Evaluation of Bond Strength of FRP Reinforcing Rods in Concrete and FE Modelling

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Citation

Abstract
The bond behavior of FRP rebars embedded in concrete was studied. A total of forty-eight pull-out specimens were tested. The effects of different parameters of FRP rebars, such as type, shape and diameter, on the bond behavior of FRP rebars and concrete were evaluated. The average bond strength developed by the Aramid, Carbon and Glass FRP bars in pull-out tests was experimentally evaluated. Test results indicated that the average maximum bond strength of FRP rebars varied from 7.6 to 28 MPa depending on surface deformation and diameter. The maximum bond strength of FRP bars to concrete was 28 MPa, which was obtained from sand-coated bars (ISOROD bars). The M-Bar smooth type had the lowest bond behavior in concrete. The surface deformation and type of risen (the mechanical and physical properties of the outer surface) are the characteristics that have the greatest effect on the bond behavior of FRP rebars in concrete. Unlike steel bars, the mode of failure was damage of the outer surface of FRP rebars. Theoretical analyses using the finite element method were conducted to study the effect of FRP rebar type, bonded length and surface characteristics of the FRP bars. The finite element simulation is in good agreement with the experimental results of the pull-out tests obtained from carbon ISOROD bars.

1. Introduction

Steel reinforcement is vulnerable to corrosion, and this problem has concerned infrastructure owners and engineers for many years. Recently, there have been increased efforts in many research centres to introduce new advanced composite materials, known as Fibre-Reinforced Polymers (FRP), as replacement for steel reinforcement in concrete structures [1]. FRP are not only more resistant to corrosion, but also lighter and stronger than steel, even with lower Young modulus. To overcome the inertia of the construction industry in adopting new structural materials, research needs to be conducted on all aspects of their structural behaviour. One of the fundamental aspects of structural behaviour is bond development, since bond is the key for co-operation between reinforcing bars and concrete.

It is important to understand the various mechanisms that come into play and how they lead to the bond of FRP bars to concrete. Due to the anisotropic properties of continuous FRP, the actual pull-out and splitting modes of failure of FRP bars are expected to be
different from those of steel bars, and experimental work is needed to quantify this. The bond strength of FRP bars in concrete depends on several factors, such as surface deformation, mechanical interlock, chemical adhesion, embedment length, diameter, environmental conditions, and loading conditions [2-10, among others].

In the past decade, studies of the bond strength of FRP reinforcing bars in concrete have evolved continuously in response to improvements in the performance of composites materials and research strategies in different countries. In the light of this development, we cite in the following paragraph some examples of research works in this field.

Achillides and Pilakoutas [6] examined the bond behavior of fiber reinforced polymer bars under direct pullout conditions. This study shows the influence of various parameters that affect bond strength such as the embedment length, type, shape, surface characteristics, and diameter of the bar as well as concrete strength. The experimental results showed that, in normal concrete, the mode of bond failure of FRP bars was found to differ substantially from that of deformed steel bars because of damage to the resin surface of the bar when pullout takes place. The obtained load-slip curves show some of the fundamental differences between steel and FRP materials.

Mosley et al. [11] assumed that the bond strength achieved by FRP reinforcement is significantly lower than that achieved by steel reinforcement and that the reinforcement modulus of elasticity is an essential variable affecting bond strength. Davalos et al. [12] presented an experimental investigation that describes the durability performance of FRP bar-concrete interface bond, purposely focused on the surface material degradation of FRP bar by using a concrete mix with high compressive strength. The conclusion of their work provides that for the concrete with high compressive strength, the pullout bond failure for GFRP bars mainly occurred within the bar surfaces. In this case, the bond strength of FRP bars was not controlled by the concrete strength. But when concrete has a relatively low strength, bond failure depends on concrete compressive strength and is due mainly to concrete failure.

Hao et al. [7] presented an experimental study on the bond behavior of glass fiber reinforced polymer (GFRP) ribbed rears with thirty different specially designed rib geometries to the normal strength concrete. The test variables were the rebar diameter, rib spacing, and rib height. The experimental results showed that, in normal strength concrete, the bond strength and bond-slip performance of these ribbed rears varied with the combinations of rib spacing and rib height, alternatively known as the relative rib area (ratio of projected rib area normal to bar axis to product of nominal bar perimeter and center-to-center rib spacing). Based on analysis of the test results, design recommendations involving optimal rib spacing and rib height were made concerning optimum rib geometries of GFRP ribbed rears with superior bond-slip performance.

Robert and Bennmokrane [8] presented the results of an experimental study on the durability of the bond between GFRP bars and concrete, especially as it relates to degradation of the GFRP-bar surface and the behaviour of the bar-concrete interface. In the same investigation, the authors have used several techniques to characterize how bar aging affected the bond between the GFRP bars and the concrete. The authors showed that aging did not significantly affect the durability of the bar-concrete interface under the conditions used in their study.

