Misan Journal of Engineering Sciences ISSN-E: 2957-4250
Vol. 4, No. 1, June 2025 ISSN: 2957-4242

A Review of the Bond Mechanism and Bond Strength of Fiber Reinforced Polymer Rebars to Concrete

Borkan M. Mutashar*[1,2], Oday A. Salih[1] and Suhaib Y. Kasim[1]
[1] *Department of Civil Engineering, College of Engineering, University of Mosul, Mosul, Iraq.*
[2]*Department of Environmental Technologies, University of Mosul, Mosul, Iraq.*
**Corresponding author E-mail:* borkanmutashar@uomosul.edu.iq

(Received 7 Dec 2024, Revised 19 Feb, Accepted 19 Feb)

Abstract: Fiber Reinforced Polymer (FRP) reinforcement bars have been increasingly utilized in reinforced concrete structures over the last two decades, substituting conventional steel reinforcement, particularly in places facing challenging environmental circumstances. A literature review is presented in this article, with the primary focus being on the bond performance of FRP bars to concrete. The purpose of this study is to cover all of the useful contributions that have been made on the bond performance in earlier research. This work is based on results from the collection of experimental data from a total of 1784 pullout tests in the existing literature. The bonding performance of FRP bars with concrete represents an extremely essential characteristic for assembling the FRP bars into corrosion-free reinforced concrete structures. FRP materials, contrary to steel reinforcements, possess non-homogeneous, anisotropic, and elastically linear features, thus resulting in a distinct force transfer mechanism between concrete and reinforcement. The most significant parameters influencing the bonding of FRP bars to concrete were outlined in this paper. The information gathered through the investigation indicated that FRP bars behave effectively as reinforcement components in reinforced concrete structures.

Keywords: FRP bar; Bond mechanism; Failure mode; Pull-out test; Post-installed; Embedment depth; Bar diameter

1. Introduction

When steel reinforcing bars in reinforced concrete (RC) structures are exposed to a harsh environment, corrosion within these bars poses an important challenge [1]. The action of corrosion and its byproducts weakens the bond between steel bars and concrete, shortening the service life of reinforced concrete structures. This might end up being an extensive expense associated with ongoing repairs, maintenance, and improvements [2]. The need for substitute materials has increased [3]. These may involve metal-free reinforcements (such as aramid, glass, and carbon fiber-reinforced polymers). FRP reinforcing bars have gained a lot of interest because of their remarkable resistance to corrosion, extremely high strength-to-weight ratio, high cost-effectiveness, and robust resistance to chemicals [4]. The key factor to consider when utilizing FRP bars to reinforce concrete structures is their bond performance. The non-homogeneous, anisotropic, linear elastic characteristics of FRP reinforcement, which differ from the behavior of steel reinforcement, lead to a distinct force transfer mechanism between the reinforcement and the concrete. Concrete cover, concrete compressive strength, FRP bar properties, structural characteristics of the member, and the effect of using self-consolidating concrete (SCC) are among the main factors impacting bond behavior of FRP bars [5] that have been evaluated with either the direct pullout test [6]. More than 1784 pullout-test specimen results were gathered from the literature, and data-based parametric research was conducted. Identifying the significant factors that influence the bonding behavior of FRP bars to concrete and the associated modes of failure and bond strength was made easier with the assistance of this database.

DOI: https://doi.org/10.61263/mjes.v4i1.127

The review showed that pullout failure, splitting failure, and rebar fracture are common bond failure modes for FRP bars in concrete. These bond failures are primarily related to the main factors mentioned previously that impact bond behavior. These factors are described in more detail in this review article.

The failure mechanisms between FRP bars and concrete, as identified in studies on bond behavior, include the following: (i) pullout, (ii) concrete splitting, and (iii) rupture. The first two mechanisms are the most frequently observed, although they also occur in pullout tests involving steel reinforcement bars. Several analyses of failure modes have been conducted in the literature [6, 7, 8]. The researchers differentiate between the failure modes of steel and FRP reinforcement bars through visual observation. On the boundary in which the steel bar together with concrete come into an impact, deformed steel bars begin to fail. Because of cracks in the concrete that have developed along the bar as a consequence of the raised tension, the failure occurs when the concrete crushes across the ribs within the steel bar. In this manner, broken bonds and failure in concrete are interconnected, and it appears that bond strength can be controlled by the mechanical properties of concrete. However, for FRP rebar, due to the separation of the outer coating layer of the FRP bar, it may fail on the outer coating surface on which the FRP bar epoxy matrix and the surrounding concrete interact or in locations where the bar interior fibers and bar coating matrix interface. In the second scenario (matrix-fiber interface), the shear stresses among the bar interior fibers and the bar coating matrix seem to govern the bond strength. This points to the fact that the bond strength may be more reliant on the characteristics of the FRP bars compared to the compressive strength of the concrete, particularly for moderate to high compressive strength concrete. The durability and acceptability of using FRP bars to serve as reinforcing materials are determined by the bond between the bar and the concrete that surrounds it. The tension forces in the FRP reinforcement bars balance out the compression forces in the concrete in reinforced concrete members, and the development of these tension forces is dependent upon how effectively the reinforcement-concrete bond mechanism is in the tension region. The bond mechanisms of fiber-reinforced polymer (FRP) bars in concrete have similarities to those of steel bars. These mechanisms include shear interlock, surface friction, and mutual adhesion. However, in comparison to steel bars, FRP bars have entirely different mechanical characteristics, as shown in FIGURE 1 [9]. As a result, the flexural behavior of FRP reinforced concrete members cannot be evaluated based on the flexural behavior of reinforced concrete members with steel reinforcement. The current study provides a very thorough review with regard to the previous investigations on the main factors influencing the bonding behavior of FRP bars in concrete that have been done in the literature. The collected test data includes 1784 pull out test specimens collected from various studies. Pullout and splitting failures, that account for about 88 percent of the specimens, are recognized in the studies as the primary failure mechanisms. Furthermore, the data that was gathered contains a number of parameters that impact the bonding ability of the FRP rebars with the surrounding concrete, such as the specimens' structural features, parameters related to the FRP rebars' characteristics, and parameters associated with the concrete's characteristics. All of these parameters are discussed in detail in Section 4.

2. Bond mechanism

In structural members, the high bond strength between the reinforcement bars and concrete is necessary for their strength and stability. A force transmission system called the bond mechanism, forms between the FRP reinforcement bar and the concrete must be present; otherwise, the FRP reinforcing may exhibit outward movement or slide off the surrounding concrete, resulting in early tensile failure [10, 11]. The reinforced concrete structure relies strongly on an adequate bond mechanism between reinforcement and concrete to function as designed [12]. The strength of the bond is believed to vary with respect to the structural components of the FRP bar, the properties of the material that surrounds the bar, and the geometry of FRP reinforcement bar [9]. Fig. 1 demonstrates the bond mechanism utilizing three steps for distributing the stresses from concrete through reinforcements, or vice versa as following:

1. Chemical bonding between the concrete and the reinforcement bar is the first step of the bonding mechanism.
2. The second step after the chemical bonding is broken, involves friction within the two materials occurs as a consequence of interconnection roughness, transverse force applied to the bar's outer surface, and the corresponding slide of the bar with the neighboring concrete.

