INVESTIGATION OF INTERFACIAL BOND STRENGTH IN CFRP ROD REINFORCED CONCRETE

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Abstract

This study includes an experimental investigation into the effects of surface geometry on the interfacial strength of carbon fiber reinforced polymer (CFRP) rods embedded in a high strength concrete. In the experimental phase of the study, a series of pullout tests are conducted on CFRP reinforcing bars with different surface configurations. The surface configurations consist of a single spiral indentation created during fabrication of the rods. The effect of variations in the spiral pitch are evaluated and compared to the case of no indentation. The results show that the shorter pitch length develops higher bond strengths. Sectioning and microscopic examination of the failed samples provides insight into the mode of failure. A simple analytical model for the effect of spiral pitch on interfacial strength based on mechanical interlocking and slippage is developed and correlated with the experimental results.

Introduction

Corrosion of steel reinforcement embedded in concrete structures is considered to be the main cause of structural concrete deterioration. Chloride ions produced by the corrosion of the steel reinforcement can cause serious damage to surrounding concrete and also depreciate the strength of the corroded member. In many regions the corrosion of the steel reinforcement is accelerated by the use of deicing salts and other chemicals to prevent freezing. Many various approaches have been attempted to control the corrosion of the reinforcing steel: epoxy coated rebar; cathodic protection; increased cover; use of polymer concretes; etc. However, none of these approaches provides a permanent solution as they all still incorporate the usage of corrosive steel. Recently advances in fiber reinforced plastics (FRP) have made replacing steel reinforcement with non-corrosive FRP's a viable alternative. This study is part of a larger investigation currently underway at the University of Rhode Island. In this paper the bond strength characteristics of carbon fiber reinforced plastic (CFRP) reinforcement embedded in high strength concrete is investigated.

CFRP's offer many advantages as compared to steel reinforcement including high strength to weight ratio, excellent fatigue characteristics, corrosion resistance, electromagnetic neutrality, low axial coefficient of thermal expansion, and handleability due to its light weight. However, the inherent differences between steel reinforcement and CFRP reinforcement necessitate the development of appropriate design procedures. Current design codes dealing with reinforced concrete do not take into consideration the two most important differences between FRP and steel reinforcement. FRP's are an anisotropic (directionally dependent) and heterogeneous (composed of constituent materials having different properties). Also, the surface geometry of FRP reinforcement is typically much different than that of steel. These significant differences in material composition/properties and physical characteristics affect the ability of FRP's to bond to concrete. Effective use of reinforced concrete structures requires the proper interaction of the concrete and its reinforcement. The strength of reinforced concrete under bending, shear and torsion loads is directly related to the development of an adequate bond [1]. There must be adequate bonding to ensure proper stress distribution and load transfer. If the bond between the concrete and reinforcement is not strong enough to facilitate this stress transfer, interfacial failure will occur. The bonding of the CFRP to concrete is controlled by many different factors including chemical bond, friction due to surface roughness of FRP rods, mechanical interlock of the FRP rods against the concrete, and induced interfacial pressure due to temperature change and/or concrete shrinkage during curing. During pull-out experiments, initially load transfer is provided by chemical bonding (adhesion). After failure of the chemical bond, mechanical interlocking mechanisms become dominant [1]. The mechanical interaction of steel reinforcement, with its capacity for large plastic deformation, provides the primary means of load transfer between steel and concrete. CFRP's on the other hand, are not capable of producing large plastic deformations. Therefore the surface geometry of the CFRP reinforcements is critical to produce the desired interfacial load transfer. This study examines the enhancement of interfacial load transfer through the changes in the pitch length of spiral indentations.

Experimental Study

Materials

The CFRP reinforcement tested in this study were produced by the Mitsubishi Chemical Company. The CFRP's consist of carbon fibers bound in an epoxy resin matrix. The CFRP's are manufactured in a pultrusion process with pre-wrappings to create surface indentations. The CFRP's can be produced in various diameters with varying surface indentation depths and configurations. The CFRP rods tested in this experiment had a nominal fiber volume ratio of 0.65.

