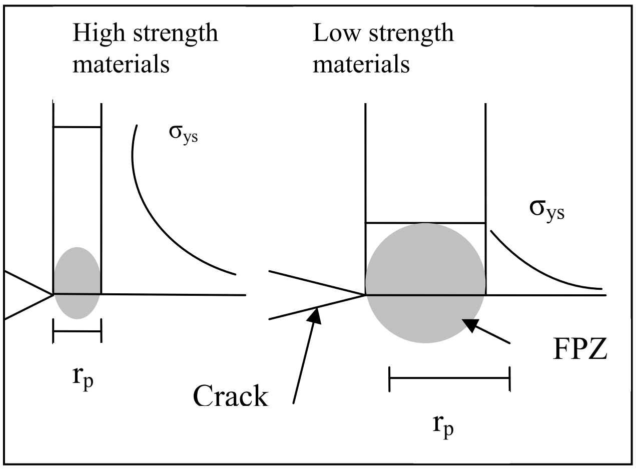

Figure 2: Fracture process zone in HSC and NSC [15]

3. Types of bond failure

There are two main types of bond failures; pull out and splitting failure. Pull out failure is likely to occur when the concrete in between the reinforcing steel bar ribs (concrete key) is weak and surrounding concrete is strong. This key will be heavily stressed due to relatively high rib height a/d >0.1, small rib spacing a/c > 0.5 and high rib angle (greater than 70^o) [16]. In case of splitting type of failure large compressive stresses occur on the contact point in front of the rib. These stresses are inclined from outwards towards the rib and the rib exerts equal and opposite stresses. The component of these stresses perpendicular to the bars exerts internal pressure on the surrounding concrete developing hoop tensile stresses [17]. There can be two further types of splitting failure. In first type rib angle varies between 40^o to 70^o. Because of the height of the rib and rib surface, which is relatively small, the stress exceeds the concrete compressive strength directly in front of the rib. Concrete is plasticized so deformation in this area supplies largest proportion of the slip [7]. Crushed concrete forms a wedge on which concrete key slips outwards as shown in Figure 3 its circumference increases, generating radial tensile stresses and longitudinal splitting cracks. In all cases this wedging action of deformed bar on the surrounding concrete cause splitting that leads to bond failure [18]. Local crushing dominates when the confinement provided by either surrounding concrete or transverse reinforcement is large and rib height is small. This mechanism of bond failure tends to be ductile [16].

Figure 3: Wedges due to crushing of concrete

In the second type of splitting failure, rib angle is so small, even less than 40^o, that concrete key slips without crushing and longitudinal splitting cracks are formed under the action of radial component of bond stress. This type of failure is more brittle as compared to the first type of splitting failure and is undesirable [13,2].

4. Subjected development length

In case of high strength concrete, concrete key is sufficiently strong and has high bearing resistance against bar ribs, increasing the bond strength of concrete. Hence required development length can be reduced as compared to normal strength concrete. As the embedment length of the specimen decreases the bond strength becomes more uniform [13]. Earlier researchers like Harajli [9] carried out experimentation using 5d_b as the development length. Nygun Viet Tue [7] used 2.5 to 3 d_b as the development length. The authors conducted experimentation using 3.5d_b and 4.5 d_b as the development length for high strength concretes using 13 mm and 19 mm diameter cold twisted steel reinforcing bars.

5. Subjected cover to the bar

Cover to reinforcing bars is another very important parameter affecting the bond behavior. The bond force spreads from the steel rib to outside cover [7]. In high strength concrete using conventional steel with ordinary profile and ordinary cover, may cause premature longitudinal cracks [9]. The effect of cover is studied by changing the c/d_b ratio. This objective was achieved by inserting the cold twisted steel bar in three different types of cylinders. These were

75mmØ 150mm high, 100 mm Ø 200mm high and 150mmØ and 300 mm high concrete cylinders. The effect of cover was kept same all around the steel bars. Resulting c/d_b ratios were 1.47, 2.13, 2.38 and 3.35. By increasing the c/d_b, confinement to the steel is increased and unevenness in bond stress distribution along the embedment length is reduced [2]. This results in increased bond strength. This was confirmed by the experimentation and results in Figures 10 and 15 clearly show this behavior for cold twisted steel reinforcement.

