Fundamental mechanisms of bonding of glass fiber reinforced polymer reinforcement to concrete

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ABSTRACT

Fundamental mechanisms of bonding between glass fiber reinforced polymer (GFRP) bar and concrete are presented. Contributions from chemical bonding, bearing resistance, and frictional resistance to bond were delineated by measuring the following: the load corresponding to complete debonding of the bar, the load corresponding to onset of sliding and pullout of the bar along the entire embedment length, and the frictional load corresponding to frictional resistance to sliding. Research findings indicate that while chemical bonding was the main contributor to the interfacial bond strength, the other two mechanisms contributed to the pullout strength of the bar. Correlation between the bar’s surface geometry and the contributions from the three mechanisms are discussed.

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1. Introduction

Recently, polymer composite materials are used in civil engineering applications in various forms including rebars for concrete structures, sheets for flexural and shear strengthening, and sheets to wrap concrete columns and bridge piers to increase the confinement. Fiber Reinforced Polymer (FRP) bar is an excellent alternative to steel bars due to their relatively higher corrosion resistance and high specific strength and modulus. Several successful applications can be found in North America. While design codes are well established for the use of steel bars in concrete members, they are slowly increasing for FRP bars. Development of these codes requires a good understanding of bond between FRP bars and concrete and the relationship between the bond strength, and various material and test parameters. Past research has substantially advanced the knowledge in this area. Nevertheless, a substantial variation is observed among the published data on interfacial bond strength, which suggests that a comprehensive understanding is yet to evolve.

Several variations of bar pullout and beam test have been used to study the bond characteristics of FRP bars. Various parameters, whose effect on interfacial bond strength have been studied in the past, are bar embedment length, bar diameter, compressive strength of the concrete, confinement pressure exerted by the concrete on the bar, and surface geometry of the bar.

Al-Zahrani [1] and Benmokrane et al. [2] have observed a decrease in interfacial bond strength with increase in embedment length, as shown in Table 1 for different glass fiber reinforced plastic (GFRP) bars with axi-symmetric lugs [1] and helical lugs [2]. It has been well established that shear stress at the fiber–matrix interface, at any applied load during a single fiber direct pullout test, is not constant. Al-Zahrani et al. [3] and Benmokrane et al. [4] have measured this shear stress distribution experimentally, for concrete reinforced with FRP bar. The interfacial bond strength tabulated in Table 1 has been determined using average shear stress and it varies with embedment length, since the shear stress distribution and the average shear stress would change with embedment length. In addition, reported bond strength values correspond to bar pullout rather than onset or completion of debonding. This is also a reason for the variation observed in Table 1 and will be discussed in subsequent sections.

Test results indicate that increasing bar diameter caused decrease in the bond strength as given in Table 2 for smooth bars [1] and bars with lugs [3]. While variation of shear stress distribution could be one reason, Tighiouart et al. [5] have indicated that bleeding of water could be another reason since an increase in bar diameter could increase the amount of water trapped near the bar leading to higher amount of voids and lesser contact area. Al-Zahrani et al. [3] have varied the compressive strength of the concrete, reinforced with bars wrapped with lugs, from 31.4 MPa
to 66.1 MPa and have observed no change in the interfacial bond strength. This is to be expected since the failure was interfacial. Another work of Al-Zahrani [1] has shown that the induced lateral force could be influenced by the mismatch of Coefficient of Thermal Expansion (CTE) between the concrete and the bar as observed in Table 3 for concrete reinforced with a smooth bar. A test temperature resulted in a bond strength higher than the reference case, for which the test and cure temperatures were same. This is probably due to increase in lateral pressure due to expansion of the bar, which starts at the contact area. While Benmokrane et al. [2] have calculated the contact surface area using the actual diameter of the reinforcing bar and the concrete were same, the difference in the definition and calculation of the contact surface area used in the two groups of researchers. In addition, the interfacial bond strength reported by Al-Zahrani [1] is higher than that reported by Benmokrane et al. [2] despite the lower value for the measured pullout load and same bar dimensions. This apparent discrepancy is believed to be due to the difference in the loading rates used by the two groups of researchers. In addition, the interfacial bond strength reported by Al-Zahrani [1] is calculated the contact area using the actual diameter of the reinforcing bar and the dimensions of the lugs. The above discussion suggests that the interfacial bond strength could be very much dependent on test parameters and surface geometry of the bar, whereas the interfacial bond strength should be a unique value independent of test parameters and surface geometry of the bar.

