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Effect of fusion bonded epoxy coating and rib geometry on cracking of reinforced concrete

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ABSTRACT: Corrosion of reinforcement in reinforced concrete is a major problem in reinforced concrete structures as it affects the overall safety and serviceability of the structures. Fusion bonded epoxy coating (FBEC) on steel bars is an effective method used for combating corrosion in reinforced concrete. However, coating of bars reduces the bond strength between bars and concrete. The crack width and crack spacing are significantly increased with epoxy coating of bars. The degree of cracking depends on various parameters such as rib geometry, coating thickness and confinement provided to the bars. As fusion bonded epoxy coated bars (FBECB) are used widely in structures such as water tanks, nuclear power plant structures and bridges, prediction and controlling of cracking is important. The main objective of the present study is to theoretically predict the effect of epoxy coating of bars on the crack width and spacing of cracks in reinforced concrete structures. The only reliable data that can be obtained from the pullout test is the pullout force. The crack width and crack spacing depend on the transfer load and transfer length required at the interface. The crack width can be predicted theoretically by knowing the transfer load and transfer length at the interface instead of using the bond stress–slip law at the interface. Experimental data generated is analyzed and the influence of coating thickness and rib geometry on the cracking behavior of epoxy coated reinforced concrete is reported. When thick coating of epoxy is applied to the bars with diamond ribs, the crack width and spacing of cracks has been observed to be high when compared to plain or inclined rib patterns.

1 INTRODUCTION

Corrosion of reinforcement is a major problem in reinforced concrete structures, which affects the overall safety and serviceability of the structures. Fusion bonded epoxy coating (FBEC) on steel bars is one of the effective methods used for combating corrosion in reinforced concrete. However, coating of the bars reduces the bond strength between bars and concrete. This influences the force transfer at the interface and on the cracking of reinforced concrete structures. Width and spacing of cracks is significantly increased when such bars used in RC elements. The degree of cracking depends on various parameters such as rib geometry, coating thickness and confinement provided to the bars. The increase in crack widths reported in literature varies widely as various uncertainties underlie the measurement of crack width in experimental investigation. As FBECB are used widely in structures such as water tanks, nuclear power plant structures and bridges predicting and controlling of crack width is important.

Crack width and crack spacing can be predicted theoretically if the bond stress variation is known. The bond stress at the interface is most commonly assumed to be uniform and the interface is modelled using appropriate bond stress vs. slip relationship. Many empirical formulations based on pullout tests are available to date to define the relationship. However, almost all the formulations are based on the slip measured experimentally and assumes constant bond stress over the embedment length. The reliability of slip measured from the experiments is questionable due to the bond stress is not being constant along the embedment length. The only reliable data that can be obtained from the pullout test is the pullout force. Crack width and crack spacing depend on the transfer load and transfer length required at the interface. The ultimate pullout force is a function of many parameters such as bar rib geometry, thickness of epoxy coating and confinement provided. The reported experimental data is analyzed and the influence of rib geometry on the cracking of epoxy coated reinforced concrete is reported.

2 BOND STRENGTH OF FFBEC BARS

Fusion bonded Epoxy coated bars are being used since 1970. The pioneering work on prediction of the effect of coating on the bond strength of coated bars was reported by Mathey & Clifton (1976). In this study, on the bond strength of epoxy coated bars, the effect of coating thickness was investigated using pullout tests. For bars with epoxy coating thickness between 25 to 280 μm, the bond strength was found to be about 6% lower than that of the uncoated bars. However, for bars with a coating thickness of 635 μm, the ultimate bond strength was found to vary between 34 and 60% of the strength of uncoated bars. Swamy & Koyama (1989) has studied the bendability, corrosion resistance and bond strength of epoxy coated bars using pullout tests. This study also reports on the effect of rib pattern on the bond strength of epoxy coated bars. Bars with lugs perpendicular to the axis of the bar had about 95% strength of the uncoated bars. The least bond strength of about 69% was reported for reinforcement with diamond pattern. For reinforcement with ribs inclined to the axis of the bar, the bond strength reduction was about 15%.

Treece & Jirsa (1989) reported that the epoxy coated bars with an average thickness of about 0.13 mm with diamond rib pattern developed 67% of the bond strength of the uncoated bars. Deveries et al. (1989) reported that epoxy coated bars developed 84 percent of the bond strength of the uncoated bars. Choi et al. (1991) reported that the ratio of the bond strength (of splices) of epoxy coated bars to that of uncoated bars ranged between 0.54 and 0.94 with an average value of 0.83. Cairns & Abdullah (1991) concluded that the friction between concrete and epoxy coating is less than that of the mill scale steel surface by about 40 percent, at low values of normal stress and reduces with increasing normal stress.