6. Experimentation

High strength concrete was used for the study. The compressive strength, maximum strain, peak strain and energy absorbed by the concrete was determined at 7 and 28 days with displacement controlled universal testing machine. Cold twisted steel bars conforming to BS 4476 having diameters from 13mm to 19 mm and yield strength of 609 MPa were used in pull-out samples consisting of 75mmØ 150mm high, 100 mm Ø 200mm high and 150mmØ and 300 mm high concrete cylinders. High strength concrete was used to prepare pullout sample.

The cylinders were used to keep the cover constant on every side of bar. PVC pipes were used to debond the steel from concrete in order to achieve the desired embedment lengths as shown in Figure 4. Immediately after pouring, the moulds were covered with polyethene sheets and tightly tied with thread to stop the loss of water due to evaporation as shown in Figure 5.

After 24 hours, demoulding was carried out and all the specimens were placed in curing tank to make sure that projecting bars should not be submerged. The samples for compressive strength were tested at 7 and 28 days as shown in Figure 7 and pull-out test were performed at the age of 28 days. Tables 1 and 2 show the concrete and steel bar properties. Scheme for pullout samples to study the variation in cover and embedment length is shown in Tables 3, 4 and 5. The measured compressive strengths, strains and energy absorbed by the concrete are shown in Figure 6 and Table 1.

Figure 4: Steel bars for pullout test

7. Testing Pullout samples

Samples were tested in a pullout assembly specially designed for the said purpose. It had a hinge on one side to eliminate the effect of eccentricity developed during fixing of sample in the machine. Pull out bar was gripped from one side of the machine and hinged bar of the assembly was on the other side. The load was applied through 1000kN displacement controlled UTM. Data acquisition system of UTM and a separate data acquisition system with high precision linear displacement transducers were used to measure slip between steel bar and concrete as shown in Figure 8. Slips measured from both sources were same.

Figure 5: Samples immediately after casting

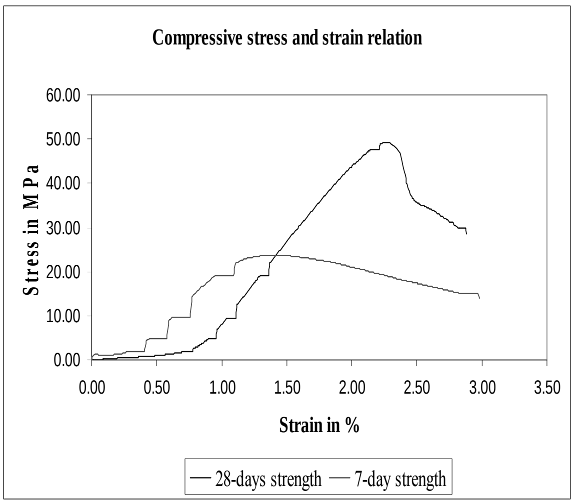

Figure 6: Compressive strengths of concrete

Figure 7: Compression test in UTM

Figure 8 shows the testing of pullout sample in strain controlled UTM to determine post peak concrete behaviour with particular reference to softening.

8. Test results and discussion

In this experimentation, pull out samples were tested and whole post peak behaviour of high strength concrete using twisted steel bars was analyzed. Strain rate was kept at 4mm/minute**.**The cover to steel bar represented by the parameter (c/d_b) is a significant factor influencing bond stress and slip relationship. Confining action of surrounding concrete increases by increasing the c/d_b. Authors studied this variation by changing c/d_b from 1.47 to 2.13 for 19mm and 2.38 to 3.35 for 13mm cold twisted steel bar. The results are shown in Figure 10, to 15. Comparing the trends it is clearly evident that by increasing the c/d_b ratio from 2.13 to 3.35 for 13mm twisted steel bar, bond strength increased and corresponding slip reduced. Similarly by increasing the confinement in terms of c/d_b from 1.47 to 2.13 for 19mm bar bond strength increased and corresponding slip decreased.