2. Fundamental behavior during pullout tests

A brief discussion on the pullout behavior of a FRP bar from concrete is included here to assist in the comprehension of the scatter in published interfacial bond strength and to provide the basis for the research approach used in this study.

This development length for civil engineers ($l_c$), which is also known as critical length among composite community, can be predicted using Eq. (1) based on assumption of constant shear stress distribution along the embedded fiber length.

$$l_c = \frac{\sigma_f d}{4\tau_w}$$

where $\sigma_f$ is the fiber stress, $d$ is the fiber diameter and $\tau_w$ is the fiber–matrix interfacial bond strength.

Load applied to the concrete–FRP bar interface, during direct pullout test of a concrete specimen reinforced with a FRP bar of embedment length ($l$) $< l_c$, is shown schematically in Fig. 1 as a function of slip between the bar and the concrete. Fig. 1a represents the possible load–slip curves for a concrete specimen reinforced with a smooth FRP bar. Curve A represents the case when debonding of the smooth FRP bar occurs at a maximum load ($F_p$). The applied load may drop either to zero or to a finite frictional force value, $F_C$. Pullout behavior of the FRP bar may also follow curves B or C since the interfacial stress varies along the embedment length. Curve C represents possible case for a stable debonding of the bar, which starts at $F_C$ and progresses to completion along the entire embedment length at $F_p$. Curve B represents possible partial debonding. In this case, the remaining bonded portion of
the sudden shearing of the remaining intact lugs or sand particles. and hence, a load drop is registered at the maximum load due to the bar debonds in an unstable manner at the peak load and the test.

A comparison of published results to illustrate the influence of test conditions and contact surface area definition on the interfacial bond strength.

Due to shear stress distribution along the embedment length, during this partial sliding, the actual load–slip behavior is dependent on the frictional resistance, the interfacial bond strength, and the length of bonded and debonded regions at any given load.

The interfacial bond strength calculated using $F_p$, for case A, or $F_i$, for cases B and C, would be a measure of the chemical bonding between the FRP bar and the concrete. Owing to weak chemical bonding between concrete and the FRP bar, researchers have modified the FRP bar surface, using lugs and sand particles, to enhance its resistance to sliding and pullout. Fig. 1b represents the load–slip plot for debonding and pullout of a bar with lugs or sand particles. Due to shear stress distribution along the embedment length, during a pullout test, debonding of the FRP bar would start at $F_i$ and would complete at $F_d$ for all the three cases in Fig. 1b. Curve $A'$ represents the case when the applied load continues to increase even after the completion of debonding at $F_d$. This increase is attributed to the bearing resistance, caused by mechanical interlocking of the surfaces of the concrete and the bar, and frictional resistance, caused by the bar’s surface roughness. When the lugs or the sand particles along the entire embedment length are sheared at the maximum load $F_p$, the bearing resistance due to them is eliminated and the load drops suddenly to the frictional force, $F_i$. Alternatively, shearing of lugs and sand particles can be progressive as observed in this study. Curve $C'$ represents the case when the shearing of lugs or sand particles is complete before reaching the maximum load. Curve $B'$ represents the case when the shearing is partial and hence, a load drop is registered at the maximum load due to the sudden shearing of the remaining intact lugs or sand particles.

Between $F_i$ and $F_d$, partial sliding and pullout of the bar occurs along the debonded length. Assuming that the contribution from bearing and frictional resistances to $F_p$, during this partial sliding and pullout, is negligible either $F_i$ or $F_d$ can be used in determining the interfacial bond strength. However, most of the researchers have used the load at which sliding and pullout of the bar occur along the entire embedment length to determine the interfacial bond strength. The maximum pullout load, $F_p$, can be predicted using the following equation

$$F_p = F_d + F_b + F_f$$  \hspace{1cm} (2)$$

where $F_d$, $F_b$, and $F_f$ are debond load, bearing load, and frictional load respectively. $F_p$, $F_p'$, and $F_f'$ represent contributions to pullout load from chemical bonding, bearing resistance, and frictional resistance respectively.