Chang et al. [13] presented a numerical investigation of pullout behavior of fiber reinforced polymer (FRP) bar from concrete matrix. A progressive damage model is used to capture the debonding process. In this study, the effects of embedded length, diameter of FRP bar and bond strength on the load-loaded end displacement are studied. What is interesting in these numerical results is that they show that: first, the bond stress decreases gradually from loaded end to embedded end along embedded bar length. Secondly, the debonding initially starts from loaded end and propagates to embedded end as load increasing and finally the embedded length and bond strength affect the load-loaded end displacement curves significantly while the diameter of the FRP bar has no obvious effect on these curves.

An experimental work was conducted by Masmoudi et al. [14] to study the effect of temperature ranging from 20°C to 80°C in dry environment on bond properties between Glass Fiber Reinforced polymer (GFRP) bars and concrete. The authors showed that no significant reduction on bond strength for temperatures up to 60°C. However, a maximum of 14% reduction of the bond strength was observed for 80°C temperature after 8 months of thermal loading.

The effects of structural fibers on bonding mechanism changes in interface between GFRP bar and concrete have been studied by kim et al. [15]. The authors presented and analyzed the results of direct pull-out testing with the aim of clarifying the effect of surface treatment of bar, fiber type, and fiber volume fraction in interface and suggesting the effective evaluation method for the improved ductility. The authors assumed that, the structural fibers in the interface changed the interfacial bond behaviors before and after the maximum stress and resulted in significant improvement of the relative bond strength, but bond failure modes largely depended on the interfacial property with the rebar.

Golafshani et al. [16] examined the bond behavior of steel and GFRP bars in self-compacting concrete (SCC). In order to investigate the effect of bleeding, the authors used two types of vertical and horizontal concrete elements with four bars located at different positions and the bond behaviors of the above-mentioned bars in two types of SCC were investigated and compared with that of normal concrete (NC). The results showed that regarding the suitable adhesion treatment of steel bars, their bond behavior is higher than that of GFRP bars in SCC.
drop-in bond strength of steel bars at the top of vertical elements averages 5.49% less in SCC than in NC and 8.06% in the case of GFRP bars. Also, for both SCC and NC, reducing the water to cement ratio and using high powdery materials decreases the bond strength variations in horizontal and vertical elements. However, the bond strength variations of steel bars are less than that of GFRP bars.

Islam et al. [9] presented the experimental results of 180 pullout tests conducted on GFRP bars embedded into high-strength concrete blocks. The test variables were bar diameter size (12 or 16 mm), embedment length (4 or 6 times the bar diameter), bar end condition (straight and headed), and concrete cover (1.5, 2.5, and 5 or 7 times bar diameter for straight bars and 8 or 10.5 times bar diameter for headed bars) in addition to a case of no embedment length except the head length for headed-end bars. The authors showed that, the bond stress was shown to be inversely proportional to the embedment length and bar diameter as expected. In addition, the smaller concrete cover appeared to have significant effect on bond stress, leading to side blow-out failure rather than bar pullout or concrete splitting in the case of headed-end GFRP bars. They also showed that, the GFRP bar with headed-end showed significant increase in pullout strength compared to that for the straight-end bars. The authors finish their work with the proposition of an empirical expression to calculate the development length of GFRP bars with either straight or headed-end, with the comparison of the results with the available design standards such as CSA-S806-02 [17], CSA S6-06 [18] and ACI 440-1R-06 [19].

Based on the results of ten pullout tests from the literature, Yan and Lin [20] presented a bond damage assessment approach for the glass fiber-reinforced polymer bar-concrete interface. The damage evolution equations are proposed based on the strain equivalence principle of damage mechanics, where the variations of the secant modulus of the bond-slip curve are utilized to evaluate the interface deterioration against slip. Numerical analyses are conducted with the ANSYS finite element (FE) program to simulate the bond behavior of pullout test. The FE models were used to predict the bond-slip relations with respect to plain concrete and fiber reinforced concrete, covering both geometry modeling and material modeling.

Yan and Lin [10] presented the results of an experimental study on the bond durability of glass fiber-reinforced polymer bars to fiber-reinforced concrete (FRC) exposed to saline solutions. A total of 105 pullout specimens reinforced with steel and polyvinyl alcohol (PVA) fibers were prepared and immersed in the saline solutions at 50 and 70°C under 30, 45, and 60 days, respectively. In this work, the durability of the specimens was quantified in terms of failure mode, adhesion stress as well as the bond strength. Test results revealed that the steel FRC samples exhibited the better bond durability than that of PVA FRC ones, when the same fiber volume fraction was used. Also, the authors have developed a detailed procedure using Arrhenius law and time shift factor (TSF) methods to predict the long-term bond degradation under different environmental temperatures and relative humidity.

