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INTERFACE BETWEEN FIBER REINFORCED PLASTIC ROD AND CONCRETE

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SUMMARY: Fiber reinforced plastic (FRP) rods have shown promise as alternatives for steel reinforced rods for concrete. This is due to the excellent corrosion resistance of fiber reinforced plastic materials. One of the main aspects in the efficiency for this reinforcement is the load transfer at the interface between the FRP rod and the concrete. The interface between fiber reinforced plastic rods and concrete is examined. Microscopic examination of the interface between the FRP rod and the concrete was carried out, both for the unloaded system and also for the system that was loaded until failure. Comparison was also made with the case where steel is used as a reinforcement. Observations revealed that the main mechanism responsible for the shear transfer between the two materials is mechanical friction and mechanical interlock (bearing). For the FRP rods, the friction was enhanced by the addition of sand particles. Some FRP rods have added helical ribs which provide some form of mechanical interlock. For the steel rods, in addition to the friction between the two surfaces, mechanical interlock was also provided by the addition of lugs incorporated into the cylindrical rods. The shear load obtained from steel rods is much larger than the shear load obtained from FRP rods. A new design for the FRP rod was proposed. Preliminary tests on this new design show great improvement on the shear load obtained for the FRP rods.

KEYWORDS: Fiber reinforced plastic rods, concrete, Interface, Reinforcement Efficiency, Mechanical Interlock, Bearing resistance.

INTRODUCTION

For material systems that rely on the synergistic effect from the different constituents, one of the most important elements in the material system is the interface. This is true for conventional composite materials where the interface between the fibers and the matrix holds dominance. This also is true for the case of reinforcement of concrete using either steel rods or Fiber Reinforced Plastics (FRP) rods. The use of FRP rods to reinforce concrete has received a lot of attention recently. This is due to the good corrosion resistance of fiber reinforced plastic materials in environments that corrode steels. As such, many researchers have spent good efforts on the study of FRP rods used in concrete. Among these include the work by Benmokrane et al [1,2] which performed bending tests on concrete beams reinforced with steel bars and GFRP bars. They found that the bond strength between the reinforcing bars and concrete vary with the diameter of the bar, for both steel and GFRP bars. The bond strength decreases as the bar diameter increases. Also steel reinforcing bars give higher bond strength than GFRP bars. This confirmed the results from Larrard and Schaller [3] and Larralde and Silva- Rodriguez [4]. The ratio (bond strength due to GFRP bar/bond strength due to steel bar) varies from 0.55 to 0.86 depending on the diameter of the bar. The explanation was that in steel reinforcing bars, bond strength is considered to depend on two mechanisms: 1)adhesion between concrete and reinforcing bar, and 2) bearing of the reinforcing bar against the concrete. It was thought that the major contribution comes from the bearing component. Since the surface deformations of GFRP reinforcing bars do not possess the characteristics of steel reinforcing bars (i.e high shear strength, high rigidity, deformation geometry) that provide enough lateral confinement through rib bearing, it follows that there is a lower bond strength for GFRP reinforcing bars. Benmokrane et al. also found that the bond strength observed from pull- out tests is approximately 5 to 82 per cent larger than that obtained from beam bending tests, depending on the reinforcing bar diameter. Ehsani et al [5] performed tests on bond of hooked glass fiber reinforced plastic (GFRP) reinforcing bars to concrete. They found that for bars with r/d_b ratio of 3 (r is the hook radius and d_b is the diameter of the bar), the maximum load is about 4 times larger than bars with r/d_b of zero. This result clearly shows the effect of mechanical interlock (or bearing) on the strength of the reinforcing bar/concrete system. Ehsani et al [6] later performed more tests on straight bars and hooked bars and provided design recommendations for bond of GFRP rebars to concrete. They provided guidelines for the embedment lengths of the rebars. In general, the embedment length is proportional to $f_bA_b/f_c^{0.5}$ where f_b is the strength of the bar (either ultimate strength or yield strength), A_b is the cross section of the bar and f_c is the compressive strength of the concrete.