The interfacial bond strength determined using the debond load would be a unique value independent of the surface geometry of the bar and the test conditions. However, the interfacial bond strength determined using the pullout load would not be a unique value because the pullout load is dependent on these three mechanisms, two of which are dependent on the surface geometry of the bar and the test conditions. Unfortunately, most of the previous studies have used the pullout load to determine the interfacial bond strength. Since the parameters that influence the bearing and frictional loads were varied arbitrarily, the reported values for the interfacial bond strength also vary by a wide margin, from researcher to researcher. In addition, owing to lack of delineation of contributions from the three mechanisms, previous researchers were unable to correlate the measured pullout load to test parameters and surface condition of the bar.

Hence, the objectives of this research are to (a) delineate the contributions from the three mechanisms (chemical bonding, bearing resistance, frictional resistance) to the pullout load, (b) correlate these contributions to bar characteristics such as surface roughness, lug pitch, and number of lugs per unit embedment length, and (c) study the effect of loading rate on pullout load. Additionally, interpretation of the published results is also complicated due to the variation in the definition of the contact surface area from one researcher to another and by the assumption of constant shear stress distribution along the embedment length. The former issue is addressed in this study through explicit definition of the contact surface area. The latter issue is deferred to a future study though the impact of this could be observed in this study too.

Since the completion of this study, there has been a number of published experimental research studies [7–11] focusing on the pullout behavior of FRP bars from concrete. However, none of them have delineated the contributions to pullout load from various mechanisms, as done in this study.

Finally, even though sliding and pullout of the bar after complete debonding is not focused in this study, it is worth mentioning to understand the measured load–slip curve. If the bar is of infinite length and the interface is not altered during pullout, the bar will pullout at constant $F_i$ or $F_d$ and curves $D$ or $D'$ would be recorded respectively. If the bar is of finite length, load required to overcome the friction will reduce with fiber pullout due to reduction in the embedment length ($l$) and curves $E$ or $E'$ would be recorded. If constant frictional resistance is assumed, then curves $E$ and $E'$ would have a constant slope. If frictional resistance is reduced due to abrasion between the bar and the concrete, curves $E$ and $E'$ would have non-linear slopes as shown in Fig. 1b. This is termed as slip weakening. In many cases, a periodic increase and drop in the load is observed during sliding and pullout as shown in curve $E$. This is due to one or more of the following: (a) resistance from the lugs in

Table 5

<table>
<thead>
<tr>
<th>Reference</th>
<th>Reinforcement</th>
<th>Nominal lug dimension depth × width (mm)</th>
<th>Nominal bar diameter (mm)</th>
<th>Loading/ displacement rate</th>
<th>Max. pullout load (kN)</th>
<th>Interfacial bond strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benmokrane et al. [2]</td>
<td>C-BAR™ (P1) commercial</td>
<td>1.3 × 2.8</td>
<td>12.7</td>
<td>22 kN/min</td>
<td>46.0</td>
<td>18.4</td>
</tr>
<tr>
<td>Al-Zahrani et al. [3]</td>
<td>Machined GFRP bar</td>
<td>1.3 × 3.8</td>
<td>12.7</td>
<td>0.125 mm/min</td>
<td>24.2</td>
<td>39.7</td>
</tr>
</tbody>
</table>

Fig. 1. A schematic of load versus slip behavior during single fiber direct pullout test.
the free end of the bar while it moves against the concrete during testing of a specimen type used in this study; all lugs in the free end of the composite reinforcing bar were removed in this study to avoid this; (b) resistance caused by the debris of sheared lugs or sand particles; (c) resistance due to mechanical interlocking of the surfaces of the bar and the concrete due to surface roughness. Alternatively, if frictional resistance is increased due to debris from interaction between the bar and the concrete during pullout, curves G or C would be observed. Such a behavior is often termed as slip strengthening.