This paper presents experimental and finite element studies conducted at the Department of Civil Engineering, University of Sherbrooke (Canada), aimed at investigating the bond performance of glass, carbon and aramid FRP bars to concrete. The effects of bar diameter were evaluated in two types of GFRP bars.

2. Research Significance

It is important to understand the bond behavior of FRP bars in concrete. FRP rebars are destined to become alternatives to traditional reinforcement. Currently, limited data are available on FRP rebars in design guidelines and recommendations [1, 17-19, 21-24]. This research was carried out to provide a better understanding of bond behavior of FRP rebars in concrete. As well, many types of available FRP bars need to be examined in order to form a database of design guidelines for using FRP rebars.

3. Experimental Program (Round Robin Test)

3.1. Test Specimens

The round robin tests (pullout-test) were carried out using a Baldwin loading machine, the concrete block was fixed, as shown in Figure 1 (a). The loading rate was 0.1 kN/min. The anchor was constructed so as to transmit loads reliably, transmitting only axial loads to the test section specimen, without introducing either torsion or bending. The anchor specified in the “Anchor for testing FRP bar under monotonic, sustained, and cyclic tension” was used [25].

Three LVDTs were used to measure the slip of the bar at the loaded end (Figure 1b), and one LVDT placed at the free (unloaded) end of the bar (Figure 1c).
3.2. Materials Properties of FRP Rebars and Concrete

FRP reinforcing bars are manufactured from continuous fibers (such as carbon, glass and aramid) embedded in matrices (thermosetting or thermoplastic). Similarly, to steel reinforcement, FRP bars are produced in different diameters, depending on the manufacturing process. The surface of the rods can be spiral, straight, sanded-straight, sanded-braided and deformed.

Ten types of FRP bars were tested in this study. Five types of FRP bars are made with carbon fibers GFRP (Carbopree, ISOROD, C-BAR, M-BAR smooth, and M-BAR rough). Four others types were made using glass fibers GFRP (ISOROD, C-BAR, Aslan, and Eurocrete). One bar containing aramid fibers AFRP (Arapree) was also tested. Photos of the carbon, glass and aramid FRP bars are shown in Figures 2a, 2b, and 2c, respectively.

It should be mentioned that the effect of the diameter of bars was evaluated for the glass FRP ISOROD (9.53, 12.7, 15.88, and 19.05 mm) and for the Aslan glass FRP reinforcing rods (6.35, 9.53 and 15.88 mm).

The properties of all FRP bars tested in this study are presented in Table 1. The bonded length for all the tests is taken as equal to 5 times the diameter (5 Ø). The bonded length was chosen to be sufficiently representative of bar surface deformations [26]. The bars were supplied in 3 samples for each diameter with 1-meter lengths.

The dimensions of the concrete cube were equal to 200 mm. The specimen was cast vertically. The composition and mechanical properties of the concrete used are given in Table 2. Concrete characteristics were obtained from the testing of at least 3 cylinders measuring 150 × 300 mm.

<table>
<thead>
<tr>
<th>FRP bars</th>
<th>Nominal Diameter (mm)</th>
<th>Tensile Strength (MPa)</th>
<th>Elastic Modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbopree</td>
<td>10</td>
<td>22800</td>
<td>130</td>
</tr>
<tr>
<td>ISOROD Carbon</td>
<td>9.53</td>
<td>1500</td>
<td>110</td>
</tr>
<tr>
<td>C-BAR Carbon</td>
<td>9.53</td>
<td>1550</td>
<td>120</td>
</tr>
<tr>
<td>M-BAR smooth &amp; rough</td>
<td>7.5</td>
<td>1400-1600</td>
<td>110-120</td>
</tr>
<tr>
<td>ISOROD Glass</td>
<td>9.53 - 12.7 - 15.9 - 19.05</td>
<td>635-747</td>
<td>37-43</td>
</tr>
<tr>
<td>C-BAR Glass</td>
<td>9.53</td>
<td>770</td>
<td>39</td>
</tr>
<tr>
<td>Aslan GFRP rebar</td>
<td>66.35, 9.53, 15.88</td>
<td>620-760</td>
<td>40.8</td>
</tr>
<tr>
<td>EUROCRETE GFRP rebar</td>
<td>8 mm (square)</td>
<td>900</td>
<td>45</td>
</tr>
<tr>
<td>Arapree AFRP rebar</td>
<td>10</td>
<td>1350</td>
<td>60</td>
</tr>
<tr>
<td>Carbopree</td>
<td>ISOROD</td>
<td>C-BAR</td>
<td>M-BAR smooth</td>
</tr>
<tr>
<td>-----------</td>
<td>--------</td>
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</tr>
</tbody>
</table>