The above brief literature survey shows that significant amount of work has been done on the bond between fiber reinforced plastic rebars and concrete. It is generally recognized that mechanical interlock plays a very important role in the strength of the rebar/concrete system. The results also show that the shear strength between the composite rebar and concrete is lower than that between steel and concrete. This is probably due to the lack of significant mechanical interlock (bearing) between the rebar and the concrete. Bank et al [7] found that smooth FRP rods, manufactured through pultrusion, suffer from weak adhesion to the surrounding concrete. Nani et al [8] indicated that additional means to improve the bond are needed. Several methods have been developed in order to improve the bond, mainly by the application of deformations on the surface using different techniques. Benmokrane et al [1] found that application of deformation by double wrapping of helical fibers around the rod significantly improved the bond. Other means such as machined rods, embedding sand particles on the surface, and roughening by sand blasting were discussed by Cosenza et al [9]. The above methods have improved the bond between the concrete and the FRP rods, however their strengths are still lower than the shear strength provided by steel rods. This is probably due to the fact that the bond between the additional roughening mechanism (helical windings, sand particles etc.) are only bonded to the main rod by adhesive bonding, which is a weak bond. Machining the rods introduce cut fibers which are detrimental to the integrity of the rods.

The objective of the current research project is to investigate the effect on shear bonding between concrete and the reinforcing rod and to come up with a new rebar design. The approach of the project is to first examine the interface between concrete and existing rebars. The knowledge obtained is useful for the design of new rebars. A new rebar design has been introduced. This new rebar design contains significant mechanical interlock (bearing) between the FRP reinforcing bars and the concrete. In this paper, observation at the interface between the reinforcing bars and concrete will first be presented. Shear strength obtained from tests on concrete system containing existing FRP rebars and steel rebars is obtained. This is followed by the preliminary results on the shear bond strength between new rebars and the concrete.

MECHANICAL BEHAVIOR AT THE INTERFACE BETWEEN EXISTING REINFORCING BARS AND CONCRETE

Rebar designs:

There are many different designs for FRP rebars. Figure 1 shows the design for the steel rebar and the FRP rebars. Even though the steel rebars have been in existence for a long time and is well known, it is included here for the sake of completeness of discussion. Figure 1a shows the end view and longitudinal view of the steel rebar. It has both longitudinal ribs and helical ribs. The ribs are molded to be integral parts of the bar itself. The bond between the ribs and the main rebar is therefore primary bond. Figure 1b shows a pultruded rod with sand coating on the outside. Figure 1c shows an FRP rebar design that has helical ribs. Different from the case of steel rebar, the ribs here are wound on top of the rebar after the rebar has been pultruded. The bond between these ribs and the main bar is made of secondary bonding. Figure 1d shows another design of an FRP rebar that has helical winding and sand particle addition. The helical windings are making impression into the main bar during the fabrication process. This does provide some degree of interlock. However the bond between the ribs and the main rebar is still of secondary bond. Other designs (not shown) have the FRP rebar machined. The machined grooves do provide mechanical interlock. However, machining creates stress concentration and cut fibers, which weaken the rebar itself.

Samples for Experiments:

In order to observe the interface between the concrete and the rebar, a few simple experiments have been performed. These were done on concrete samples with steel rebars and with one form of FRP rebar (type 1c in Figure 1). Samples of concrete containing the rebar were made. The concrete was made at Ciment St. Laurent in Montreal. The concrete has a compression after 28 days of 47 MPa. The glass fiber reinforced plastic rod was supplied from Hughes Brothers company. The rod was made using pultrusion method. The rods have diameter of 3/8 inch with helical ribs wound over the rod. The rods were incorporated into the concrete during molding. The rod/concrete system was left in calcium chloride solution for 28 days before testing. The concrete column is 3 inch long and 3 inch in diameter. In order to assist to assure a good test and to avoid premature failure of the concrete, fiber glass/polyester sheets were wrapped around the concrete column. This technique was proved to be successful in obtaining the slipping failure of the rebar rather than the falling apart of the concrete.

Observation at the interface, untested condition:

Cutting a cross section across each of the bars and observing them under the microscope reveals the details at the interface. Figure 2a shows the interface between the GFRP rod and the concrete in the untested condition (at magnification 100). The upper left hand corner shows part of the composite cross section with the many fine fibers. There is a dark diagonal strip which represents the adhesive layer. Below that dark strip there is another diagonal but wider strip with irregular lower edge. This wider strip represents the sand particles. On the lower right hand corner is the concrete.

Figure 2b shows the interface between the steel rod and the concrete in the untested condition (at magnification 100). The white region on the upper right hand corner is a portion of the steel cross section. Note that the steel cross section is not completely round. The lower portion of the steel section shows the lug. On the lower left hand corner is the concrete.