Figure 8: Pull out test in UTM

Figure 9: Longitudinal splitting cracks

Mathematical relationship and co-efficient of correlation for pre-peak behavior are obtained from the results using least square method of curve fittings for the representative samples as shown here.

$$U = 0.0819\delta^2 + 0.119\delta + 0.145$$

Correlation co-efficient $R^2 = 0.999$, $c/d_b = 1.47$

$$U = 0.1549\delta^2 + 0.4434\delta + 0.1567$$

Correlation co-efficient $R^2 = 0.9979$, $c/db = 2.13$

$$U = 0.2748\delta^2 - 0.6471\delta + 0.7829$$

Correlation co-efficient $R^2 = 0.9851$, $c/d_b = 2.38$

$$U = 0.4467\delta^2 + 2.0666\delta - 1.0442$$

Correlation co-efficient $R^2 = 0.9993$, $c/d_b = 3.38$

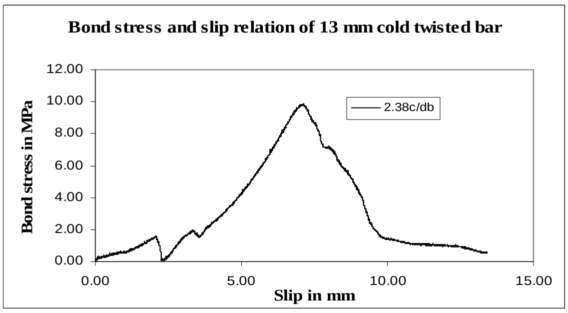

Figure 10: Bond behavior with c/d_b=2.38

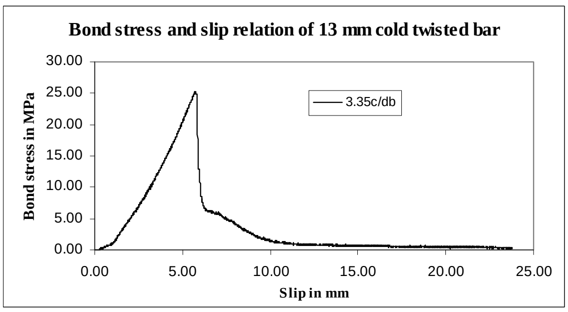

Figure 11: Bond behavior with c/d_b=3.35

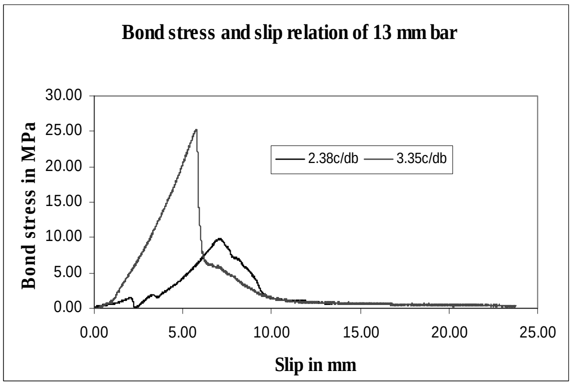

Figure 12: Comparison of cover variation

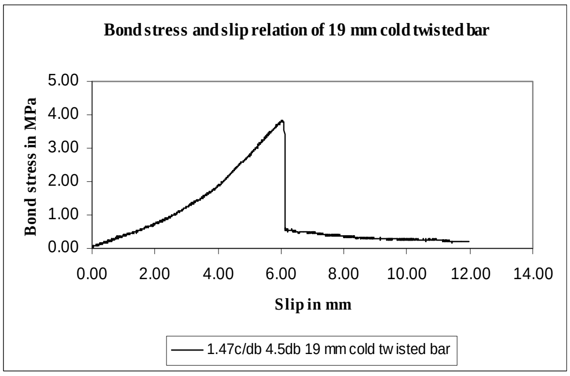

Figure 13: Bond behavior with c/d_b=1.47

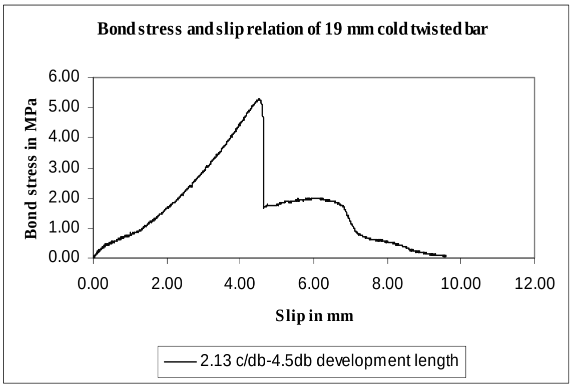

Figure 14: Bond behavior with c/d_b=2.13

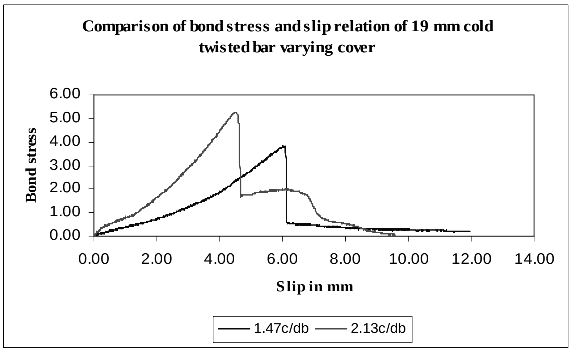

Figure 15: Comparison of cover variation

Table 1: Properties of concrete

S.No	Concrete type	Age days	Specimen type mm	Energy Joules	Max strain	Break strain	Strength MPa
1	HSC	7	100x100x100	469.25	1.390	2.984	23.74
2	HSC	28	100x100x100	631.66	2.272	2.884	49.34

Table 2: Properties of steel bar used

S.No	Diameter mm	Mass/unit length Kg/m	Actual mass/kg Kg/m	Actual Area mm^2	Deviation of mass %	Ultimate tensile strength MPa
1	13.0	1.25	1.39	113.1	10.0	605
2	13.0	1.25	1.40	113.1	11.4	605
3	19.0	3.17	2.91	201.1	09.1	609
4	19.0	3.00	2.70	201.1	11.1	609
5	19.0	3.11	2.90	201.1	08.1	609

The observed effect of cover and confinement may be due to the reason that concrete surrounding the skewed concrete keys was strong and exerted high confining pressure on these keys. Since embedment length was kept constant, the number of keys that resisted the slip were same. The increased confinement reduced the uneven stress distribution along the embedment length. Stress concentration on the front skewed key was reduced. Therefore confinement offered