Table 1: Material Tensile Properties

	Leadline CFRP	Typical Steel Values
Yield Stress	No Yield	275 to 480 MPa
Ultimate Strength	2,550 MPa	480 to 690 MPa
Young's Modulus	147 GPa	200 GPa
Fiber Volume Ratio	0.65	N/A
Ultimate Elongation	1.6%	10%
Coefficient of Thermal Expansion	0.7×10^{-6} /°C	11.7×10^{-6} /°C

Testing method

The direct pull-out is a commonly used test method for determining the bond strength of FRP reinforcing rods in concrete. The American Concrete Institute (ACI), the American Standards of Testing Materials (ASTM) and the Japan Society of Civil Engineers (JSCE) have all recommended using the direct pull-out test for determining the bond strength of FRP's to concrete. The direct pull-out test method consists of an FRP embedded through a cylindrical or rectangular concrete specimen. The concrete is constrained and the FRP rod is pulled from one end of the specimen. The bond strength of the FRP to concrete is determined from the force applied to the FRP divided by the interfacial contact area of the FRP bonded region. This method has many advantages including its simplicity, the free and loaded ends are accessible for displacement measurement, and the direct correlation between bonded region of FRP and bond strength. Disadvantages to this method include the compression loading of the concrete at the loaded surface leading to enhanced confinement of the FRP near the loaded end. Also, the mechanical interaction of the rod and the concrete induces tensile hoop stresses in the concrete which leading to splitting failure. Other methods have also been utilized to determine the bond strength of FRPs in concrete including the hinged beam test method, axial tension test, rod-rod pull out test, cantilever beam test and the eccentric pull-out test. The concentric direct pull-out test method was implemented in this study. Both the ACI proposed ACI 440 [2] and the JSCE Concrete Engineering Series 23 [3] were used to guide the design of the test procedures. The testing conducted utilized high strength concrete (approx. 65 MPa), hoop reinforcement and cylindrical concrete specimens.

Specimen Preparation

The CFRP reinforcement rods used in these experiments had a nominal diameter of 10mm with varying surface indentations. The surface indentations were produce using a patented pultrusion method that produces small spiral surface indentations. An indentation width of 4 mm and a depth of 0.25mm was used on all of the test specimens. It is generally believed that while the bond strength increases with increasing indentation depth, increased indentation depth also leads to decreased tensile strength of the CFRP rod. Studies conducted by Mitsubishi Chemical Foundation Products, Inc. suggest that at indentation depths greater than 0.4mm there is a significant tensile strength loss. Therefore, an indentation depth of 0.25mm is expected to provide adequate bond strength without compromising tensile strength of the CFRP rod.

Previous testing had also been conducted on differing surface indentation configurations and pitch lengths. While these tests have indicated that single spiral indentations, as compared to double spiral

Figure 1. CFRP reinforcement with spiral indentation pitch lengths of 8 mm, 10mm and 12 mm.

indentations, provide better bond strength, the optimum pitch length was not clearly identified. To address this issue, pitch lengths of 8mm, 10mm and 12mm were selected for this study (see Figure 1).

The direct bond strength pull-out tests were conducted on CFRP samples of each of the three pitch lengths (3 samples per pitch length), #4 (diameter =12.7 mm) steel reinforcement rod (2 samples), and smooth CFRP rods (2 samples) embedded in high strength concrete. The compressive strength of the concrete was tested at 90-plus days and found to have an average value (based on three samples tested) of 65 MPa.