Observation at the interface, after tested condition:

The rebar/concrete system was tested by pulling the rebar from the concrete. Testing was done on an MTS testing machine at a cross head rate of 2 mm/minute. The apparent shear strength of the two types of reinforcement is obtained by dividing the maximum load by the contact area between the concrete and the rod. (☺ = P/(✍dl) where ☺ is the apparent shear strength, P is the maximum load, d is the diameter of the rod and l is the embedment length .The apparent shear strength of the two types of reinforcement are:

For FRP rod: 9 MPa
For Steel rod: 13 MPa.

The appearance of the broken interface between the FRP rod and concrete and of the interface between steel/concrete show that the fracture surface is clean, indicating that there is little chemical bonding between the two interfaces, for both the steel rebar and for the FRP rebar. For the FRP rebar, fracture occurs between the sand particles and the concrete whereas the sand particles adhere well to the composite material.

The new rebar design:

The concept for the new rebar design is to enhance the mechanical interlock. This mechanical interlock does improve the shear load transfer between the FRP rod and the concrete. The design consists of a regular rod but it also has lobes along the rod that give the rod a wavy configuration. Figure 3 shows the configuration of the wavy rebar rod. This rebar is term HOAREBAR🖮. The reinforcement is continuous throughout the rod and the wavy part contains fibers that are part of the main rod (rather than just bonded in). In order to show the efficiency of the method, the following preliminary analysis is made.

Preliminary analysis:

As a preliminary analysis, a view of the longitudinal cross section of the rebar is shown in Figure 4. The enlarged portion has been approximated to have straight edge rather than curved edge as a first approximation. The stress in the rebar is ☞$_u$, the compressive stress in the concrete is ☞$_c$ and the shear stress between the concrete and the rebar is denoted as ☺.

The surface area of the conical section can be shown to be ✍ (D + d) (☼$_2$)/(2 cos🖹). The horizontal component of the shear force at the interface between the concrete and the conical surface of the rod is:

$$S_1 = tp(\frac{D+d}{2})\lambda_2 \qquad (1)$$

The normal reaction from the concrete gives rise to the compressive stress in the concrete. The horizontal component of the force acted by the concrete on the rod can be shown to be:

$$S_2 = \boldsymbol{s}_c \boldsymbol{p}(\frac{D^2 - d^2}{4}) \qquad (2)$$

The equilibrium equation for the rod can be written to be:

$$\boldsymbol{s}_u \boldsymbol{p}(\frac{d^2}{4}) = \boldsymbol{tp} d\lambda_1 + \boldsymbol{tp}(\frac{D+d}{2})\lambda_2 + \boldsymbol{s}_c \boldsymbol{p}(\frac{D^2 - d^2}{4}) \qquad (3)$$

Defining the nondimensional parameters:

✂ = D/d, 👓 = $☼_2/☼_1$ ☎ = $☺/☞_c$ 📭 = $d/☼_1$

the above equation can be written as:

$$\boldsymbol{s}_u = 4\boldsymbol{t}\frac{\lambda_1}{d}\left[1 + \boldsymbol{b}(\frac{\boldsymbol{a}+1}{2}) + \frac{\boldsymbol{e}}{4\boldsymbol{g}}(\boldsymbol{a}^2 - 1)\right] \qquad (4)$$

In the above equation, the first term in the bracket represents the resistance due to the friction along the length $☼_1$ of the rod. If the rod were a regular straight rod, then the second and third terms in the bracket would become zero and only the first term stays. The second and third terms in the bracket represent the relative contribution from the enlargement of the rod. The second term represents that shear contribution and the third term represents that contribution from the bearing action or mechanical interlock. The friction contribution from the enlargement depends on the relative length of the enlargement as compared to the regular length of the rod (👓) and also on the relative size of the enlargement compared to the size of the rod (✂). The relative contribution from the mechanical interlock depends on three factors: the inverse of the slenderness ratio of the regular rod (📭), the relative size of the enlargement as compared to the size of the regular rod (✂) and the relative magnitude between the shear strength at the interface and the concrete compressive strength. It can be seen that the larger is the concrete strength as compared to the shear strength at the interface, the stronger is the effect of the enlargement.