(a) Tested CFRP rods

<table>
<thead>
<tr>
<th>ISOROD</th>
<th>C-BAR</th>
<th>Aslan</th>
<th>EUROCRETE</th>
</tr>
</thead>
</table>

(b) Tested GFRP rods

<table>
<thead>
<tr>
<th>Arapree</th>
</tr>
</thead>
</table>

(c) Tested AFRP rods

*Figure 2. FRP rods used in this study.*
Table 2. Mix design and mechanical properties of concrete.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water-to-Cement Ratio (W/C)</td>
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</tr>
<tr>
<td>Water (kg/m³)</td>
<td>167</td>
</tr>
<tr>
<td>Cement - type 10 (kg/m³)</td>
<td>372</td>
</tr>
<tr>
<td>Fine aggregate (kg/m³) 0/5 mm</td>
<td>737</td>
</tr>
<tr>
<td>Coarse aggregate (kg/m³) 0/14 mm</td>
<td>990</td>
</tr>
<tr>
<td>Water-reducing agent (ml/m³)</td>
<td>930</td>
</tr>
<tr>
<td>f’c (MPa) 28 days</td>
<td>40</td>
</tr>
<tr>
<td>f’c (MPa) at the daytime of the test</td>
<td>55</td>
</tr>
<tr>
<td>Ec (GPa) 28 days</td>
<td>30</td>
</tr>
<tr>
<td>Ec (GPa) at the daytime of the test</td>
<td>32</td>
</tr>
</tbody>
</table>

4. Discussion of the Experimental Results

The results obtained concerning the round robin tests are shown on graphs connecting the pull-out load with the end slip, characterized by the readings obtained from the LVDT placed at the bottom. For each type of bar, three pull-out tests were carried out. The three curves obtained for each bar are presented on the same graph. However, some tests could not be performed adequately, and for some types of bar, only the two curves obtained are shown.

The surface of all the bars was examined after each pullout test to evaluate the damage to the bar and its surface. Figures 3-28 show pullout-slip curves for both FRP and steel-bars at unloaded and loaded ends.
Figure 5. Pull-out load versus slip at unloaded end of ISOROD Carbon bar ($\phi = 9.53$ mm).

Figure 6. Pull-out load versus slip at loaded end of ISOROD Carbon bar ($\phi = 9.53$ mm).

Figure 7. Pull-out load versus slip at unloaded end of C-BAR Carbon bar ($\phi = 9.53$ mm).
Figure 8. Pull-out load versus slip at loaded end of C-BAR Carbon bar ($\Theta = 9.53$ mm).

Figure 9. Pull-out load versus slip at unloaded end of M-bar rough CFRP ($\Theta = 7.50$ mm).

Figure 10. Pull-out load versus slip at loaded end of M-bar rough CFRP ($\Theta = 7.50$ mm).
Figure 11. Pull-out load versus slip at unloaded end of M-bar smooth CFRP (Ø = 7.50 mm).

Figure 12. Pull-out load versus slip at loaded end of M-bar smooth CFRP (Ø = 7.50 mm).

Figure 13. Pull-out load versus slip at unloaded end of ISOROD Glass bar (Ø = 9.53 mm).
Figure 14. Pull-out load versus slip at loaded end of ISOROD Glass bar ($\phi = 9.53$ mm).

Figure 15. Pull-out load versus slip at unloaded end of C-BAR Glass bar ($\phi = 9.53$ mm).

Figure 16. Pull-out load versus slip at loaded end of C-BAR Glass bar ($\phi = 9.53$ mm).
Figure 17. Pull-out load versus slip at unloaded end of Aslan GFRP rebar (Ø = 6.35 mm).

Figure 18. Pull-out load versus slip at loaded end of Aslan GFRP rebar (Ø = 6.35 mm).

Figure 19. Pull-out load versus slip at unloaded end of Aslan GFRP rebar (Ø = 9.35 mm).
Figure 20. Pull-out load versus slip at loaded end of Aslan GFRP rebar ($\varnothing = 9.35$ mm).

Figure 21. Pull-out load versus slip at unloaded end of Aslan GFRP rebar ($\varnothing = 15.88$ mm).

Figure 22. Pull-out load versus slip at loaded end of Aslan GFRP rebar ($\varnothing = 15.88$ mm).
Figure 23. Pull-out load versus slip at unloaded end of EUROCRETE GFRP rebar (square 8x8 mm).

Figure 24. Pull-out load versus slip at loaded end of EUROCRETE GFRP rebar (square 8x8 mm).