Cylinders with a diameter of 102 mm were made with embedded 10 mm diameter CFRP rods with approximately 100 mm of CFRP rod protruding at the free end of the cylinder and approximately 300 mm protruding at the loaded end of the cylinder. The cylinder was then reinforced with 6 mm diameter steel hoop reinforcement with a hoop diameter of 80 mm with a 25 mm spiral pitch extending along the entire length of the cylinder. The bars were set in the concrete cylinders with embedment lengths of 88mm. The embedment length was obtained using a 14 mm bond breaker at the loaded end of the specimen. An elastomeric bond breaker tape prevented localized failure due to the compressive load on the concrete prior to being transferred to the FRP. The cylinder was then filled with high strength concrete, embedding the bonded and de-bonded region of the FRP a total of 102 mm, and vibrated for confinement. The top surface of the cylinder was then struck off with a trowel and covered with a plastic cap to avoid evaporation near the area adjacent to the protruding FRP rod. The cylinders were allowed to cure in a moist environment for 24 hours. The molds were then removed and the cylinders were cured in accordance with ASTM C511-85 standards until the time of the testing. Just prior to testing the cylinders were capped at the loaded/bearing surface with a sulfur dioxide capping compound in accordance with ASTM C617-87, with special care to ensure that none of the capping compound bonded to the CFRP rod.

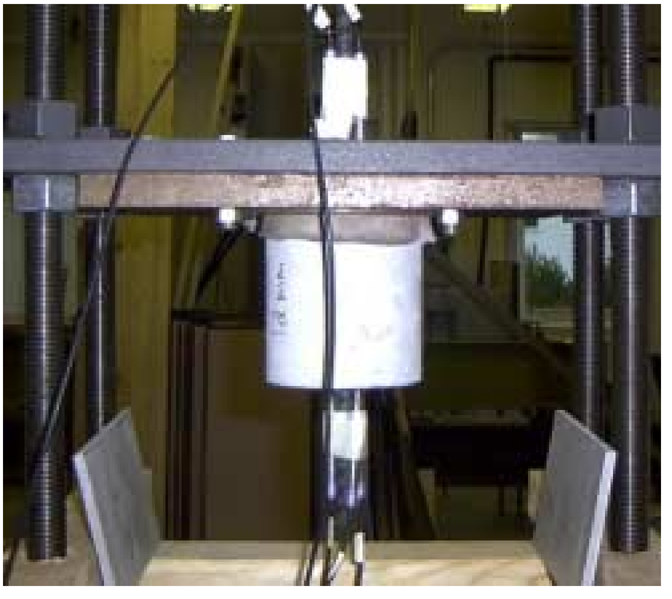

Figure 2. Bond Strength Test Set-up.

Experimental Procedure

The finished specimens were loaded into a test fixture mounted in an MTS servo hydraulic testing machine. As shown in Figure 2, a steel bearing plate rigidly attached to the test frame provided a bearing surface to constrain the upper surface of the concrete during loading. The 300 mm of CFRP rod protruding from the loaded end of the concrete was passed through a 25 mm opening of the steel bearing plate. The end of the loaded end of the CFRP was gripped with a 38 mm OD dowel split down the center with a 10 mm ID at the center to fit snugly around the CFRP rod over a length of 75 mm. The dowel's interior surface was roughly finished and tapered at the ends to ensure that the CFRP would not slip from the dowel surface. The dowel was then gripped using hydraulic grips capable of exerting 70MPa of gripping pressure.

The specimen was pulled snug against the self-leveling bearing surface to a pre-load of approximately 1 kN. Low voltage displacement transducers (LVDT's) were attached at both the free and loaded ends of the CFRP rods to measure the relative slippage of the CFRP rod through the concrete cylinder. Three LVDT's were attached at the free end of the FRP to measure the relative displacement between the free-end concrete surface the CFRP rod. Two LVDT's were attached to the loaded end of the CFRP to measure the relative displacement between the steel bearing plate and the CFRP rod. After mounting, the LVDT's were zeroed prior to application of load.