3. The final step involves mechanical anchoring, which depends on the geometry or structure of the reinforcing bar surface [12- 15].

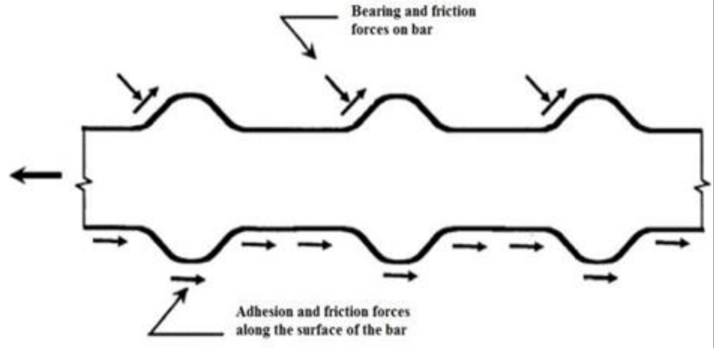

Fig. 1. Bond transfer mechanism (ACI 408R, 2003) [1].

Additionally, ACI 408R-03 [4] also divides the elements that form the bonding mechanism into three categories which lie under the structural, bar, and concrete properties. Furthermore, concrete coating, bar spacing, and transversal reinforcement are the structural qualities. Moreover, the bar properties include geometry, size, material, and surface texture. Lastly, the properties of concrete include compressive and tensile strength and mix characteristics (aggregates, slump, and workability) [4]. The bond mechanisms start with the mechanical interlocking between the FRP bar exterior surface and the surrounding concrete then the friction takes place, and finally the ribs' motions against the concrete induce shear resistance, which ends in concrete strut failure [7]. Furthermore, the force distribution in the case of cast-in-place FRP bars is significantly straightforward, the tie forces in the reinforcement bar are balanced by the micro-struts generated in the surrounding concrete as shown in Fig. 2 [16]. Moreover, Looi 2020 illustrates how the bond mechanism works when the FRP bars are post-installed into concrete by adhesives, Fig. 2 shows how mechanical interlocking of the adhesive to the concrete and reinforcing bar bonding to the adhesive material when an external tension force is applied the strut forces are assembled in case of the FRP bar is post installed. Concrete micro struts form subsequently to act over the hardened adhesives [16].

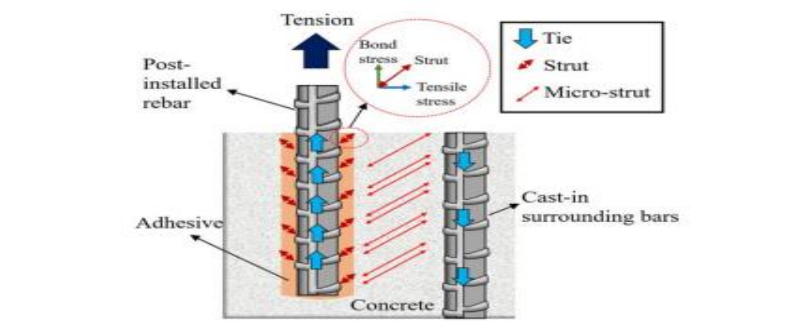

Fig. 2 Mechanism of bond transfer (ACI 408R, 2003) [1].

In order to maintain equilibrium, the bar forces are balanced by the growing compressive and shear stresses on the contact surface of the concrete [9].

3. Failure modes of bond

The research on bond behavior also made an effort to define the various failure modes that could occur between FRP bars and concrete. These failure modes included (i) pullout, (ii) splitting concrete, and (iii) rebar fracture. The first two of these are the ones that are noticed the most frequently, and they are also shown in pullout tests that are performed with steel bars.

3.1 Splitting failure

The transverse splitting cracks in concrete adjacent to reinforcement might cause mode of failure as shown in Fig. 3(a), Splitting failure results in cracks in planes parallel and perpendicular toward the reinforcement. Loading the reinforcement bars causes a radial stress in the neighborhood concrete[7]. If the applied stresses rise above the tensile strength of the concrete or the transverse reinforcement, the concrete-rebar contact gradually begins cracking, and cracks extend to the concrete outermost layer [10].

3.2 Pullout failure

Failure to pull out occurs when the cover of concrete, the space between bars, or transverse reinforcement prevents splitting from occurring. When the radial forces are lower than the resistance of the surrounding concrete and the transverse reinforcement, but the tangential forces are higher than the resistance of the concrete, this mode of failure occurs [10]. Shearing occurs at the top of the bar's ribs in a direction that is parallel to the bar when pullout failure occurs [18] as shown in Fig. 3(b).

The crushed concrete was observed as a result of both pullout and splitting failure, especially on the bearing areas of the deformations. It should also be recognized that each type of failure mode occurs as a consequence of reinforcement bars sliding within concrete [18]. As a result of the concrete confinement, pullout failure has a stronger bond strength compared to splitting failure, and hence radial splitting cracks require more energy to reach the concrete outer surface [7]. The pie chart shown in as shown in Fig. 4 describes the percentage of each failure mode with respect to the total failures. It is clear that pullout is overwhelmingly dominant, accounting for over 60% of all the failure modes, splitting 24%, and rebar fracture 12%. GFRP reinforcement bars have an entirely different bond characteristic than steel reinforcement bars. The variation is mostly due to differences in material characteristics and surface roughness across reinforcement bar types, which affect the method of transferring force between the reinforcement bar and the concrete [17]. Okelo and Yuan identified additional factors that influence the bond behavior of GFRP reinforcement bars, such as bar diameter, embedment length, spacing between bars, and the compressive strength of concrete [18]. ACI 440.1R-15 [1] declares that the connection of the FRP reinforcement bars with the surrounding concrete forms in a way that's comparable to steel reinforcement bars, yet parameters that include type of fibers used in the FRP rebar (e.g., CFRP, AFRP, GFRP), modulus of elasticity, texture of the bar, and bar geometry affect this interaction.

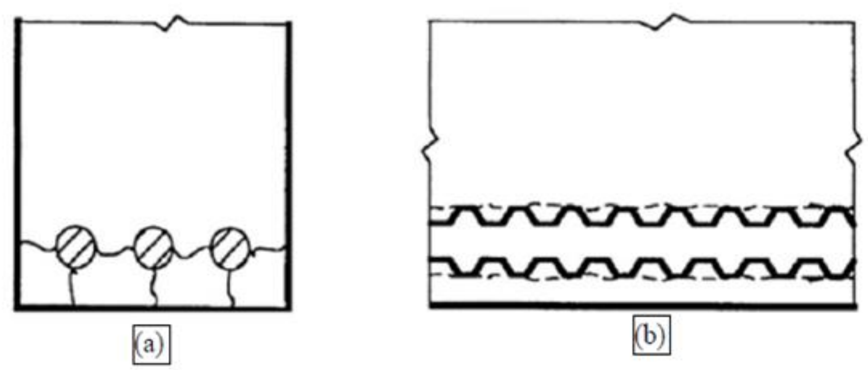

Fig. 3 Bond cracking: (a) splitting cracks between bars and concrete cover, and
(b) Shear cracks and regional crushing from pullout (ACI 408R 2003) [9].