Cleary & Ramirez (1991) tested eight-slab type specimens under monotonic loading and found that the bond ratio varied from 0.82 to 0.95. Hester et al. (1993) concluded that epoxy coating significantly reduces the splice strength. Hamad & Jirsa (1993) reported that the bond strength of 36 mm diameter epoxy coated splices relative to the uncoated bar splices improved from 74 percent without transverse reinforcement to around 80 to 85 percent with transverse reinforcement. The improvement was independent of the number of splices or bar spacing. The strength improvement was varied from 67 to 74% with 20 mm bars.

Ghaffari et al. (1994) reported that the bond ratio increases with increase in concrete cover. Top bar effect was observed with increasing slump, which is more for uncoated bars as compared to the coated bars. Lack of vibration is more detrimental with coated bars. Cairns & Abdullah (1995) reported that the loss in bond strength depends on the rib geometry. The bond ratio decreases with increasing the relative rib area and reduction in rib face angle. Hamad et al. (1995) studied the bond strength of coated and uncoated bars with different rib geometries. The bars with rib face angle of 60^0, rib spacing of 50% of bar diameter and rib height of 10% bar diameter would improve the bond performance. Cairns & Abdullah (1996) presented the mechanics of bond strength in coated and uncoated bars in splitting modes of failure and suggested that the bond strength can be improved by using steeper rib face angle and more heavily ribbed deformation patterns. Idun & Darwin (1999) found that epoxy coating is less detrimental to bond strength in bars with high relative rib area. Miller et al. (2003) studied the effect of thickness of epoxy coating on the bond strength of rebars. It was recommended that the coating thickness may be increased from 300 μm to μ420 m for 20 mm and larger diameter bars without significant loss of bond strength. Anda et al. (2006) studied the bond strength of prefabricated epoxy coated reinforcement. For coating thickness as large as 508 μm, the bond strength reduction of prefabricated bars was less than 15%.

3 SERVICABILITY OF FBEC BARS

Johnson & Zia (1982) performed static and fatigue tests on slabs. It was reported that there was little difference in the crack spacing, crack width, deflection and ultimate strength of coated and uncoated bars. Treece & Jirsa (1989) reported that epoxy coating significantly increased the crack width and crack spacing. For specimens with 20 mm bars the average width of cracks was twice that of the uncoated bars. Cleary & Ramirez (1991) reported that the average crack width for beams with epoxy coated bars was 23% greater than that of the uncoated bars. Epoxy coating increases the crack widths but the magnitude of crack width reported was different. Blackman & Forsch (1996) reported that as the thickness of epoxy coating increases, spacing of the primary cracks decreases. The load-deflection response was not affected by epoxy coating thickness. When coating thicknesses was between 7 to 12 mils, both the average and maximum crack widths are 30% larger than those with black bars. Abrishami et al. (1995) reported that epoxy coating did not alter the overall load-deflection response of beams when the bar stress was up to its yield stress. Epoxy coating of reinforcement resulted in fewer cracks with larger widths. More splitting cracks were observed in beams with coated bars than those with uncoated bars. Cairns (2001) studied the influence of fusion bonded epoxy coated reinforcement on beam deformations and rotation capacity and found that coating had no effect on plastic deformations. However the tension stiffening effect is reduced when the coated bars are used. Oh & Kim (1997) proposed a theoretical method to predict the crack width of RC beams under repeated loading.

4 DIFFERENTIAL EQUATION OF INTERFACE

The differential equation in slip at the interface in a smooth bar is given below as reported by Somayajili & shah (1982) and Naaman et al. (1991) .

$$\frac{d^2w_x}{dx^2} - \frac{(1+n\rho)\sum 0}{A_s E_z} f_{bx} = 0 \qquad (1)$$

where w_x is the slip between reinfrocement and concrete, f_{bx} is the bond stress, n and ρ are the modular ration and percentage of steel respectively. For a given load (P), cross-sectional dimensions (A_s, A_m and $\sum o$) , and the given constitutive laws for concrete and steel, the solution for bond slip depends on the transfer length, L_t .