3. Experimental details

3.1. Material

Four types of GFRP bars used in this study are shown in Fig. 2. The diameters of smooth (S) and sand-coated (SC) bars were 12.7 mm and 13.6 mm respectively. Their average tensile strength and modulus, as per manufacturer’s data sheet, were 683 MPa and 40 GPa respectively. The bars with lugs (RL), which were basically resin-impregnated fiber strands, had shape and dimensions as shown in Fig. 3. They had two longitudinal lugs positioned opposite to each other. The helical lugs were wound on the bar between the longitudinal lugs such that it started at one longitudinal lug and ended at the other. The number of lugs in the as-received RL bars was 12 per 88.9 mm, i.e. a pitch of 4.4 mm. Their average tensile strength and elastic modulus, as per manufacturer’s data sheet, were 770 MPa, and 42 GPa respectively. These as-received RL bars were machined in a lathe to remove the lugs. The pitch of lugs was altered by removing alternate lugs or two consecutive lugs to result in bars with six (SL) and three (TL) lugs per 88.9 mm respectively. The pitch of the lugs in SL and TL bars was 11.95 mm and 26.9 mm respectively. Complete removal of lugs resulted in machined (M) bars. While 5 bars were used as the reference, SC and M bars were used to study the influence surface roughness. RL, SL and TL bars were used to study the influence of lugs and the pitch of lugs. The air-entrained concrete used in this study was a proper mixture of water, Portland cement, sand and gravel in the ratio 1:2.1:4:31:6, as suggested by Portland Cement Association [12].

3.2. Test specimen

The pullout specimen was a concrete cylinder with the FRP bar embedded at its center, as shown in Fig. 4. Diameter and height of these specimens were 152.4 mm and 304.8 mm respectively. Bonding between the bar and the concrete was prevented at both the ends of the cylinder using PVC tubes, to eliminate any end effect. The length of this tube at the load end was maintained at 152.4 mm. The length of this tube at the free end was varied to accommodate bars with various embedment lengths. Preliminary experiments were carried out using RL and M specimens, with various embedment lengths given in Table 6, to determine the embedment length that would yield interfacial failure during subsequent tests. Based on these tests, an embedment length of 88.9 mm was chosen for subsequent tests. A steel tube was bonded to the load end of the bar using a room temperature curing epoxy and used as a gripping system for the GFRP bars.

The specimens were cast using a plastic mold. The bars were held in position at the center of the mold using a specially designed wooden fixture. The PVC tubes were bonded to the bars using clay, which was subsequently removed after curing. Concrete was mixed in a concrete mixture, poured into the mold, and packed using a hand-held ram. The molds were covered with a plastic sheet and the specimens were allowed to cure for 28 days. The specimen identification codes are tabulated in Table 6. The compressive strength of the concrete was determined as per ASTM C39-88 to be 45.77 ± 2.26 MPa.

3.3. Direct pullout test

The direct pullout test was carried out in stroke-control mode using a MTS hydraulic test frame with a maximum loading capacity of 1000 kN. The test setup is shown in Fig. 4. During loading the concrete cylinder was pressed against a steel plate, bolted to the ground using two 2.25 in. diameter bolts. Since the test specimen surface was not flat, a thin layer of plaster was applied on the test specimen surface to ensure uniform contact with the steel plate. Two LVDTs were attached rigidly to the specimen. One LVDT was attached near the bar and the concrete to measure pullout at both ends of the bar. The LVDT data was acquired using a data acquisition system and stored in a computer. All tests were done at a displacement rate of 1.3 mm/min. Two additional loading rates of 0.26 mm/min and 6.5 mm/min were used to study the influence of loading rate on pullout load. While most of the specimens were unloaded after recording the minimum load to which the applied load dropped beyond $F_p$, few specimens were loaded beyond this point to record the pullout behavior. A minimum of three specimens was tested to obtain each data point. All tested specimens were dissected to confirm the mode of failure. The specimens were cut using a water-cooled 14 in. diameter diamond tipped blade to a distance of about 1 in. from the bar. Subsequently all the specimens were pried open using a chisel and a hammer to reveal the interface. In order to study the progression of debonding, lug failure, and shearing of sand particles during loading, RLC, TLC, SCC, MC, and SC specimens were loaded to pre-selected load levels below $F_p$ and then unloaded. Subsequently the specimens were dissected to examine the interface.