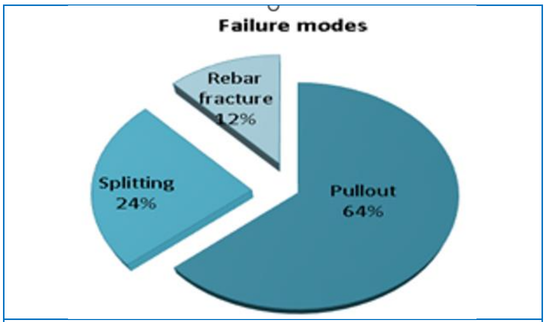

Fig. 4 Failure Modes Proportions [17].

Authors used visual assessments to distinguish FRP and steel bar failure mechanisms [6, 19-21]. Deformed steel bars fail at the concrete-steel interface. Cracks occur around the steel bar, and as tension grows, the concrete crushes along the bar's ribs, failing. Thus, bond failure is linked to concrete failure, and bond strength appears to depend on concrete mechanical properties. However, peeling of the bar's surface layer can cause FRP bar failure on the concrete-FRP bar interface or the FRP bar fiber-FRP bar interface. In the other scenario (the interface of matrix fibers), shear stresses between the bar matrix and the bar fibers seem to affect bond strength, showing that FRP bar characteristics are more important than compressive strength, especially for concretes with medium or high compressive strength.

4. Parameters affecting FRP-concrete bar bonding

A number of elements affect the bond that exists between FRP bar and concrete. This portion covers three significant factors: structural features, bar characteristics, and the properties of concrete. The structural features are mostly connected to concrete covering, bar cast location, embedment length, and transverse reinforcement. The bar's characteristics include its size, fiber material, and the state of its surface. The properties of concrete that impact the bond in FRP include compressive strength as well as fiber reinforcement [10].

4.1 Structural features

The bonding behavior of fiber-reinforced plastic (FRP) reinforcing bars has been shown to be controlled by a variety of structural parameters, including concrete cover, bar casting position, transverse reinforcement, and embedment depth.

4.1.1 Concrete cover

Improving the confining pressure by expanding the concrete cover led to the bond strength significantly enhances [22]. Moreover, the confinement is improved as concrete cover increases because the failure mode mechanism is shifted from concrete splitting mode to pull-out (bar debonding) mode [7]. Previous studies have shown that when the cover of concrete is equal to the diameter of the bar, the final mode of failure is mostly concrete splitting [23]. Depending on the embedment length, the failure mode might shift into bar rupture or even bar debonding once the cover of concrete reaches 2d [8]. The influence associated with bottom concrete cover upon FRP bar-concrete bond strength remains insignificant throughout values exceeding 2.5 db. As a result, bottom covers with a depth greater than 2.5 db had a negligible effect on the failure mechanism as well as on values of bond strength [24]. However, to avoid the splitting failure completely, another study requires clear cover equal to 3d [25]. According to ACI 440 1R-15 [1], as long as the embedment length exceeds 19 db and the concrete cover is over 3.5 db the mode of failure is typically pullout. It is extremely difficult to draw accurate deductions on the requirement of concrete cover without entirely avoiding splitting the concrete. The reason is that earlier researches employed a wide range of FRP mechanical characteristics and surface textures. In addition, there was a substantial difference in concrete strength and embedment length. Consequently, splitting of concrete will probably occur with a limited amount of embedment length and concrete cover values; moreover, when the embedment length and concrete cover exceed their respective limits, the reinforcement bar is predicted to fail by tensile rupture or debonding [26]. That is why crucial values for concrete cover and embedment length must be indicated in order to identify rupture or debonding failures, and these crucial values must be ascertained by supplementary experimental investigations.

The number of investigations on the impact of bar spacing regarding the FRP concrete bond is quite limited; however, these investigations have found that expanding the space between bars may improve the bond strength by up to 50% [24]. If the distance reaches 7d, increasing the space between bars has no effect on the bond strength [24].

4.1.2 Bar casting position

In order to take into account the casting position of the GFRP reinforcing bar in concrete, it is necessary to have a top bar modification factor. It is possible to select a value of 1.0 for this factor. According to the American Concrete Institute's 440.1R-15 [1], a top bar is defined as a bar that has more than twelve inches of concrete below it. If this is the case, then we can consider it to be equivalent to 1.5. The reason for this is that water, air, and minute particles are able to escape to the upper region of the concrete section, which might therefore result in a reduction in the strength of the bond [1]. For steel reinforcing bars, the American Concrete Institute (ACI) 318-19 [27] suggests a top bar modification factor that is equivalent to 1.3. When compared to steel reinforcing bars, GFRP reinforcing bars have a different surface roughness and a lower bond strength, which results in a larger factor value from the combination of these two characteristics. Researchers Rossetti et al. [28], Cosenza et al. [29], and Yan et al. [17] looked into the impact that casting position has on the bonding strength of general-purpose reinforced plastic (GFRP) reinforcing bars. For the purpose of determining the bonding ability of FRP reinforcing bars in concrete, Cosenza et al. [29] gathered data from a number of different investigations. After doing an analysis of the data provided by Ehsani et al. [30], Chaallal and Benmokrane [31], and Benmokrane and Masmoudi [32], the authors came to the conclusion that the permitted bonding stress for the top bars was roughly 66% of the value for the bottom bars. Similarly, Yan et al. [17] collected data concerning the bonding strength of GFRP reinforcing bars with concrete. They reported that the permissible bond stresses for top bars were 66% of those for bottom bars. This was seen in a manner that was comparable to the previous example.

4.1.3 Transverse reinforcement

As per the American Concrete Institute's 408R-03 [9], transverse reinforcement is used to restrict the expansion of splitting fractures, hence increasing the bond stress that is necessary for failure to occur. Wambeke and Shield [33] discovered that the degree of confinement supplied by transverse reinforcement has little impact on the bonding strength of GFRP reinforcing bars when compared with steel reinforcing bars. The authors related this issue to the small rib area of GFRP reinforcing bars in contrast to steel reinforcing bars. Despite the fact that transverse reinforcement increases the amount of force required to cause bond failure, the bonding strength of GFRP reinforcing bars is not significantly affected by insufficient confinement. Through their research, Harajli and Abouniaj [34] discovered that the bonding strength of GFRP bars [35] is improved by the addition of transverse reinforcement. Furthermore, it was found that reducing the distance between each of the shear stirrups resulted in an increase of up to 31% in the bond efficiency of the GFRP bars. On the other hand, Wambeke and Shield's [33] research showed that the bonding strength between FRP bars and concrete was not significantly affected by the presence of transverse reinforcing reinforcement.