The relationship between the transfer load and the transfer length shall be assumed to be linear and was determined from the results of the pullout tests. This linear relationship can be expressed as

$$L_t = K_p \frac{P_{trans}}{\sum 0} \qquad (2)$$

where, K_p is a constant determined from the pullout tests. At any applied load, the concrete strain ε_{mx} is maximum at x= L_t. At x = L_t, the strain in steel is equal to the strain in concrete. Hence the transfer load at this instant is equal to $A_m E_m \varepsilon_s$. Knowing the pullout force P, the strain in steel can be found and the transfer length can be obtained. The transfer force can be calculated using the relation

$$P_{trans} = \frac{P}{(1+n\rho)} \qquad (3)$$

Once the transfer length is calculated, the crack spacing and crack-width can be predicted. In order to find the influence of fusion bonded epoxy coating and rib geometry on the transfer length and crack spacing, 80 pullout tests were conducted as detailed below.

5 EXPERIMENTAL PROGRAMME

5.1 *Materials*

A 43 grade Portland Pozzolanic Cement (PPC) was used for preparation of test specimens. Fe 415 grade high yield strength deformed (HYSD) bars of diameters 8mm, 20mm and 32 mm as main reinforcement, and 6 mm mild steel (MS) bars as spirals as confinement reinforcement, were used. Concrete was made from normal weight black granite aggregate. M30 concrete with the following proportions were used. Weight of cement was 300 kg/m^3 and water-cement ratio was 0.45. Fine aggregate in the total aggregate was 35%. The concrete mix proportions are (C:FA:CA:W) 1: 2.30: 4.27: 0.45. Three standard cubes of size 150mmx150mmx150mm were cast in each batch of concrete to determine its characteristic compressive strength.

5.2 *Details of test specimen*

The test specimen is basically a plain concrete cube of dimensions 150mmx150mmx150mm with a rebar embedded coaxially. One end of the rebar is projected about 15mm to measure the free end slip and the forced end is projected about 750mm in order to grip for applying the tensile force. Tests were conducted on pullout specimen with two parameters with one variable in each set of specimens. In a set, there were 11 cubes, out of which, four were with uncoated bars, and four were with coated bars. Three plain concrete cubes were tested for compressive strength. In the 80 pullout specimens, different bar diameters such as 8mm, 20mm and 32mm with different rib geometries such as diamond, inclined and plain were studied. Steel moulds were fabricated to prepare 8 specimens in a single casting. Holes were provided on the vertical faces of the mould to accommodate the rebars centrally. The bars were placed horizontally and concrete was poured vertically. Lubricating oil was applied on all the inner sides of the moulds for easy removal of specimens. After twenty four hours, the specimens were removed from the forms and cured for 28 days before testing of specimens.

5.3 *Experimental set-up and testing*

The testing of pullout specimens was carried out in a universal testing machine (UTM), which is shown in Figure 1. The UTM was connected with a data acquisition system, using which the slip and the corresponding loads are measured. A digital dial gauge was used for measuring the slip when the load was applied. The test specimen shall be mounted in the testing machine in such a manner that the bar is pulled out axially from the cube. A Teflon sheet used as a capping material was placed between the top surface of the machine and the bottom face of the concrete cube. This ensures smooth contact between the machine and concrete surface, which was used to avoid friction at the interface of the machine and specimen.

The reinforcing bar is pulled axially along the vertical direction. The load was applied to the reinforcing bar at a rate not greater than 2250 kg/min. The movement between the reinforcing bar and the concrete cube as indicated by the dial gauge is read at a sufficient number of intervals throughout the test. The loading was continued and the movement of the bar was recorded at appropriate intervals until any one of the following conditions were reached.

Figure 1. Pullout Test Set Up.

1. The yield point of the reinforcing bars was reached
2. The enclosing concrete was failed and the type of failure was noted, whether it is pull out failure or splitting failure or yield failure and
3. A minimum slip of 2.5mm occurred at the loaded end. The maximum load and the corresponding slip for each type of failure were recorded.

The comparison of bond strengths between the concrete and the reinforcing bar was made on the basis of the average bond stresses calculated from the loads at the measured slips i.e. the load at a slip of 0.025mm and the load at a slip of 0.25 mm at the free end. The test results are shown in Table 1.

Table 1. Results of the Pull out Test.

Diameter, mm	Type of Rib	Bond Ratio
8	Diamond	0.811
20	Diamond	0.935
8	Inclined	0.994
20	Inclined	1.003
32	Inclined	0.906
8	plain	0.977
20	plain	0.921
32	plain	0.902

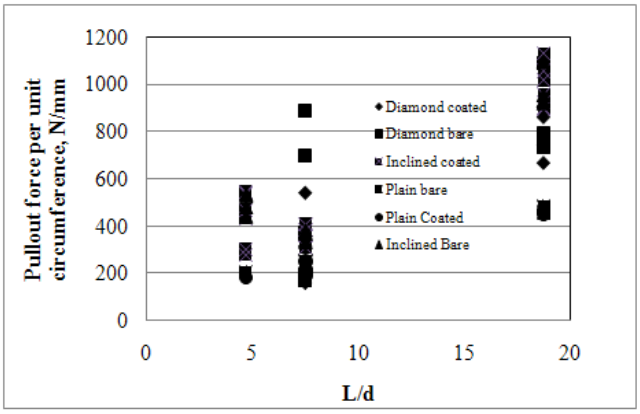

Figure 2. Determination of Kp.