Figure 25. Pull-out load versus slip at unloaded end of Arapree bar (Ø = 10 mm).
Figure 26. Pull-out load versus slip at loaded end of Arapree bar (Ø = 10 mm).

Figure 27. Pull-out load versus slip at unloaded end of steel bar (Ø = 11.30 mm).

Figure 28. Pull-out load versus slip at loaded end of steel bar (Ø = 11.30 mm).
4.1. Bond Strength

Bond strength was determined using the equation based on the maximum pullout load $P_{\text{max}}$, assuming a uniform bond stress distribution along the embedded length of the rod in the concrete. The average maximum pull-out load and bond strength of all experimental programs are presented in Table 3.

The bond strength was calculated using the nominal rod diameter. There was a small difference in concrete strength, but this was neglected in the bond strength evaluation [27]. For Aramid bars, the average bond stress obtained was 13.5 MPa. The maximum pullout force obtained was between 19 and 23 kN. The maximum average bond stress obtained for the C-BAR of 9.53 mm in diameter was approximately 18.5 MPa. Also, the maximum pullout loads obtained for the three specimens tested were between 23 kN and 28 kN. The highest bond values were obtained on ISOROD Glass bars with a maximum average bond stress about 28 MPa.

The effect of diameter is presented in the histogram shown in Figure 29. For ISOROD Glass series (Figure 29 a), the bond stress of FRP bars of 9.53 mm in diameter developed 14%, 8% and 24% more than specimens of 12.7, 15.88 and 19.05 mm in diameter respectively. Whereas for the Aslan GFRP bars series (Figure 29b) a linear relationship between the load and the end slip was observed before reaching 75%, 60% and 45% of the maximum load, respectively, for the rebars measuring 6.35, 9.53 and 15.88 mm in diameter.

The average bond stress obtained for Carbopree was 18.2 MPa. Results for maximum pullout force were between 23 and 36 kN. Two types of M-carbon bars were tested, having a rough and a smooth surface respectively. The average adhesion bond stress obtained was 19.2 MPa for the bar with a rough surface and 7.6 MPa for the bar with a smooth surface. The lowest bond strength was obtained in smooth bars. The maximum pullout force at this phase was 17 kN and 6.8 kN, respectively. Finally, for the EUROCRETE GFRP rebar with square section, the average maximum bond strength obtained was 12 MPa. In this case, the average maximum pullout force was between 11 and 21 kN.

![Figure 29. Effect of diameter on average bond stress.](image)

<table>
<thead>
<tr>
<th>FRP bars</th>
<th>Nominal Diameter $d$ (mm)</th>
<th>Bonded length $l$ (mm)</th>
<th>Average maximum pullout load $F$ (KN)</th>
<th>Average maximum bond stress $\tau$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arapree AFRP rebar</td>
<td>10</td>
<td>50</td>
<td>20.99 ±3.7</td>
<td>13.36±2.34</td>
</tr>
<tr>
<td>Carbopree CFRP bar</td>
<td>10</td>
<td>50</td>
<td>28.47±6.8</td>
<td>18.12±4.35</td>
</tr>
<tr>
<td>Aslan GFRP rebar</td>
<td>6.35</td>
<td>31.75</td>
<td>19.37 ±1.2</td>
<td>30.59±1.95</td>
</tr>
<tr>
<td>Aslan GFRP rebar</td>
<td>9.53</td>
<td>47.65</td>
<td>35.20 ±0.65</td>
<td>24.65±0.46</td>
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<tr>
<td>Aslan GFRP rebar</td>
<td>15.88</td>
<td>79.40</td>
<td>82.35 ±6.22</td>
<td>20.79±1.57</td>
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<tr>
<td>Eurocrete GFRP rebar</td>
<td>8 mm</td>
<td>40</td>
<td>16.15 ±5.08</td>
<td>12.62±3.96</td>
</tr>
<tr>
<td>M-BAR rough (CFRP)</td>
<td>7.5</td>
<td>37.5</td>
<td>First pick: 17.0 ±4.24</td>
<td>First pick: 9.24±4.80</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>First pick: 21.2 ±3.71</td>
<td>First pick: 27.76±4.92</td>
</tr>
<tr>
<td>M-BAR smooth (CFRP)</td>
<td>7.5</td>
<td>37.5</td>
<td>First pick: 6.72 ±0.22</td>
<td>First pick: 7.61±0.25</td>
</tr>
<tr>
<td>C-BAR Carbon</td>
<td>9.53</td>
<td>47.65</td>
<td>27.53 ±1.55</td>
<td>18.99±1.07</td>
</tr>
<tr>
<td>C-BAR Glass</td>
<td>9.53</td>
<td>47.65</td>
<td>25.09 ±1.98</td>
<td>18.52±1.46</td>
</tr>
<tr>
<td>ISOROD-Carbon</td>
<td>9.53</td>
<td>47.65</td>
<td>38.43 ±3.33</td>
<td>27.10±2.34</td>
</tr>
<tr>
<td>ISOROD-Glass</td>
<td>9.53</td>
<td>47.65</td>
<td>39.81 ±1.01</td>
<td>28.08±0.71</td>
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<tr>
<td>ISOROD-Glass</td>
<td>12.7</td>
<td>63.5</td>
<td>61.44 ±2.84</td>
<td>24.25±1.12</td>
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<tr>
<td>ISOROD-Glass</td>
<td>15.88</td>
<td>79.40</td>
<td>102.79±0.93</td>
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<tr>
<td>ISOROD-Glass</td>
<td>19.05</td>
<td>95.25</td>
<td>122.17±5.42</td>
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<tr>
<td>Steel bar</td>
<td>11.3</td>
<td>56.50</td>
<td>44.40±1.10</td>
<td>25.01±0.62</td>
</tr>
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</table>
4.2. Surface Examination