4.1.4 Embedment depth

Several researchers, including Larralde et al. (1993) [36], Shield et al. (1997) [37], Cosenza et al. (1997) [29], Tighiouart et al. (1998) [38], Achilides and Pilakoutas (2004) [20], Okelo and Yuan (2005) [18], Aly et al. (2006) [39], and Yan et al. (2016) [17], investigated the impact that the embedment depth within concrete had on the bonding behavior of GFRP reinforcing bars. There were pullout test studies conducted by Larralde et al. (1993) [36] that utilized both fiber-reinforced plastic (FRP) and steel reinforcing bars within concrete. They came to the conclusion that an increase in the embedment depth between three and six inches led to an increase in the pullout force that was required for the two different types of reinforcing bar structures. On the other hand, the authors demonstrated that the bond stress reduced as the embedment depth grew. They attributed this to the nonlinear distribution of the bond stress across the whole length of the bar that was embedded, as seen visually in Figure 15. The findings of many investigations utilizing FRP reinforcing bars were reviewed by Cosenza et al. (1997) [29], who came to the conclusion that embedment depths covering the rang from 5 db to 10 db, where db is the diameter of the bar, demonstrated more robust bond strength in comparison to deeper embedment depths. Through the use of direct pullout analysis, Achillides and Pilakoutas (2004) [20] discovered that a decrease in the strength of the bond is associated with an increase in embedment depth. The maximum bond stress decreases as one raises the embedment depth, according to the findings of Yan et al. (2016) [17], who gathered information regarding the bond strength.

4.2 Bar properties:

4.2.1 Bar diameter

Over the course of the past twenty years, the researchers have conducted studies to determine the effect that the diameter of the bar has on the bond strength of FRP bars. Some of the studies that have been conducted include Larralde and Silva-Rodriguez (1993), Benmokrane et al. (1996), Cosenza et al. (1997) [29], Tighiourat et al. (1998) [38], Achilides and Pilakoutas (2004) [20], Okelo and Yuan (2005) [18], Aly et al. (2006) [39], Okelo (2007) [40], Baena et al. (2009) [19], Hao et al. (2009) [41], Alves et al. (2011) [42], and Yan et al. (2016) [17]. It was demonstrated that decreasing the diameter of the bar led to an increase in the binding strength. There is a rise in the quantity of water from bleed retained beneath the bar, which causes bigger amounts of voids for larger bars than those with smaller diameters [38]. This is one reason for the difference in bond strength that occurs with larger bar diameters. A decrease in bond strength occurs as a consequence of the presence of voids, which lower the area of contact that exists between the surface of the bar and the concrete that is adjacent to it. It was discovered by Achilides and Pilakoutas (2004) [20] that the decrease in bonding strength for larger bars is associated with the production of poorer adhesion along with the concrete that surrounds it. This is in contrast to the lower bonding strength that is observed for smaller bars. According to Baena et al. (2009) [19], Poisson's ratio additionally has the potential to alter the bond characteristics of FRP bars due to the reductions in diameter that are caused by tension.

4.2.2 Bar type

While CSA S806-12 [45] considers the impact of fiber variation on bond strength and defines an alternation factor that applies to each type of fiber used to determine bond strength, CSA S6-06 [43], JSCE [44], and ACI 440.1R-06 [1] did not take this into account. For CFRP and GFRP bars, this factor has a value of one; for AFRP bars, the value is 1.25 for determining development length. This suggests that compared to CFRP and GFRP bars, AFRP produces a weaker connection. The binding strength of glass and carbon fibers was discovered to be the same by Achillides et al. [20] in their discovery that both GFRP and CFRP were able to attain 72% of the bonding strength of steel bars. When GFRP and steel bars were compared, Tigiouart et al. [38] found that the steel bars had a stronger bond than the GFRP bars. They determined that the difference in surface form deformation within different kinds of bars was the cause of the outcome. The bonding strength of GFRP bars ranged from 60 to 90% of steel bars, according to Benmokrane et al. [32]. This is in line with the findings of Tigiourat et al. [38]. Using specimens from beam testing, Okelo [40] conducted more research on CFRP bars and found that their bonding strength was roughly 85% that of steel bars [10].

4.2.3 Surface texture

FRP reinforcement bars come in a range of surface textures, including as ribs, sand coating, and helical wrapping. It has been discovered that the roughness of the FRP reinforcement bars' surface affects how well they adhere to concrete. Pullout testing was done on FRP bars by Okelo et al. [18]. They observed that surface imperfections (like those of steel reinforcement bars) or any type of surface texture other than perfectly smooth, like the sand-coated surface texture mentioned earlier, enhanced bond strength and affected the mechanism of failure of FRP bars in a tensioned state. Similar methods were employed by Achillides et al. [20] to examine how surface deformations affect bonding behavior with FRP bars. Initially, those authors found that compared to smooth FRP bars, deformed FRP bars had a bonding stress that was almost 70% higher. Additionally, they pointed out that mechanical interlock between the concrete and the FRP bar surface has a significant impact on the bonding strength of FRP bars. They also assessed GFRP bars that were ribbed and had varying rib heights. The findings of these studies showed that in order to produce an acceptable bond in concrete, a minimum rib height of roughly 5.4% of the bar diameter must be reached. Similarly, Hao et al. [41] used ribbed GFRP reinforcement in concrete to carry out (90) pullout tests. The authors came to the conclusion that, in order for ribbed GFRP bars to create a suitable bond, the ideal rib height should be equal to 6% of the bar's diameter, and the ideal rib spacing should be equal to the diameter of the bar. Similar to this, three different types of GFRP bars with various surface textures were examined by Ruiz Emparanza et al. [46]: ribbed, external cross fibers, and helical wrapping with sand coating. The researchers found that ribbed GFRP bars had an exceptional bond strength. Sand-coated bars with helical wraps and reinforcing bars with external cross fibers came next. Additionally, there was a discussion focused on studies by Wambeke et al. [47], Mosley et al. [48], and Baena et al. [19]. After conducting (269) tests on concrete beams, Wambeke et al. [47] found that the bonding strength was unaffected by the surface texture of GFRP bars. Beam splice tests were used by Mosley et al. [48] to validate the same results. However, Baena et al. [19] found that bar surface features had a significant impact on the bonding strength after conducting (88) pullout tests on FRP bars.