maximum possible resistance to bond failure and bond strength increased and slip was decreased. Once one key is failed, failure propagated immediately. However, increased confinement offered a little resistance due to tension stiffening effect. Failure was close to pull out when c/d_b ratio was higher and close to splitting when c/d_b ratio was less. The effect of cover plate on confinement is not significant in case of high strength concrete. Embedment length was another factor studied during the experimentation keeping the

Table 3: Properties of pullout sample.

S.No	Bar No	Diameter d_b		**75mmØ 150mm High (3"Ø 6") Cylinder** High strength concrete		
		mm	inch	Cover "c" mm	c/d_b	Development length mm
1	4	13	½	31.0	2.38	$4.5d_b = 58.5$
2	6	19	¾	28.0	1.47	$4.5d_b = 85.5$

Table 4: Properties of pullout sample.

S.No	Bar No	Diameter d_b		**100mmØ 200mm High (4"Ø 8") Cylinder** High strength concrete		
		mm	inch	Cover "c" mm	c/d_b	Development length mm
1	4	13	½	43.5	3.35	$4.5d_b = 58.5$
3	6	19	¾	40.5	2.13	$3.5d_b = 66.5$
4	6	19	¾	40.5	2.13	$4.0d_b = 78.0$
5	6	19	¾	40.5	2.13	$4.5d_b = 85.5$

Table 5: Properties of pullout sample.

S.No	Bar No	Diameter d_b		**150mmØ 300mm High (6"Ø 12") Cylinder** High strength concrete		
		mm	inch	Cover "c " mm	c/d_b	Development length mm
1	4	13	½	68.5	5.27	$4.5d_b = 58.5$
2	6	19	¾	65.5	3.45	$3.5d_b = 66.5$

c/d_b ratio constant. Confining action was same; however the development length was variable. Therefore number of concrete keys taking part in resisting the slippage were more. Ten pull out samples were tested by varying the embedment length from $3.5d_b$ to $4.5d_b$. Comparing the trends of Figures 16 to 18 it is evident that by increasing the development length bond strength and corresponding slip both increased. This is due to the fact that bond stress distribution remains almost uniform. However more concrete keys resist the slip and bond strength is increased. Moreover cumulative slip of all the concrete keys increased the total slip. Mathematical relationship for pre-peak behavior were obtained from the results using least square method of curve fittings for the representative sample of the experimentation and are given.