The surface of all rods was examined after pull-out tests to evaluate the damage to the rod and its surface. Figures 30, 31 and 32 show the surface deterioration of FRP bars due to the friction between the bars and concrete. Unlike steel bars, the damage is at the outer surface of the bar. We can observe the failure mode of the embedded length of the bar characterized by the shearing off of all lugs and rough surfaces at the end of the pull-out test. These results confirm that adhesion and friction are the most important components of bond stress in FRP reinforcing bars.

<table>
<thead>
<tr>
<th>Carbopree</th>
<th>ISOROD</th>
<th>C-BAR</th>
<th>M-BAR smooth</th>
<th>M-BAR rough</th>
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</table>

*Figure 30. CFRP bars after pullout test.*

<table>
<thead>
<tr>
<th>ISOROD</th>
<th>C-BAR</th>
<th>Asland</th>
<th>EUROCRETE</th>
</tr>
</thead>
<tbody>
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*Figure 31. GFRP bars after pullout test.*

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td><img src="image10.png" alt="Image" /></td>
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</table>

*Figure 32. AFRP bar after pullout test.*
4.3. Pre-peak Behaviour

The slope of the pre-peak curve can be considered to be the bond stiffness, as it indicates a relationship between load and deformation. Its value has an important effect on the width of primary cracks in reinforced concrete and on the deflection of the beams and slabs. The bond behavior of Aramid bars before peak is linear (elastic-no debonding) at early age. For ISOROD Glass bars, a linear relationship between the load and the end slip was observed before reaching 60% of the maximum load. Up to the peak, the curve becomes non-linear until the maximum. In Aslan GFRP bars, after the early stage, debonding was initiated and the load continued to increase. In this case, we observe a change in the slope of the curves, and that adhesion bond strength has been exceeded. This increase is due to the contribution of the first helical braid. For Carbopree bars, before peak load level in the early stage of loading, the stress transfer mechanism is elastic (no debonding) and the curve is linear. For M-BARS, the pullout force continues to decline progressively as the bar is extracted. The behavior of the bond strength of M-BARS is non-uniform and displays two stages of debonding, slipping and/or separation during the early age. For ISOROD GFRP bars tested. The decreasing curve continuously decreasing. For all bars tested, we observed that the residual loads were very weak, even though, a stick-slip phenomenon appeared on some pull-out tests. For Aslan GFRP bars, we observed a drop in the load after it attained its maximum. The decrease in load was linear and progressive due to the frictional resistance influenced by abrasion between the coated sand of the rebar and concrete. We noticed a second increase in the load, which was due to the contribution of the second helical braid present on the rebar. Similar steps continued after the second peak in comparison with the first post-peak behavior. After the maximum pullout load of Carbopree bars, the debonding of the bar decreased the pullout load to about 50% of the maximum load. For M-BARS, after the adhesion bond strength was exceeded, debonding was initiated and the pullout force dropped gradually. In the case of EUROCRETE GFRP bars, after maximum pullout load, the debonding of the bar decreased the pullout load by about 50% of the maximum load.