While the nominal bar diameter, measured using a digital caliper, was used in calculating the contact surface area for the S, M and SC specimens, Eq. (3) was used to calculate the contact surface area for the RL, SL and TL type specimens.

$$A = A_{hel} + \left( N \times A_{lugs} \right) + A_{int} = \left( N \times A_{overlap} \right)$$

where $A_{hel}$ is the total surface area without lug + $\Delta A_{hel}$ is contact surface area for one helical lug + $2 \times \left( \pi \left( D^2 - d^2 \right) / 4 \sin \alpha \times \left( \pi D a / \sin \alpha \right) \right)$, is number of helical lug, $A_{lugs}$ is contact surface area for longitudinal lugs $= 2(2\pi + Wp)$, and $A_{overlap}$ is the overlap area between bar and lug = $\pi D h / \sin \alpha$.

Values for $D$, $d$, $a$, $W$, $P$, $x$ are given in Fig. 3. It was assumed in this study that the area over which debonding occurred was the same area over which subsequent frictional sliding occurred. Hence, the same contact surface area was used in the determination of both the interfacial bond strength and the frictional stress. However, this assumption has to be examined in future studies since progressive shearing of lugs and sand particles was observed in this study.

While the interfacial bond strength was determined using the debond load, no attempt was made to determine the pullout strength since it would not be a unique value that can be used in any design.

4. Results and discussion

The experimental program undertaken in this study was designed to measure the debond load ($F_d$), the pullout load ($F_p$), and the frictional load ($F_f$). Representative load–slip curves for SC, MC, SCC, and SLC specimens are shown in Fig. 5. Elastic deformation of the bar has been deduced from the LVDT measurements to obtain the relative slip between the bar and concrete. Load versus slip relationship for the free end is nearly a mirror image of that for the load end. The load at which the free-end slip started to increase was defined as $F_d$ since the free end of the bar could start to slip only after the debonding had progressed completely from the load end to the free end. For all specimens, the load-end slip started to increase immediately after the start of application of load while the free-end slip was zero until $F_d$. Since the free-end slip started to increase beyond $F_d$, debonding was believed to be complete at $F_p$. All specimens loaded to a load slightly higher than $F_d$ were unloaded and dissected to confirm the mode of failure. Clean bar surface without any adhering concrete particles confirmed that the failure mode was interfacial [13]. This confirmed that debonding was complete at $F_d$.

The maximum measured load was defined as $F_d$ and $F_f$ was defined as the value to which the applied load dropped beyond $F_d$. Subsequently, the bearing load was determined using Eq. (2) and experimentally measured values of $F_d$, $F_f$ and $F_p$. Thus, the contribu-
tions from chemical bonding, bearing resistance, and frictional resistance to the measured pullout load were delineated in this study.

While the relative movement between the bar and the concrete is possible along the entire embedment length at loads greater than \( F_d \), this is possible only along the debonded length at loads less than \( F_p \). This relative motion would be resisted by the lugs and the sand particles bonded to the surface of the bar and hence the observed increase in load between \( F_d \) and \( F_p \) is due to frictional and bearing resistance. Beyond \( F_p \), the applied load suddenly dropped to a minimum value, \( F_f \), in all specimens except SC. Unlike the schematic shown in Fig. 1 this load drop was accompanied with simultaneous pullout of the bar. Beyond \( F_f \) (\( F_p \) for SC), a stick–slip type of pullout behavior was noticed for all specimens. This is believed to be due to surface roughness and, in case of bars with lugs or sand particles, to be due to sheared lugs or sand particles caught between the sliding bar and the concrete. It can be observed in Fig. 5 that the maximum and minimum loads for MC and SLC specimens, during the stick and slip behavior, decrease with increase in slip. This indicates a change in surface characteristics of the bar and the concrete, and hence, the frictional condition.

An examination of the dissected RLC and SCC specimens, loaded to \( F_p \), revealed complete shearing of lugs and sand particles as shown in Figs. 6 and 7 respectively. Since lugs and sand particles are the source of bearing resistance, it can be concluded that the bearing resistance did not contribute to the load recorded beyond \( F_p \). If there were no frictional resistance, the load would drop to zero beyond \( F_p \). Hence, the recorded \( F_f \) is a measure of contribution of frictional resistance to measured \( F_p \). Since SC samples did not have any surface features that would cause mechanical interlocking, bearing resistance was assumed to be zero and hence, the increase in load between \( F_d \) and \( F_p \) was taken to be due to frictional resistance to slip.