4.2.4 Modulus of elasticity

An average steel reinforcing bar under tension has a modulus of elasticity of (200000 MPa), whereas a typical green fiberglass reinforced plastic (GFRP) reinforcing bar encounters a modulus of elasticity of (43000 MPa) (ACI Committee 440) [1]. The modulus of elasticity of common steel reinforcing bars is different from the one found in FRP reinforcing bars. Okelo et al. [18] conducted pullout studies upon GFRP reinforcing bars and concluded that the modulus of elasticity of these bars seems to possess a specific impact regarding the bonding strength that joins the bars with the concrete. In their study, Larralde and colleagues [36] demonstrated the bond-slip behavior exhibited by FRP reinforcing bars on the counter was increased to the same degree as that of steel reinforcing bars. This was due to the lower modulus of the FRP reinforcing element. After conducting beam testing, Aly et al. [39] determined that the bonding strength between concrete and FRP reinforcing bars is proportional to the square root of the bars' modulus [12]. This was discovered through the evaluation of the bonding strength between the two materials.

4.2.5 FRP Compressive strength

The compression strength associated with GFRP bars ranged between 300 and 600 Mpa. Furthermore, there is ambiguity about the performance of FRP bars at compression, also ACI440.1R-15 [1] design code ignored their role in compression. Despite this, subsequent studies have concentrated on the FRP bars behavior in reinforced concrete columns as the main longitudinal reinforcement. ElMessalami et al. [49] conducted a comprehensive assessment of concrete columns reinforced with FRP bars and concluded that FRP bars compressive strength ranged from 10% to 86% of its tensile strength. Different factors attribute to this large variation including the material and size of the fibers, specimens' structure, how it was prepared and test patterns. It implies that to assess the compressive characteristic of FRP bars more research should be conducted. Concrete cylinders reinforced with GFRP bars and subjected to axial compressive loads was tested by Fillmore et al. [50]. Ultimately, the compressive strength for the GFRP bars was measured to equal 67% of its tensile strength, while their modulus of elasticity under compression appeared quite higher than its value under tension [50].

Sadeghian et al. [51] suggested an alternative approach to evaluate the compressive strength of GFRP bars. They intended to develop a standard test which kept the bars that were tested from buckling while yet providing the results appropriately. Their findings indicated the fact that GFRP bar elastic modulus in both compression and tension were nearly equal. Moreover, the ratio of compressive to tensile strength ratios were between 55% to 99% indicating that GFRP bars' compression role is not neglect able [52].

4.3 Concrete properties

4.3.1 Concrete compressive strength

Square root compressive strength and FRP bond strength in concrete are strongly correlated, according to regression studies (Ehsani et al., 1996 [53]; Okelo and Yuan, 2005 [18], and Okelo, 2007 [40]). As to ACI 408.03, this relationship applies to steel bars installed in normal concrete strength under (55 MPa) [9]. Ehsani et al. [54] and Doost et al. [55] found that increasing concrete compressive strength slightly increased FRP bar bond strength. Tighiourat et al. [38] examined concrete strength and bonding. This study found that bond strength increased with concrete's square root compressive strength. Figure 5 shows stress development for standard and high-strength concrete under different loading stages. Under certain loads, the nearest rib to the load becomes active. More ribs engage as the load increases. Normal strength concrete smashes along the rib edges at high weights, distributing load along the bar, but high strength concrete only affects the first few ribs since it does not crush [56]. The pullout failure of FRP bars with concrete compressive strength of less than (30 MPa) was caused by surrounding concrete cracking, according to Cosenza et al. [57]. The bar itself was undamaged. The bar's outer surface and surrounding concrete eroded at 30 < f′c < 55 MPa, whereas bond strength improved [10, 17]. In the same study, concrete with a compressive strength between 55 and 60 MPa was found to have damage in the FRP bar ribs, causing failure, even when the nearby concrete was overlooked [57-59]. Achillides et al. [20] conducted over (125) direct pullout experiments on FRP reinforcement bars (GFRP, CFRP, AFRP, and hybrids) to prevent splitting failures and specify all mechanisms of failure as pullout. Due to FRP bar resin ripping, concrete compressive forces beyond (30 MPa) did not affect bond strength. Cracking occurred in concrete at compressive strengths below (15 MPa), however bond performance was strongly affected by concrete strength.

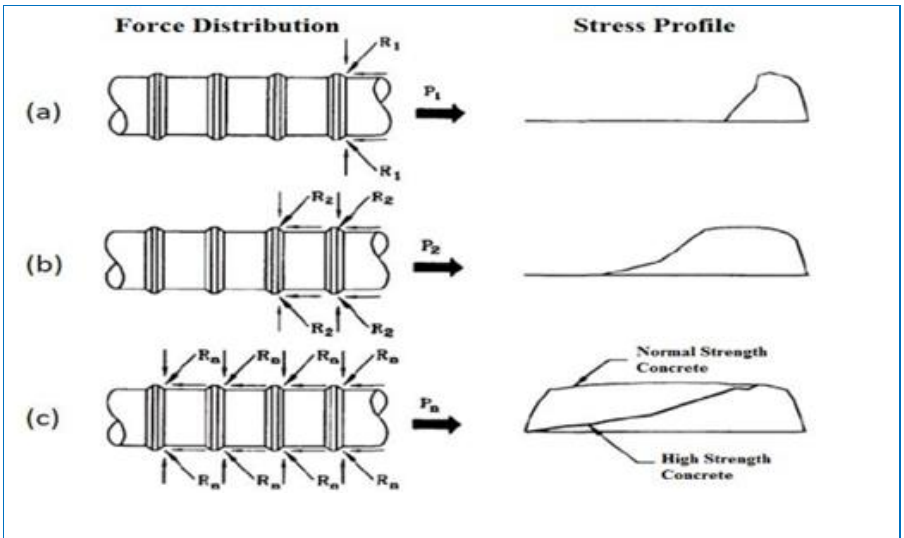

FIGURE 5. Behavior of steel reinforcing bars under tension in concrete (a) Minimal axial load; (b) developing load; and (c) high load [52].

4.3.2 Self-consolidating concrete (SCC)

Steel bars possess superior adhesion as compared to FRP bars when used with normal or self-compacting concrete, as evidenced by the stronger bond strength, linear behavior of bond at the initial stage of the loading process and steel bars have a significantly higher modulus of elasticity than FRP bars [58]. The average bonding strength related to steel and FRP bars using SCC is 12.83% and 10.98% more than that using normal concrete, respectively. This occurred due to the significantly higher filling ability of SCC over NC [61]. One feasible explanation for SCC's greater bonding strengths is due to the fact that the concrete surrounding the reinforcement bars appears more homogeneous, allowing it to completely surround the FRP reinforcing bars [62]. The average bonding strength associated with the FRP reinforcement experienced 73% that of the steel reinforcement [63].There were a few studies conducted on bond strength in SCC, yet they did not always obtain comparable results. Nearly all of the literature indicates that SCC bond stress goes above that of NC [64] even though the results are slightly varied. As stated by Gibbs et al.[65] the variations regarding each of these categories of concrete were approximately 4 %, according to Wang et al. [66] the variations were close to 9%, whereas for Sonebi et al. [67] were 16-40%, for Zhu et al. [68] were 10-40%, and for Collepardi et al. [69] were in the range of 70 %. In certain scenarios, the results have been quite comparable [70], [71]. On the other hand, authors indicate that NC behave better and may attain a 15% stronger final bond strength [72-75]. Furthermore, the bond stress variations observed between SCC and NC dropped as the embedment length increased subsequently disappearing when the embedment length to bar diameter ratio around 37.5 [62]. Regardless of these differences, scholars normally accept that SCC performs with higher degrees of stiffness [66, 72]. The FRP bars exhibited a weaker degree of bonding than steel bars in SCC samples. However, SCC samples had a greater bonding strength and stiffness compared to those of NC. Bond behavior in GFRP reinforced specimens appeared more ductile in contrast to specimens reinforced using steel bars [76,77].