$$U = 0.1638\delta^2 + 0.4119\delta + 0.1731$$

Correlation co-efficient R^2=0.999 for $4.5d_b$ development length

$$U = 0.1233\delta^2 + 0.983\delta + 0.1502$$

Correlation co-efficient R^2=0.9993 for $3.5d_b$ development length

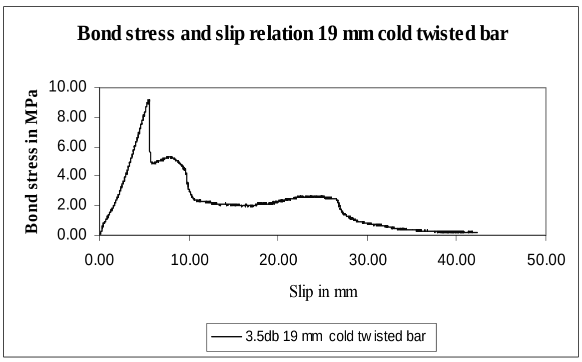

Figure 16: Bond stress with $3.5d_b$

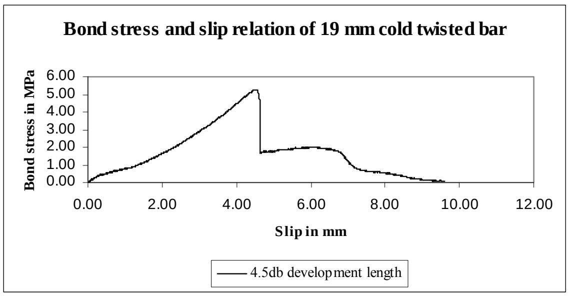

Figure 17: Bond stress with $4.5d_b$

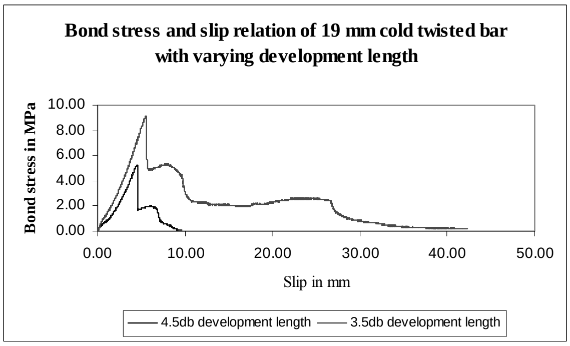

Figure 18: Comparison of $3.5d_b$ and $4.5d_b$

9. Conclusions

1. The results showed that by increasing c/d_b ratio, confinement increases, bond strength increases and slip decreases. However the extent of increase is pronounced in case of 13 mm bars as compared to 19mm bars. This is attributed to increased confinement that offers more resistance to longitudinal splitting cracks and reduces the uneven bond stress distribution along the embedment lengths.

2. In cold twisted steel bars there is a continuous concrete key due to spirals around the steel bar. However locally skewed keys can be considered for the analysis.

3. The results have shown that by increasing the embedment length, bond strength and corresponding slip both increases. This is due to the fact that there are more keys that resist the bond failure and cumulative slip of all keys is increased as shown in Figure 18.

4. Another very important observation is regarding the abrupt failure of samples in a highly brittle manner. When first key fails in a brittle manner for high strength concrete, formation of longitudinal splitting cracks occurs simultaneously bond strength reduces drastically. This may be explained on the basis of fracture mechanics. According to energy criterion of fracture mechanics, strain energy keep on accumulating in the material as micro cracking starts at about 70-80 % of the ultimate. As soon as a primary crack forms along the boundary between steel and concrete, it immediately leads to crack propagation utilizing accumulated energy. Formation of longitudinal splitting cracks occurs rapidly causing the bond failure in highly abrupt and brittle manner.

5. Post peak tension stiffening effect is a function of concrete confinement only. When it is kept constant by keeping same c/d_b ratio then post peak behavior remained the same as can be seen in Figure 18.

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