4.4. Post-Peak Behaviour

After the maximum pullout load of Aramid bar, the debonding of the bar decreases the pullout load to about 50% of the maximum load. The decreasing curve commencing after this is the result of frictional resistance, while the Aramid FRP bar is being extracted from the concrete, which is an embedded length continuously decreasing. This zone is characterized by a ‘stick-slip’ behavior, which occurs when the ductile FRP bar is drawn from the brittle concrete. After peak load of the C-BAR, debonding of the bar decreases the pullout load to about 90% of the maximum load (rapid drop or sharp drop). Following that, the surface deformations in the C-BAR allowed an increase in pullout load. A progressive debonding continues thereafter until no load. In this case, there was no stick-slip phenomenon because the frictions were applied to a smooth surface. Normally, lugs dissociate progressively one after the other from the loaded end until the unloaded end. After the maximum pullout load of ISOROD GFRP bars (this value remains constant until a certain value of end slip, which is a function of the diameter of bars), the debonding of the bar was catastrophic for all the ISOROD GFRP bars tested. The decreasing curve commencing after this is the result of the residual frictional resistance while the ISOROD GFRP bars were being extracted from the concrete, which is an embedded length continuously decreasing. For all bars tested, we observed that the frictional shear stress has an initial value $C$. It increases proportionally to the normal stress up to a limiting value of $\mu$ as expressed in the following equation (Coulomb’s law):

$$\tau = C - \mu \sigma$$  \hspace{1cm} (1)

Where $\mu$ coefficient of friction between FRP and matrix (note that the shear strength at the interface is directly proportional to the clamping pressure). Parameter $\tau_0$ represents the frictional shear strength in the absence of normal stress. The second term in the equation takes into account the effect of normal stress in the debonding zone. Increasing the clamping pressure increases the shear strength. The loading is applied in two steps. Initially, the clamping pressure is applied along the outer layer of the mesh, and the elastic solution is obtained. The typical compressive pressure $p$ applied was in the range of 55 MPa. The level of displacement was achieved in approximately 15 increments. After each incremental solution was derived, load and end

5. Finite Element Modelling of Pull-Out Bond Behaviour

A 2-D axisymmetric finite element model (FEM) formulation was used to formulate the pull-out of FRP bars from concrete. A schematic representation of the finite element mesh is shown in Figure 33. A clamping pressure $p$ was applied at the outer layer of matrix elements to simulate the effect of residual compressive stresses due to concrete shrinkage. This results in a normal stress distribution on the interface layer. Two sliding contact surfaces were defined (one on the elements representing the FRP bar and the other on the concrete). The thickness of the contact elements was zero, as they are initially bonded. As debonding occurs between these two contact surfaces, they may go through stages of debonding, slipping and/or separation during the FRP pull-out process. After debonding, only the stress continuity across the sliding contact elements is preserved.

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slip at the bar were obtained.

As shown in Figure 34, it is possible to distinguish two cases: when the normal stress is greater than \( \sigma_d \), the separation occurs between concrete FRP. In this case the shear and the normal stresses are reduced to zero. In the second case, when the normal stress is lower than \( \sigma_d \), a slip occurs between the concrete and FRP bars.

In this study, the simulations of the pullout test using the finite element model (FEM) were carried out solely for the case of ISOROD carbon bars. The \( C \) and \( \sigma_d \) parameters that characterize the quality of the bond between the concrete and the FRP are taken to be equal to 1 MPa (\( C = \sigma_d = 1 \) MPa). The coefficient of friction and the clamping pressure were evaluated experimentally, as follows.

### 5.1. Frictional Slip and Normal Stresses

The discussion in this section emphasizes the important role of frictional slip resistance in stress transfer mechanisms. The magnitude of this effect is a function of the normal stress that develops across the interface, and the apparent coefficient of friction:

\[
\tau_{fu} = \mu \sigma_n
\]  

Normal stresses are generated by a misfit (\( \delta \)) between the radius of the bar and the radius of the hole in the free matrix, i.e. the matrix in the absence of the bar. A reduction in the radius of the matrix hole for any reason would induce normal compressive stresses, which increase the frictional resistance. The normal strain, associated with the misfit would be:

\[
\epsilon_{no} = \frac{\delta}{r}
\]  

If the value of \( \delta \) is negative (the reduction in the radius of the hole in the free matrix is greater than the reduction of the bar radius), the resulting normal compressive stress will lead to enhanced frictional resistance. If, however, the value of \( \delta \) is positive, normal compressive stresses will not develop, and the frictional resistance to slip will be greatly reduced. These effects should be considered when predicting the magnitude of the bar-matrix misfit and of normal stresses:

a. Volume changes: drying shrinkage of the concrete is an example of matrix contraction in excess of that of the bars. Although this effect can be simply analysed in terms of shrinkage strains, it may involve some additional complexities arising from cracks generated during shrinkage.

b. External stresses: external pressure on the composite could generate normal compressive stresses across the interface.

c. Poisson effect: if the Poisson's ratio on the bar is smaller than that of the concrete, under tensile loading, the misfit would be negative, resulting in normal compressive stresses and increased frictional resistance.