5. Conclusion

This article has reviewed a total of 1784 pullout test specimens, which were subsequently utilized to conduct parametric study. According to the review, frequent bond failure types for FRP bars to concrete include pullout failure, splitting failure, and rebar fracture. The main conclusions of this paper are as follows:

- All the data revealed that pullout failure mode dominated all other failure modes.
- These bond failures, as well as bond strength, are mainly influenced by the structural features, bar characteristics, and the properties of concrete.
- There are linear relationships between bond strength and three important factors: concrete cover, bar casting position, and transverse reinforcement. However, the bonding strength and embedment length parameter have a nonlinear relationship.
- The confinement of concrete cover to FRP rebars significantly affects FRP bars' bond behavior and failure mechanism. Even though there is minimal improvement in bond strength over 2.5 db, increasing the concrete cover enhances bond strength. Furthermore, concrete splitting is the mechanism of failure when the concrete cover is the same diameter as the bar. Increasing the concrete cover to a value more than the bar diameter reduces the concrete splitting. To avoid concrete splitting completely a confinement equal to three times the bar diameter is often advised since this alters the failure mode to pull out or FRP rupture, which is managed by the embedding length.
- The Larger diameter of FRP bar possess small contact region, weaker adhesion to concrete, and vital effect of FRP poisson’s ratio are the reasons that lead to the lower bond strength than that of the FRP with smaller bar diameter.
- Steel bars have higher bond strength than FRP bars. In addition, AFRP creates a lesser bond strength than CFRP and GFRP bars.
- Most of the research state that deformed FRP bars with any sort of deformations possess better bond strength than smooth ones. However, two studies clarify that the surface texture of GFRP bars had no impact on the bonding strength.
- FRP bar elastic modulus in compression and tension has a quite remarkable value even if it is less than its value in tension. Moreover, the ratio of compressive to tensile strength ratios were between (55% to 99%) indicating that FRP bars' compression role is not neglect able.
- Concrete compressive strength plays a vital role in bond behavior of FRP reinforced concrete, increasing the compressive strength lead to a slight enhancement in bond strength. However, normal strength concrete crushes along the edges of the ribs, leading to distribution of load along the bar, while high strength concrete only influences the first few ribs mainly because concrete is unlikely to crush.

- The bond strength of FRP bars when implemented in SCC is generally considered higher than that used with NC. Furthermore, SCC reinforced with FRP bars performs with higher degrees of stiffness.
- The compressive strength of concrete is considered as the most important parameter affecting the bond strength between the FRP bar and the concrete. As it directly affects the mechanism of stress transmission and the compressive strength of the concrete controls the failure mode. To obtain the optimal design, it is necessary to balance the strength of the concrete with the other parameters.
- Although the acquired data is extremely valuable in understanding the bonding behavior of bars and concrete, there are some limitations. These include the fact that the gathered data pertains only to bars that were cast in concrete, and the bars that use the post-installation technique were not considered. Future studies taking into account the bond performance of post-installed FRP bars into existing concrete may fill this gap.

Author Contributions: The authors contributed to all parts of the current study.

Funding: This study received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

References

[1] ACI PRC-440.1-15 (2015), Guide for the Design and Construction of Structural Concrete Reinforced with Fiber-Reinforced Polymer Bars, American Concrete Institute, Farmington Hills, MI, USA.

[2] French, C. (2003), “Durability of Concrete Structures”, Structural Concrete, **4**(3), 101–107.

[3] Nanni, M., Al-Zaharani, S., Al-Dulaijan, C., Bakis, C. and Boothby, I. (1995), “Bond of FRP Reinforcement to Concrete-Experimental Results”, in Non-metallic (FRP) Reinforcement for Concrete Structures: Proceedings of the Second International RILEM Symposium, CRC Press, London, August.

[4] Nanni, A., De Luca, A. and Zadeh, H. (2014), “Reinforced Concrete with FRP Bars”, CRC Press, London, United Kingdom, doi: 10.1016/b16669.

[5] Yan, F. and Lin, Z. (2016), “New Strategy for Anchorage Reliability Assessment of GFRP Bars to Concrete Using Hybrid Artificial Neural Network with Genetic Algorithm”, Composites B: Engineering, **92**, 420–433, doi: 10.1016/j.compositesb.2016.02.008.

[6] Lee, J.Y. et al. (2008), “Interfacial Bond Strength of Glass Fiber Reinforced Polymer Bars in High-Strength Concrete”, Composites B: Engineering, **39**(2), 258–270, doi: 10.1016/j.compositesb.2007.03.008.

[7] Zhang, P. et al. (2021), “Influence of Rib Parameters on Mechanical Properties and Bond Behavior in Concrete of Fiber-Reinforced Polymer Rebar”, Advances in Structural Engineering, **24**(1), 196–208, doi: 10.1177/1369433220947196.

[8] Ehsani, M.R., S.H. and T.S. (1997), “Bond Behavior of Deformed GFRP Rebars”, Journal of Composite Materials, **31**(14), 1413–1430.

[9] ACI Committee 408 (2003), “408R-03: Bond and Development of Straight Reinforcing Bars in Tension”, Technical Documents.

[10] Abolghasem, A. (2013), "Experimental Investigation on Pull-out Strength of Pre-and Post-Installed GFRP Bars for Bridge Barrier Construction", Digital Commons @ Ryerson. [Online]. Available: http://digitalcommons.ryerson.ca/dissertations.

[11] Alavi-Fard, M. (1999), "Bond Characteristics of High Strength Concrete", Ph.D. Dissertation, Memorial University of Newfoundland, Newfoundland.

[12] Demars, T.J. (2021), "Tensile and Shear Capacity of Post-Installed GFRP Bars in Concrete".

[13] Tayeh, B.A., El Dada, Z.M., Shihada, S. and Yusuf, M.O. (2019), "Pull-out Behavior of Post-Installed Rebar Connections Using Chemical Adhesives and Cement-based Binders", Journal of King Saud University - Engineering Sciences, **31**(4), 332–339, doi: 10.1016/j.jksues.2017.11.005.

[14] Haidar, H.H., Mussa, F.I., Dawood, A.O., Ghazi, A.A. and Gabbar, R.A. (2020), "Experimental Study of Post-Installed Rebar Anchor Systems for Concrete Structure", Civil and Environmental Engineering, **16**(2), 308–319, doi: 10.2478/cee-2020-0031.