The CFRP was loaded at a constant rate of 1.27 mm/min until a load drop of 80% below maximum load was reached. The average free end slip was recorded as well as the average loaded end slip corrected for tensile elongation of the loaded CFRP. The average interfacial stress was then calculated and recorded at intervals of 0.01mm of average loaded end slip. The average interfacial stress is given by

$$\tau = \frac{F}{\pi D L} \tag{1}$$

where τ is the average interfacial stress, F is the tensile load, D is the diameter of the CFRP rod (10 mm) and L is the bonded length (88 mm). The average interfacial stress resulting in slippage at the free end of 0.05 mm, 0.10 mm, and 0.25 mm, and the maximum interfacial stress at failure were calculated.

Experimental Results

The results of the interfacial strength testing are shown in Table 2 where bond strength is taken to be the maximum interfacial stress. The smooth rods exhibited minimal bond strength (less than 2 MPa). This result is consistent with published interfacial strength tests performed on smooth CFRP rods [4-7]. The CFRP indented rods and the steel samples all exhibited maximum interfacial stress just prior to failure of the concrete cylinder by concrete splitting. Figure 3 shows a typical example of concrete splitting failure.

Free-end and Loaded-end Slip

The free-end and loaded-end slip of the CFRPs were very closely related. All tests showed a slight "lag" in free-end slippage compared to loaded-end slippage. Figure 4 shows a typical example of the CFRP free-end and loaded-end slip. Part of this "lag" can be attributed to play in the support fixture used to hold down the concrete specimen. It is also likely that this "lag" is due in large part to initial failure of the bond between the CFRP and the concrete and wedging of concrete into the indentations in the CFRP rod. Another minor contribution to the lag between free-end and loaded-end slip is axial deformation of the rod within the concrete. In all cases the free-end slippage was approximately 0.4 mm less than the loaded-end slip at any given bond stress. While the difference in free-end and loaded-end slippage was very apparent in the CFRP specimens it was not apparent in the steel samples. The steel bond strength specimens reached maximum interfacial stress with little to no slippage at the free-end. It is of interest to note that the observed failure mechanism, concrete splitting, was apparent for both the indented CFRP specimens and the steel specimens.

Table 2. Bond Strength Test Results

Reinforcement	Bond Strength (MPa) at Various Free End Slippage Points				
	0.05mm	0.10mm	0.25mm	Max. Bond Strength	Slippage at Max. (mm)
8mm-1	10.3	12.18	15	18.34	0.605
8mm-2	9.53	11.1	14.5	19.35	0.717
8mm-3	9.55	11	14.15	18.43	0.648
10mm-1	6.9	8.35	11.2	16.32	0.88
10mm-2	7.89	9.35	12.25	16.68	0.7
10mm-3	7.12	8.54	11.35	16.09	0.83
12mm-1	6.62	8.12	10.61	14.62	0.82
12mm-2	6.2	7.48	9.91	14.41	0.93
12mm-3	6.3	7.41	9.53	14.04	0.94
Smooth-1	1.5	1.55	1.52	1.55	0.09
Smooth-2	1.58	1.60	1.58	1.62	0.09
½” Steel-1	22.1	21.4	NA	22.18	0.06
½” Steel-2	25.2	NA	NA	25.5	0.046

Figure 3. Concrete splitting failure.