The measured pullout load (\( F_p \)) is plotted in Fig. 8 as a sum of the debond load (\( F_d \)), the frictional load (\( F_f \)), and the bearing load (\( F_b \)) for various types of bars. The pullout load increased from SC to SCC and this is attributed to increase in surface roughness from SC to SCC. It also increased from TLC to RLC and this is attributed to increase in the number of lugs from TLC to RLC. It is interesting to note that the pullout load for SCC specimens is comparable to that for RLC specimens.

Normally, relative sliding of two surfaces at a frictional interface would not occur until the interfacial shear force exceeds the fric-

![Fig. 3. Shape and dimensions of lugs.](image)

![Fig. 4. A schematic of specimen dimensions and test setup used in the present study.](image)

<table>
<thead>
<tr>
<th>Table 6</th>
<th>Test specimen identification codes.</th>
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<tbody>
<tr>
<td>Bar type</td>
<td>Bar diameter (mm)</td>
</tr>
<tr>
<td>RL</td>
<td>13.94</td>
</tr>
<tr>
<td>SL</td>
<td>11.95</td>
</tr>
<tr>
<td>TL</td>
<td>26.90</td>
</tr>
<tr>
<td>SC</td>
<td>13.6</td>
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<td>M</td>
<td>12.0</td>
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<td>S</td>
<td>12.5</td>
</tr>
</tbody>
</table>
tional resistance for sliding. This is referred to as static friction and the maximum force \( F_{\text{static}} \) for initiation of the sliding is related to normal force \( N \) acting on the interface through static friction coefficient, \( \mu_{\text{static}} = F_{\text{static}} / N \). The force \( F_{\text{dynamic}} = F_{f} \) required to maintain the sliding of the interfaces may be equal to or less than \( F_{\text{static}} \). In case of the latter, \( \mu_{\text{dynamic}} \leq \mu_{\text{static}} \), which has been noted by numerous published literature. Whether this would be applica-

**Figure 5.** Representative load–slip curve for SC, MC, SCC, and SLC specimens.

**Figure 6.** Complete shearing of all lugs along the embedment length of a RLC specimen loaded to \( F_{p} \).

**Figure 7.** Complete shearing of sand particles along the embedment length of a SCC specimen loaded to \( F_{p} \).

**Figure 8.** Measured pullout load plotted as a sum of measured debond load, measured frictional load, and calculated bearing load for various specimens.

**Figure 9.** Load–slip curve for SC, MC, SCC, and SLC specimens.

4.1. Contribution from chemical bonding

Since debonding is complete at \( F_{d} \), it would be expected to be a measure of chemical bonding and the interfacial bond strength \( \tau_{d} \) determined using this would be expected to be same for all specimens. However, it varied from a minimum of 1.01 MPa for SC specimen to a maximum of 5.68 MPa for SCC specimen as shown in Fig. 9. Possible reasons for this variation are:

(a) Underestimation of contact surface area, especially in SCC and MC samples, since calculation using nominal bar diameter would have excluded the increase in surface area due to surface roughness.

(b) Contribution from the bearing resistance, especially in SCC and LC samples, since measured \( F_{d} \) corresponds to debond completion rather than debond onset. The increase in \( F_{d} \) with increase in the number of lugs in LC (i.e. RLC/TLC/SLC) specimens (Fig. 8) supports this reasoning.

(c) Contribution from static friction as discussed above. However, contribution from the dynamic friction to \( F_{d} \) is believed to be minimal because the magnitude of load-end slip recorded at \( F_{d} \) is very low. This is supported by the observation of clean bar surface without any scoring marks during post-mortem examination of the specimens loaded to \( F_{d} \).

Nevertheless, the value of 1.01 MPa obtained for SC specimen would be the maximum limit to the interfacial strength since the
This resulted in a higher had relatively rougher bar surface after removal of lugs in a lathe. However, the MC specimens were same. This is to be expected since the surface of bar in SC specimens was smooth. However, the MC specimens had relatively rougher bar surface after removal of lugs in a lathe. This value is comparable to the published values. Since lateral pressure was not determined, its contribution to $F_d$ is unknown.