In order to get a feel for the magnitude of the contribution, a few numbers are used here for illustration. Assuming that the enlargement is 30% more than the regular diameter (✂ = 1.3), the length of the enlargement is 20% of the regular length (👓 = 0.2), taking the compressive strength of concrete to be 47 MPa and the shear strength at the interface to be 9 MPa (☎ = 9/47 = 0.19), and the slenderness ratio to be 2 (📭 = 0.5), the above equation would give:

$$\boldsymbol{s}_u = 4\boldsymbol{t}\frac{\lambda_1}{d}[1 + 0.23 + 0.45] \qquad (5)$$

The additional contribution from the enlargement therefore would account for another 68% of the regular reinforcement as based on the case of a rod of regular shape.

Equation (3) or (4) above can also be used to design the amount of reinforcement for the rod. If the tensile stress in the rod is less than the right hand side of the equation (3 or 4), and the shear strength is already more than the value of ☺, then slipping will be the failure mode. On the other hand, if the tensile stress in the rod is more than the right hand side of the equation and the interfacial shear strength is more than ☺, then fracture of the rod will occur. The optimal arrangement would be for both the slipping at the interface and rod fracture to occur at the same time.

Conclusion:

Interfaces between the reinforcement bars and concrete were examined. It was found that the bond between the concrete and the rebar (either steel or fiber reinforced plastics) is mainly due to friction or mechanical interlock. For steel bars, the ribs on the surface of the rebar provide efficient mechanical interlock. For current FRP rebars, the mechanical interlock is weak due to the secondary bond strength between the reinforcing ribs and the main pultruded bars. A new composite rebar has been designed. This rebar provides additional inherent mechanical interlock which has primary strength. A preliminary analysis provides equations that can be used to design rebars that would maximize the efficiency of the reinforcement system. The new rebar design can provide great potential to provide efficient reinforcement for concrete.

Work to be done in the near future would be to test these new rebars of different configurations and in concrete of different strengths, to provide validation for the design model.

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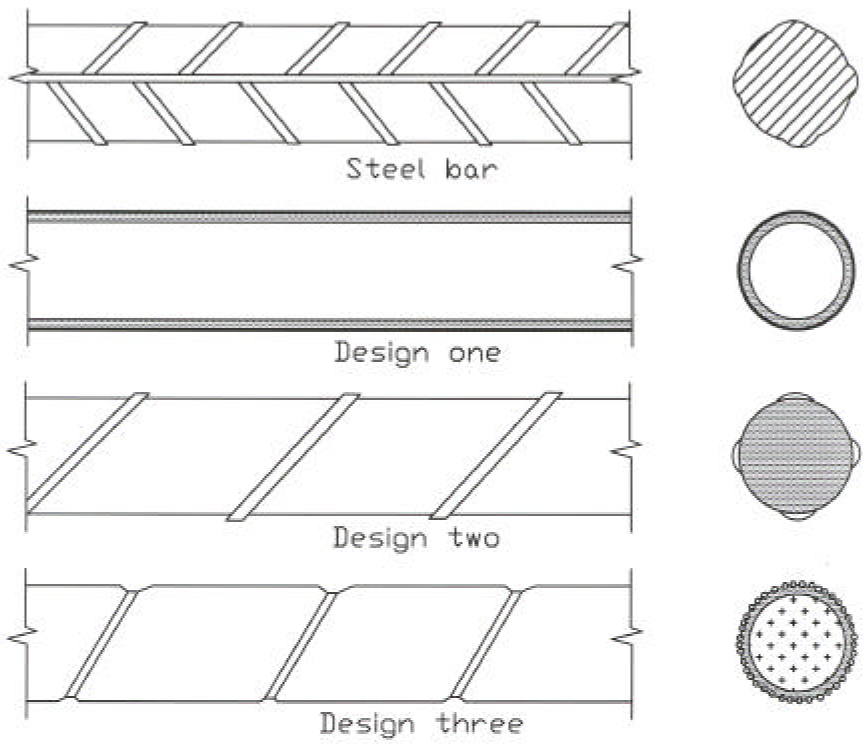
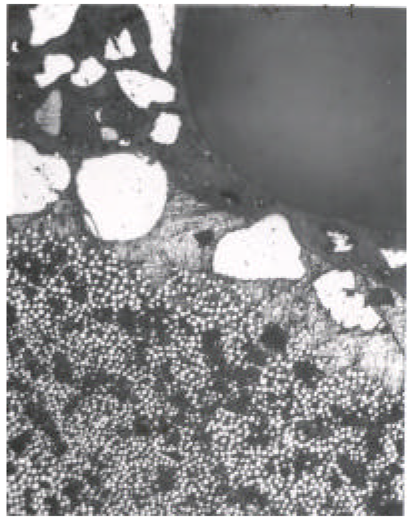