#### 5.1.1. Clamping Pressure

To determine the clamping pressure, a strain gage was used to measure the radial strain in the FRP due to the effect of concrete shrinkage. The value of measured strain was used.
to deduce the clamping pressure using a finite element simulation. The Figure 35 shows the evolution of the radial strains during time in the case of ISOROD carbon bar until the day of test.

Figure 35. Evolution of the clamping pressure in ISOROD carbon before the test.

5.1.2. Coefficient of Friction
An experimental procedure (Figure 36) was adopted to measure the friction coefficient of the FRP bars used in this study. The measured value of the friction coefficient obtained was for the ISOROD carbon bars only. The value of this coefficient is equal to $\tan \alpha$, where alpha ($\alpha$) is the necessary angle to permit the slip of the bar.

Figure 36. Experimental procedure to determine the coefficient of friction of the FRP bars.

5.2. Finite Element Model Results
Figure 37 shows the comparison of the load vs. slip at unloaded end displacement for the FEM model, with experimental results. We can observe that the finite element simulation is in agreement with the experimental result of the round robin test obtained for the ISOROD carbon bar with 9.53 mm in diameter. Note that the pullout force increases linearly up to 50% of the peak load (24 kN). Beyond this level, the response becomes non-linear due to the propagation of the debonding zone. The corresponding shear stress distribution during debonding stages is shown in Figure 38.

Figure 37. Comparison of the load vs. end slip for the FEM model with the experimental results.
In many simplified treatments of the stress transfer problem, reference is made to an average bond stress value, assuming a uniform interfacial shear distribution along the embedded length \( d \) of bar under a maximum pullout load:

\[
P. \tau = \left( \frac{P}{\pi d l} \right)
\]

(4)

This value has no physical significance; the FEM results obtained confirm that. Indeed, according the curves of the shear stress distribution along the ISOROD carbon bar, we notice that the average shear bond strength (28 MPa) was an underestimate of the adhesion shear strength and an overestimate of the frictional strength.

6. Conclusions

The physical and mechanical properties of the outer surface of FRP rebars have the greatest effects on the bond behavior of FRP rebars to concrete. The bond strength depends on surface deformation and type of matrix. For an embedded length lower than the developed length, the type of fiber having the same characteristics does not have a significant effect on bond strength. Sand-coated rebars show higher bond strength (28 MPa) than deformed bars (18.5 MPa) or sand-coated with helical deformed bars (24 MPa). For their part, smooth bars had the lowest bond strength in concrete (7.6 MPa).

Sand coating improves the bond strength of FRP rebars in concrete, which means that increasing the friction resistance of the bar to concrete increases the bond strength. Unlike steel bars, friction controls the bond strength of FRP rebars to concrete. The pre-peak behavior, which is important in design recommendations regarding the use of FRP bars, is linear. Also, the bond stiffness in some types of FRP bars is greater than the corresponding deformed steel. The bond strength of FRP rebars also decreases when the diameter of the rebar increases.

Post-peak behavior of bond strength of some types of FRP bars shows sharp or sudden drops of maximum load, which depends on the roughness of the surface and stick-slip behavior. In addition, the pullout test of deformed steel bars shows a sudden drop in maximum load when the concrete fails due to the very stiff deformations of steel bars. A slight ductile behavior of bond failure appears in sand-coated FRP bars.

The finite element model indicates a good agreement with experimental results obtained from the pull-out test performed on ISOROD carbon bars with a nominal diameter of 9.5 mm. From the bond distribution model, we can deduce that the maximum bond stress moves toward the unloaded end of the bar by increasing the pullout force.

According the curves of the shear stress distribution along the ISOROD carbon bar, we notice that the average shear bond strength was an underestimate of the adhesion shear strength and an overestimate of the frictional strength. The FEM results obtained confirm that.

Acknowledgment

The authors wishes to thank the Natural Sciences and Engineering Research Council of Canada (NSERC), as well as the ISIS Canada Network of Centers of Excellence for the support of various companies in providing the FRP rods used in this study.

Notation

\[
\begin{align*}
P & : \text{Clamping pressure} \\
C & : \text{Initial shear stress}
\end{align*}
\]
\( \mu \) : Friction coefficient
\( \sigma \) : Normal strength
\( \tau \) : Frictional shear strength
\( \tau_o \) : Frictional shear strength in an absence of normal stress
\( \sigma_d \) : Normal tensile strength
\( \delta \) : Misfit (between the radius of the bar and the radius of the hole in the free matrix)
\( \varepsilon_{na} \) : Normal strain
\( r \) : Radius of the bar
\( \tau_{se} \) : Frictional slip resistance
\( \sigma_n \) : Normal stress
\( P \) : Pull-out load
\( d \) : Diameter of the bar
\( l \) : Embedment length

**References**