[15] Allen, J.H., Felder, A.L., Mcdermott, J.F., Azizinamini, A., Frosch, R.J., Mitchell, D., Balázs, G.L., Hamad, B.S., Hawkins, N.M., Porter, M.L., Cox, J.V., Leon, R.T., Ramirez, J.A., DeVries, R.A., Lutz, L.A., Silva, J.K., Eligehausen, R., Mccabe, S.L., Zuo, J., Fagundo, F.E., & Darwin, D. (2003),." Bond and Development of Straight Reinforcing Bars in Tension ACI 408 R-03 Reported by ACI Committee 408.

[16] Looi, D. (2020), "Design Methods for Anchorage of Post-Installed Rebars: Rebar End Anchorage Design, Introduction to Anchor Theory and the Improved Bond Splitting Provision", Recent Advances in Design Methodology for Post-Installed Reinforcements, p. 11.

[17] Yan, F., Lin, Z. and Yang, M. (2016), "Bond Mechanism and Bond Strength of GFRP Bars to Concrete: A Review", Composites B: Engineering, **98**(1), 56–69, https://doi.org/10.1016/j.compositesb.2016.04.068.

[18] Okelo, R., Asce, A.M., Yuan, R.L. and Asce, M. (2005), "Bond Strength of Fiber Reinforced Polymer Rebars in Normal Strength Concrete", https://doi.org/10.1061/ASCE1090-026820059:3203.

[19] Baena, M., Torres, L., Turon, A. and Barris, C. (2009), "Experimental Study of Bond Behaviour Between Concrete and FRP Bars Using a Pull-out Test", Composites B: Engineering, **40**(8), 784–797, https://doi.org/10.1016/j.compositesb.2009.07.003.

[20] Achillides, Z. and Pilakoutas, K. (2004), "Bond Behavior of Fiber Reinforced Polymer Bars under Direct Pullout Conditions", https://doi.org/10.1061/ASCE1090-026820048:2173.

[21] Kim, B., Doh, J.H., Yi, C.K. and Lee, J.Y. (2013), "Effects of Structural Fibers on Bonding Mechanism Changes in Interface Between GFRP Bar and Concrete", Composites B: Engineering, **45**(1), 768–779, https://doi.org/10.1016/j.compositesb.2012.09.039.

[22] Kauffman, L. and Fam, A. (2024), "Effect of GFRP Bar Diameter and Concrete Cover on Bond and Development Length in UHPFRC", Available online: https://ssrn.com/abstract=4646143.

[23] Michaud, D., Fam, A. and Dagenais, M.A. (2021), "Development Length of Sand-Coated GFRP Bars Embedded in Ultra-High Performance Concrete with Very Small Cover", Construction and Building Materials, 270, February, https://doi.org/10.1016/j.conbuildmat.2020.121384.

[24] Basaran, B. and Kalkan, I. (2020), "Investigation on Variables Affecting Bond Strength Between FRP Reinforcing Bar and Concrete by Modified Hinged Beam Tests", Composite Structures**, 242**, https://doi.org/10.1016/j.compstruct.2020.112185.

[25] Krem, S. and Soudki, K. (2010), "Development Length of Carbon-Fiber-Reinforced Polymer Bars in Self-Consolidating Concrete", RILEM Bookseries, 1, 379–391, https://doi.org/10.1007/978-90-481-9664-7_32.

[26] Islam, S., Afefy, H.M., Sennah, K. and Azimi, H. (2015), "Bond Characteristics of Straight- and Headed-End, Ribbed-Surface, GFRP Bars Embedded in High-Strength Concrete", Construction and Building Materials, **83**, 283–298, https://doi.org/10.1016/j.conbuildmat.2015.03.025.

[27] ACI Committee (2019), 318-19 Building Code Requirements for Structural Concrete and Commentary, American Concrete Institute, https://doi.org/10.14359/51716937.

[28] Rossetti, V.A., Galeota, D. and Giammatteo, M.M. (1995), "Local Bond Stress-Slip Relationships of Glass Fibre Reinforced Plastic Bars Embedded in Concrete".

[29] Cosenza, E., Manfredi, G. and Realfonzo, R. (1997), "Behavior and Modeling of Bond of FRP Rebars to Concrete", Journal of Composites for Construction, **1**(2), 40–51, https://doi.org/10.1061/(ASCE)1090-0268(1997)1:2(40).

[30] Ehsani, M.R., Saadatmanesh, H. and Tao, S. (1993), "Bond of GFRP Rebars to Ordinary-Strength Concrete", Special Publication, **138**, 333–346.

[31] Chaallal, O. and Benmokrane, B. (1993), "Pullout and Bond of Glass-Fibre Rods Embedded in Concrete and Cement Grout".

[32] Benmokrane, B. and Masmoudi, R. (1996), "FRP C-bar as Reinforcing Rod for Concrete Structures", Proceedings of the 2nd International Conference on Advanced Composite Materials in Bridges and Structures (ACMBS-II), Montreal, Canada.

[33] Wambeke, B.W. and Shield, C.K. (2006), "Development Length of Glass Fiber-Reinforced Polymer Bars in Concrete", ACI Materials Journal, **103**(1), 11.

[34] Harajli, M. and Abouniaj, M. (2010), "Bond Performance of GFRP Bars in Tension: Experimental Evaluation and Assessment of ACI 440 Guidelines", https://doi.org/10.1061/ASCECC.1943-5614.0000139.

[35] Abbas, H., Elsanadedy, H., Alaoud, L., Almusallam, T. and Al-Salloum, Y. (2023), "Effect of Confining Stirrups and Bar Gap in Improving Bond Behavior of Glass Fiber Reinforced Polymer (GFRP) Bar Lap Splices in RC Beams", Construction and Building Materials, **365**, https://doi.org/10.1016/j.conbuildmat.2022.129943.

[36] Larralde, J. and Silva-Rodriguez, R. (1993), "Bond and Slip of FRP Rebars in Concrete", Journal of Materials in Civil Engineering, **5**(1), 30–40.

[37] Shield, C., French, C. and Retika, A. (1997), "Thermal and Mechanical Fatigue Effects on GFRP Rebar-Concrete Bond", Proceedings of the 3rd International Symposium on Non-Metallic (FRP) Reinforcement for Concrete Structures (FRPRCS-3), Sapporo, Japan, November.

[38] Tighiouart, B., Benmokrane, B. and Gao, D. (1998), "Investigation of Bond in Concrete Member with Fibre Reinforced Polymer (FRP) Bars".

[39] Aly, R., Benmokrane, B., & Ebead, U. (2006), "Tensile lap splicing of fiber-reinforced polymer reinforcing bars in concrete", ACI Structural Journal, **103**(6), 857 . https://www.researchgate.net/publication/260368643.

[40] Okelo, R. and Asce, A.M. (2007), "Realistic Bond Strength of FRP Rebars in NSC from Beam Specimens", doi: 10.1061/ASCE0893-1321200720:3133.