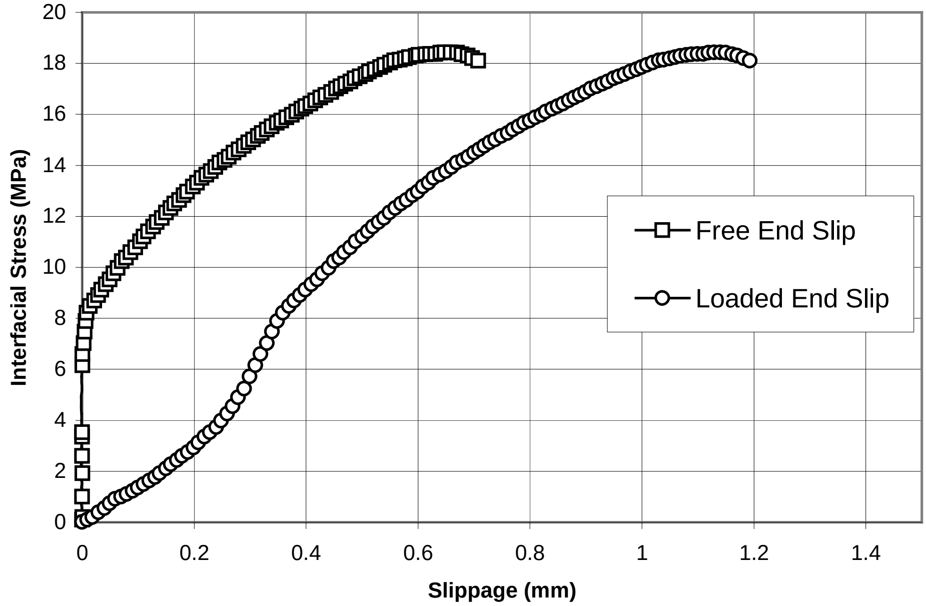

Figure 4. Typical CFRP Interfacial stress vs. slippage (8mm pitch length).

Maximum Bond Strength

Figure 5 shows the free end slip of the various indented CFRP and steel specimens. From this comparison, it is clear the CFRP rods exhibit significantly more slippage as compared to the steel reinforcements. The average bond strength and free-end slip for each of the configurations tested are given in Table 3. The relatively low standard deviations are a good indication that the results were consistent. Figure 6 shows the average interfacial stress at free-end slip values of 0.05 mm, 0.10 mm, 0.25 mm and at maximum load for each of the rods. The increase in interfacial stress with pitch length is consistently observed for all of the indented rods tested.

Table 3. Comparison of Average Bond Strength and Free-end Slippage

Reinforcement	Average Bond Strength / Std. Deviation (MPa)	Free-end Slippage / Std. Deviation at Max. Interfacial Stress (mm)
Steel	23.8 / 2.35	0.053 / .010
Smooth CFRP	1.59 / .049	0.090 / .000
8mm pitch	18.7 / 0.65	0.657 / .049
10 mm pitch	16.4 / 0.42	0.803 / .092
12 mm pitch	14.4 / 0.26	0.897 / .007

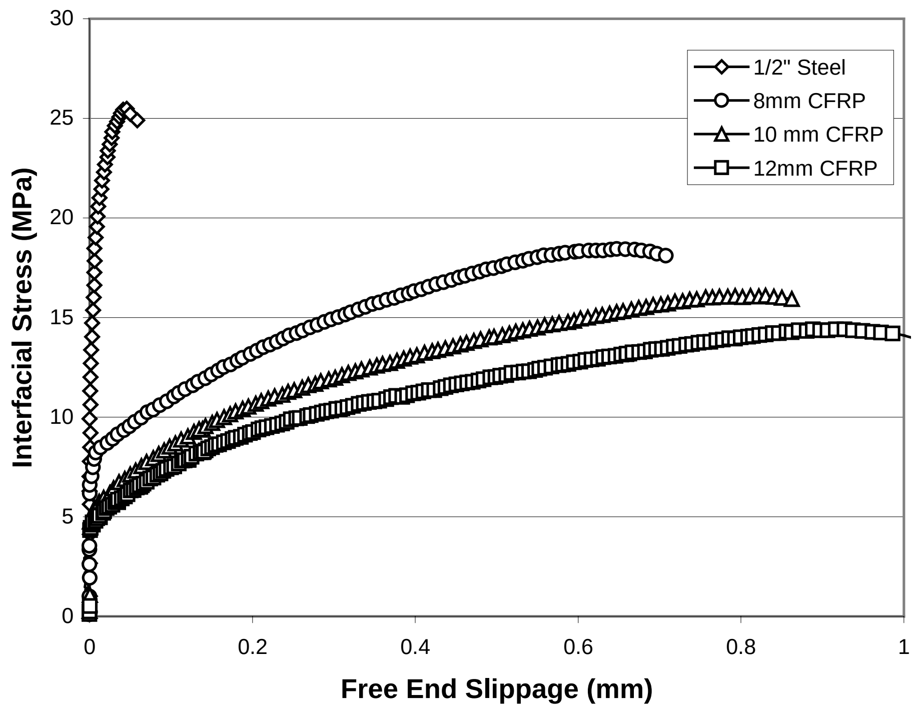

Figure 5. Interfacial stress vs. free end slippage.