Figure 1: Rebar designs



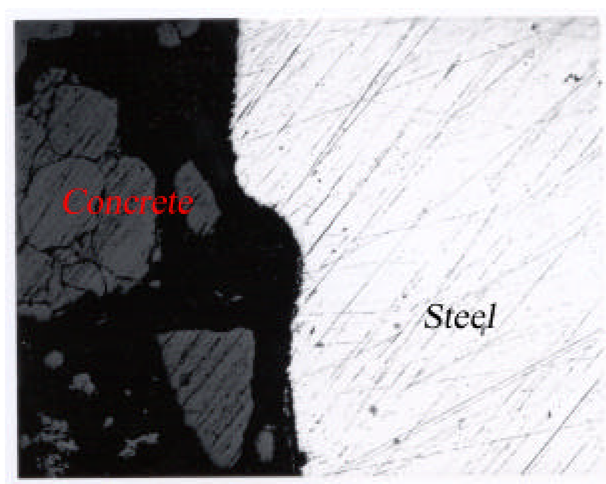


Figure 2: Interface between concrete and (a) FRP rebar (b) concrete rebar

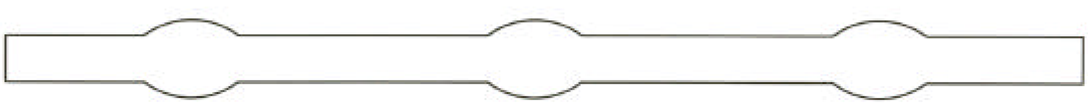


Figure 3: Configuration of the new rebar design.

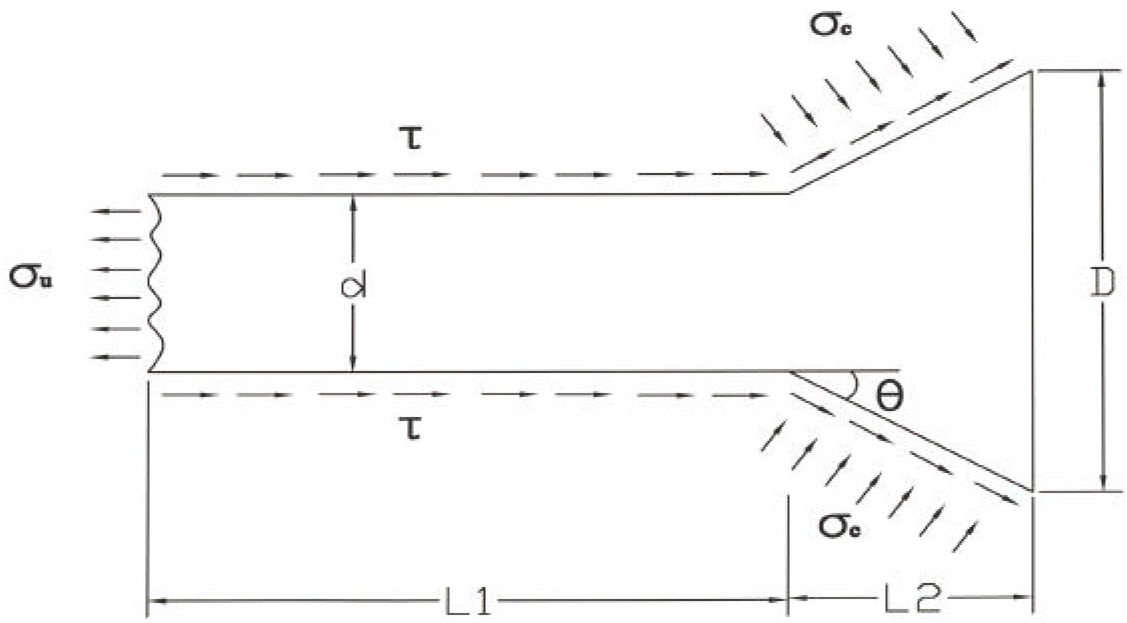


Figure 4: Approximate configuration for analysis