4.2. Contribution from frictional resistance

Frictional load varied with type of bar as shown in Fig. 8. Lateral pressure was same for all specimens. In order to eliminate the effect of difference in contact area, these frictional loads are normalized with contact surface area and plotted in Fig. 10 as frictional stresses ($\tau_f$) for various specimens. Comments made in Section 4.1 regarding the error in the calculation of the contact surface area for MC and SCC specimens are also applicable here.

It can be inferred from Fig. 10 that the frictional stress is negligible for SC specimens. This is to be expected since the surface of bar in SC specimens was smooth. However, the MC specimens had relatively rougher bar surface after removal of lugs in a lathe. This resulted in a higher $\mu_{\text{dynamic}}$ and frictional stress in MC specimens when compared to SC specimens. SCC specimens with sand-coated bars recorded the maximum frictional stress and this is believed to be due to higher $\mu_{\text{dynamic}}$ for the sand–concrete interface when compared to lower $\mu_{\text{dynamic}}$ for the relatively softer polymer composite–concrete interface. Since the SCC specimens had higher contact area due to higher surface roughness, when compared to SC and MC specimens, any error in the contact area used in determining $\tau_f$ could also be another contributing factor to the observed difference. The frictional stress values for LC specimens were same. This is to be expected since $\mu_{\text{dynamic}}$ and the surface roughness in these specimens would not change with the pitch of lugs. Contribution from frictional resistance (hence $\mu_{\text{dynamic}}$) for LC specimens was higher than that for the SC specimens but lower than that of MC specimens. This is believed to be due to (a) longitudinal lugs with relatively higher surface roughness, (b) rough bar surface in locations where lugs were removed to alter the pitch, and (c) the resistance offered by the sheared lugs caught between the bar and concrete.

Since complete shearing of sand particles from the bar’s surface is observed in Fig. 7, it can be concluded that $F_f$ recorded for SCC specimens is not representative of the frictional resistance encountered during loading to $F_p$. In addition, examination of dissected SCC specimens loaded to load levels between $F_d$ and $F_p$ revealed progressive shearing of the sand particles with increase in load [13]. This suggests that the frictional stress changed continually during loading and the values in Fig. 10 represent the state of friction after the load drop at $F_p$. Future studies should focus on characterizing this change in frictional stress during loading. Since the change in friction stress during sliding and pullout was not characterized, error in the values of $F_d$ and $F_p$ is unknown. Similar conclusion is valid for LC specimens since progressive shearing of lugs was observed with increase in load.

4.3. Contribution from bearing resistance

The bearing resistance is negligible in SC and MC specimens due to lack of geometrical features on the bar surface that can cause mechanical interlocking of the bar with the concrete. However, the bearing resistance is substantial in SCC and LC specimens. It is interesting to note (Fig. 8) that the bearing resistance due to small sand particles in SCC specimens is comparable to the bearing resistance due to the lugs in SLC and TLC samples.

The bearing resistance increased from SLC to RLC due to decrease in the pitch of lugs (i.e. increase in the number of helical lugs). In order to quantify the influence of the pitch and the number of helical lugs on the bearing resistance, a number of LC specimens were unloaded after loading to specific load levels between $F_d$ and $F_p$ and were dissected and examined to determine the number of sheared lugs. It can be inferred from Fig. 6 that all the lugs in the LC specimens sheared at $F_p$. However, at loads less than $F_p$ fewer helical lugs were sheared as shown in Fig. 11 for a RLC specimen loaded to $0.85F_p$. At this load, only two lugs near the load end were sheared. The sheared lugs appear milky-white while the intact lugs have the same color as the bar. It is also interesting to note that the very first lug at the load end was not sheared. This was noticed in all specimens with bars with lugs. Experimental studies [1,4] have shown that the maximum interfacial shear stress occurs just below
the lugs (depending on the lowest of concrete between the lugs when the width of the lug was impossible to increase the bearing resistance and length of the bar, which depends on the pitch. Theoretically, it is strength of the concrete, and

\[ F_b = \tau_c A_c N_l \]  

where \( \tau_c \) is the shear strength of a helical lug, \( A_c \) is the contact surface area of a lug (\( \pi d a \)), and \( N_l \) is the number of lugs per embedment length of the bar, which depends on the pitch. Theoretically, it is possible to increase the bearing resistance and \( F_b \) by increasing \( A_c \) and/or \( N_l \) provided the concrete between the lugs can withstand the compressive and shear stresses introduced in it by the applied load. This is supported by the results of Al-Zahrani et al. [3], who observed a change in failure mode from shearing of lug to fracture of concrete between the lugs when the width of the lug was increased. Hence, the maximum bearing stress contribution from one lug can be determined from Eq. (5a), and either (5b), (5c) depending on the lowest \( F_{\text{max}} \).