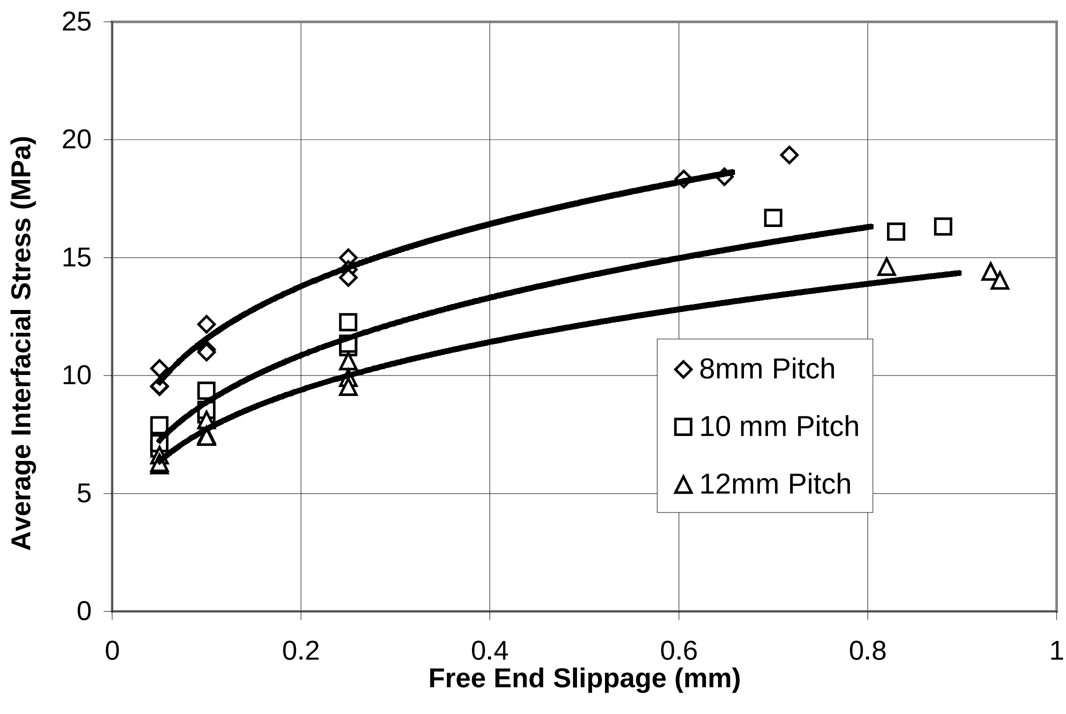

Figure 6. Average interfacial stress vs. free end slippage.

Post Test Investigation

The tested CFRP and steel test specimens were sectioned using abrasive waterjet cutting to examine the interfacial failure mechanism. As shown in Figure 7, the regions near the spiral indentions contain predominantly epoxy resin. Examination of the sectioned specimens reveals that this epoxy region is sheared off, presumably at relatively low load levels. No damage to the concrete or the fiber reinforced region of the CFRP rods was apparent. It is therefore concluded that as the load increases, the composite rod is wedged by the concrete that has filled the indented region, providing load transfer through mechanical interlocking. This mechanical interlocking induces radial compressive stresses and circumferential (hoop) tensile stresses in the concrete. It is believed that these tensile stresses ultimately lead to concrete splitting and ultimate failure of the specimen.