The results of the 80 experimental pullout test data are grouped based on the rib geometry of the bar and the coating to the bar and are shown in Figure 2. In Figure 2 the observed pullout force is divided by the surface area of the bar and is plotted against the embedment length/ diamter ratio(L/d). The inverse slope of the best fit line divided by the diamter of the bar gives the value of K_p (mm^2/N) . The values of K_p for different rib geometries is listed in Table 2. The transfer length required to transfer the pullout force can be calculated using Equation 2. The transfer length for bare and coated bars with different geometries is calculated and reported in Table 2.

6 INFLUENCE OF RIB GEOMETRY

Crack spacing depends on the bond strength. The bond strength is influenced by the bar diameter, rib geometry, coating to the bar etc. Transfer length, L_t is the length required to transfer the stress in the steel bar to the concrete. Along the transfer length, strain in steel reduces and strain in concrete increases and at the end of the transfer length, strain in concrete equals to the strain in steel. Spacing of primary cracks lies between L_t and $2L_{t.}$ Hence, the transfer length can be used to compare the effect of coating and rib geometry on the crack spacing and crack width.

The transfer lengths of various bars are listed in Table 2. The results indicate that irrespective of whether the bar is coated or not, the transfer length increases with increase in diameter of the bar. The transfer length of coated bars is more than the spacing of concrete reinforced with bare bars. Crack spacing in smaller diameter coated bars with diamond rib pattern is close to the transfer length of the plain bars. In the case of plain bars, the influence of

Table 2. Transfer Length for Rib Geometries.

Diameter ,mm	Type of bar	Type of Rib	$K_{p,}$ mm^2/N	Transfer Length, mm
8	Bare	Diamond	0.0183	122.75
8	Coated	Diamond	0.0224	140.01
8	Bare	Plain	0.0387	142.62
8	Coated	Plain	0.0400	143.96
8	Bare	Inclined	0.0182	146.00
8	Coated	Inclined	0.0218	170.01
20	Bare	Diamond	0.0183	279.34
20	Coated	Diamond	0.0224	180.02
20	Bare	Plain	0.0387	165.12
20	Coated	Plain	0.0400	157.13
20	Bare	Inclined	0.0182	120.47
20	Coated	Inclined	0.0218	144.32
32	Bare	Inclined	0.0182	229.68
32	Coated	Inclined	0.0218	248.35
32	Bare	Plain	0.0387	200.00
32	Coated	Plain	0.0400	187.00

coating is found to be negligible. In bars with inclined rib pattern, crack spacing is 15 to 20 % more in smaller diameter bars and the influence of coating is less in larger diameter bars.

The coating thickness provided to the bars ranges from 150 µm to 300 µm. As per the manufacturing standards, the thickness of coating applied to the bars is not proportional to the bar diameter. Therefore the coating to diameter ratio in smaller diameter bars is more when compared to large diameter bars. Moreover the rib heights are proportional to the bar diameters, smaller diameter bars have smaller ribs as compared to larger diameter bars. Hence coating on smaller diameter bars will have more effect on the bond strength and crack width. The transfer length of bars with diamond rib pattern seems to be more than that with inclined rib pattern. This is due to the fact they restrain for the coating to flow out of the region covered by diamond rib pattern and due to this coating gets accumulated within the boundaries of the diamond pattern and the thickness of coating provided looks more. This effect is more significant in smaller diameter bars usually used in reinforcing slabs and water tanks, where cracking is a very important criterion that is to be satisfied.

7 CONCLUSIONS

From the limited analysis of the experimental work, the following conclusions may be drawn

1. The influence of fusion bonded epoxy coating on the crack spacing in concrete with plain bars is negligible.
2. Irrespective of whether the bar is coated or not, the crack spacing with large diameter bars seems to be more than that of smaller diameter bars.
3. Influence of fusion bonded epoxy coating on small diameter bars with diamond rib pattern bars is more than that of large diameter bars
4. Crack spacing of smaller diameter bars with inclined rib pattern is 15 to 20 % more than that of uncoated bars.
5. Crack spacing in smaller diameter bars with diamond rib pattern is more than that observed in similar bars with inclined ribs.

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