\[ F_b \text{ per helical lug} = F_{\text{max}} \text{ in the concrete} \]  

\[ F_{\text{max}} = \sigma_c A_c / (\sin \alpha) \text{ for compressive failure} \]  

\[ F_{\text{max}} = \tau_c A_c / (\sin \alpha \cos \alpha) \text{ for shear failure} \]  

\( \sigma_c \) is the compressive strength of the concrete, \( \tau_c \) is the shear strength of the concrete, and \( A_c \) is the area of the concrete between the lugs (\( \pi(D^2 - d^2)/4 \)). For the lug shape and dimensions shown in Fig. 3, \( F_{\text{max}} \) would be minimum for compressive failure even if the shear strength is assumed to be one-half of the concrete compressive strength of 49.77 MPa. The calculated \( F_{\text{max}} \) of 2.09 kN is within

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**Fig. 12.** Progression of lug failure in LC specimens with increase in applied load.

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4.4. Effect of loading rate

The pullout load for SCC specimens increased with increase in loading rate as shown in Fig. 13. However, such a clear trend was not observed in RLD specimens. This is believed to be due to higher contribution from frictional resistance in SCC specimens when compared to RLD specimens. Further investigation is required to clearly understand the relationship between the loading rate, and the frictional resistance and the bearing resistance. Nevertheless these preliminary results highlight the need to control the loading rate while evaluating the interfacial bond strength using the pullout test.

In summary, the approach used in this study has clearly delineated the contributions from various mechanisms to the interfacial bond strength and the pullout load (i.e. the resistance to bar pullout). The results of this study have also demonstrated the depen-

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**Fig. 13.** Influence of loading rate on pullout load.
idence of these contributions on parameters such as bar surface geometry, test conditions, and concrete strength. Since these parameters varied from researcher to researcher in the past, the reported strength corresponding to the pullout load also varied widely. Hence, instead of using this strength corresponding to pullout load for design as suggested in the reviewed literature, the approach used in this study is suggested. Eq. (2) can be modified, for bars with lugs, as

\[ F_p = \tau d A_d + \tau l A_l + \mu_{\text{dynamic}} N \]

where \( A_d \) is the contact surface area between the concrete and the bar. Other parameters have been defined before. The maximum limit for \( F_p \) is the force required to fracture the bar and this can be calculated using the tensile strength and the cross sectional area of the bar. The areas, \( A_d \) and \( A_l \) are functions of bar embedment length and bar diameter. If the lug dimensions and shape, bar diameter, shear strengths, \( N \), and \( \mu_{\text{dynamic}} \) in Eq. (6) are known, the critical embedment length (i.e. development length) that would yield maximum \( F_p \) can be predicted using Eq. (6). Alternatively, the dimension and shape of lugs wrapped on a bar, which would result in maximum pullout load, can be designed for a chosen embedment length.

5. Conclusions

Debonding load, corresponding to debond completion, is much lower than the pullout load, corresponding to onset of sliding and pullout of the bar along the entire embedment length. While the former is mainly a measure of chemical bonding, the latter is a sum of contributions from chemical bonding, frictional resistance, and bearing resistance. The maximum value for the interface bond strength for the concrete–bar specimen used in this study is 1.01 MPa. The resistance from lugs to bar pullout is comparable to that from sand particles bonded to the bar. Bearing resistance due to lugs is a function of shear strength of the bar–lug interface. Lug dimensions, pitch of the lug, and number of lugs, and is limited by the concrete’s compressive or shear strength. Bearing resistance due to sand particles is a function of surface roughness amplitude and is limited by the shear strength of the bond between the sand particles and the bar. Frictional resistance is a function of surface roughness and it may vary during loading due to progressive shearing of lugs or sand particles. Loading rate influences the pullout load.

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