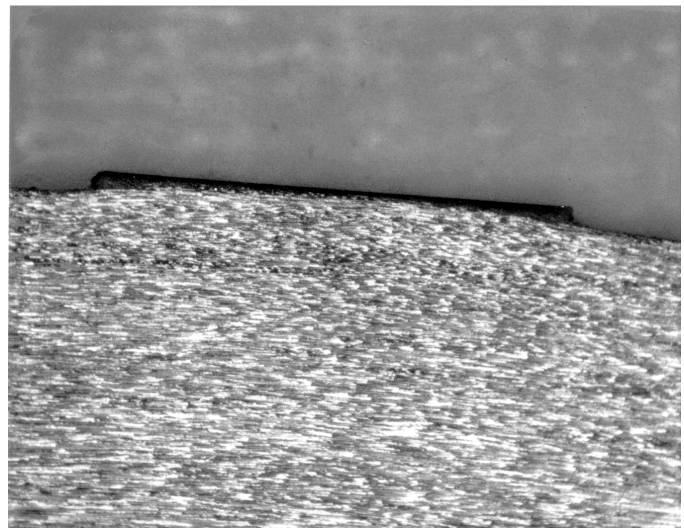

Figure 7. Micrograph showing resin rich region between spiral indentations.

Analysis Of Results

Examination of the failed specimens also reveals that the amount of interfacial slippage appears to be uniform over the length of the rod. This observation is consistent with the nearly constant lag between the loaded-end and free-end slippage discussed previously. It is therefore reasonable to assume that load transfer occurs uniformly along the length of the rod. Also, the load transfer is likely to occur at the loaded end of the spiral indentation where the mechanical interlocking occurs. In order to compute the force transferred per unit length along the spiral indentation, the spiral length, l_s, is calculated using the equation

$$l_s = L\sqrt{1+\left(\frac{\pi D}{P}\right)^2} \tag{2}$$

where L is the length of the embedded rod (88 mm), D is the rod diameter (10 mm) and P is the pitch. From equation 1, the maximum force is related to the bond strength through the relation

$$F_{\max} = \tau_{\max}\left(\pi D L\right) \tag{3}$$

Combining equations 2 and 3 gives the maximum force per unit length along the spiral indentation

$$\frac{F_{\max}}{l_s} = \frac{\tau_{\max}\left(\pi D P\right)}{\sqrt{P^2 + \left(\pi D\right)^2}} \tag{4}$$

As shown in Table 4, the value F_{max}/l_s is nearly constant for the three pitch lengths evaluated. Hence, F_{max}/l_s can be taken as a strength parameter for a given indentation width and depth and rod/concrete material combination.

Table 4. Distributed Load Along Spiral Indentation at Maximum Load

Pitch, P (mm)	Length of spiral indentation, l_s (mm)	Bond Strength, τ_{max} (MPa)	Distributed Load, F_{max}/l_s *(N/mm)*
8	356	18.7	145
10	290	16.4	156
12	247	14.4	161

It is interesting to note that for cases where $\pi D > P$ (πD = 31.2 mm and P=8, 10 or 12 mm in these experiments), equation 4 can be approximated as

$$\frac{F_{\max}}{l_s} \cong \tau_{\max}\ P \tag{5}$$

Therefore, for a given indentation width and depth and rod/concrete material combination, the measured bond strength is approximately inversely proportional to pitch length.

Conclusions

The experimental and analytical results indicate that the measured bond strength in approximately inversely proportional to the indentation pitch length of the CFRP rods. It was also observed that the free-end slippage in the CFRP reinforcement rods was far greater than that of steel reinforcement. Despite this result, the maximum interfacial stress for the indented CFRP rod was comparable to that of steel. It was also observed that for both the indented CFRP and the steel reinforcements, maximum load was associated with radial splitting of the concrete. This splitting is believed to be due to circumferential tensile stresses induced by the mechanical interlocking of the reinforcement and the concrete. Based on this observation, it is speculated that increased bond strength measurements would be obtained if enhanced confinement of the concrete were introduced. Further investigations are required to determine the effects of concrete confinement on measured interfacial strength.

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