[41] Hao, Q., Wang, Y., He, Z. and Ou, J. (2009), "Bond Strength of Glass Fiber Reinforced Polymer Ribbed Rebars in Normal Strength Concrete", Construction and Building Materials, **23**(2), 865–871, doi: 10.1016/j.conbuildmat.2008.04.011.

[42] Alves, J., El-Ragaby, A. and El-Salakawy, E. (2011), "Durability of GFRP Bars' Bond to Concrete under Different Loading and Environmental Conditions", Journal of Composites for Construction, **15**(3), 249–262, doi: 10.1061/(asce)cc.1943-5614.0000161.

[43] "Commentary on CAN/CSA-S6-06, Canadian Highway Bridge Design Code", www.ShopCSA.ca.

[44] "Recommendation for Design and Construction of Concrete Structures Using Continuous Fiber Reinforcing Material", doi: 10.5169/seals-61419.

[45] Canadian Standards Association. (2012), Design and Construction of Building Structures with Fibre-Reinforced Polymers, Canadian Standards Association, Toronto, ON, Canada.

[46] Ruiz Emparanza, A., De Caso Y Basalo, F.J. and Nanni, A. (2018), "Bond Evaluation of GFRP Reinforcing Bars Embedded in Concrete under Aggressive Environments". https://www.researchgate.net/publication/327405996.

[47] Wambeke, B.W. and Shield, C.K. (2006), "Development Length of Glass Fiber-Reinforced Polymer Bars in Concrete" ACI Materials Journal, **103**(1), 11.

[48] Mosley, C.P., Tureyen, A.K. and Frosch, R.J. (2008), "Bond Strength of Nonmetallic Reinforcing Bars", ACI Structural Journal, **105**(5), 634.

[49] ElMessalami, N., Abed, F. and El Refai, A. (2021), "Response of Concrete Columns Reinforced with Longitudinal and Transverse BFRP Bars under Concentric and Eccentric Loading", Composites Structures, **255**, doi: 10.1016/j.compstruct.2020.113057.

[50] Fillmore, B. and Sadeghian, P. (2014), "Contribution of Longitudinal GFRP Bars in Concrete Cylinders under Axial Compression". www.nrcresearchpress.com.

[51] Khorramian, K. and Sadeghian, P. (2019), "Material Characterization of GFRP Bars in Compression Using a New Test Method", Journal of Testing and Evaluation, **49**(2), doi: 10.1520/JTE20180873.

[52] Abed, F., Mehaini, Z., Oucif, C., Abdul-Latif, A. and Baleh, R. (2020), "Quasi-Static and Dynamic Response of GFRP and BFRP Bars under Compression", Composites Part C: Open Access, **2**, doi: 10.1016/j.jcomc.2020.100034.

[53] Ehsani, M.R., Saadatmanesh, H. and Tao, S. (1996), "Bond Behavior and Design Recommendations for Fiberglass Reinforcing Bars", First International Conference on Composites in Infrastructure, National Science Foundation.

[54] Ehsani, M.R., Saadatmanesh, H., and Tao, S. (1995), "Bond of Hooked GFRP Rebars to Concrete", Materials Journal, **92**(4), 391–400.

[55] Doost Mohamadi, A., Vatani Oskouei, A., and Kheyroddin, A. (2021), "An Experimental Study on Effect of Concrete Type on Bond Strength of GFRP Bars", Journal of Rehabilitation in Civil Engineering, **9**(1), 52–70, doi: 10.22075/JRCE.2020.19922.1392.

[56] Azizinamini, A., Chisala, M., and Ghosh, S.K. (1995), "Tension Development Length of Reinforcing Bars Embedded in High-Strength Concrete".

[57] Cosenza, E., Manfredi, G., and Realfonzo, R. (2002), "Development Length of FRP Straight Rebars" www.elsevier.com/locate/compositesb

[58] Won, J.-P., Park, C.-G., Kim, H.-H., Lee, S.-W., and Jang, C.-I. (2008), "Effect of Fibers on the Bonds Between FRP Reinforcing Bars and High-Strength Concrete", Compos B Eng, **39**(5), 747–755.

[59] Dancygier, A.N., Katz, A., and Wexler, U. (2010), "Bond Between Deformed Reinforcement and Normal and High-Strength Concrete with and Without Fibers", Materials and Structures/Materiaux et Constructions, **43**(6), 839–856, Jul. 2010, doi: 10.1617/s11527-009-9551-6.

[60] Salim, Z.S., Salih, O.A., and Kasim, S.Y. (2022, November), "Investigating the Behavior of Post-Installed Reinforcing Bars Fixed by Chemical Adhesives with Different Concrete Base Compressive Strength," AIP Conference Proceedings, 2660(1), AIP Publishing.

[61] Golafshani, E.M., Rahai, A., and Sebt, M.H. (2014), "Bond Behavior of Steel and GFRP Bars in Self-Compacting Concrete", Constr Build Mater, **61**, 230–240, doi: 10.1016/j.conbuildmat.2014.02.021.

[62] Ballesteros-Pérez, P., Pellicer, E., & González-Cruz, M. C. (2017), "Economic scoring formulae in multi-attribute construction auction", in Resilient Structures and Sustainable Construction, Pellicer, E., Adam, J. M., Yepes, V., Singh, A., & Yazdani, S. (eds.), ISEC Press, pp. 1-6. ISBN 9780996043748.

[63] Zemour, N., Asadian, A., Ahmed, E.A., Khayat, K.H., and Benmokrane, B. (2018), “Experimental Study on the Bond Behavior of GFRP Bars in Normal and Self-Consolidating Concrete”, Constr Build Mater, **189**, 869–881, doi: 10.1016/j.conbuildmat.2018.09.045.

[64] Valcuende, M., and Parra, C. (2009), “Bond Behaviour of Reinforcement in Self-Compacting Concretes”, Constr Build Mater, **23**, (1), 162–170, doi: 10.1016/j.conbuildmat.2008.01.007.

[65] Gibbs, J.C., and Zhu, W. (1999), “Strength of Hardened Self-Compacting Concrete”, in 1st International RILEM Symposium on Self-Compacting Concrete, Stockholm, Sweden, 199–209.

[66] Wang, G., and Zheng, J. (2005), “Bond Behaviors of Self-Compacting Concrete”, in SCC’2005-China-1st International Symposium on Design, Performance and Use of Self-Consolidating Concrete, 465–471.

[67] Sonebi, M., and Bartos, P.J.M. (1999), “Hardened SCC and Its Bond with Reinforcement”, in Proceedings of the First International RILEM Symposium on Self-Compacting Concrete (PRO 7), Stockholm, Sweden.

[68] Zhu, W., Sonebi, M., and Bartos, P.J.M. (2003), “Bond and Interfacial Properties of Reinforcement in Self-Compacting Concrete”, in Proceedings of the 3rd International Symposium on Self-Compacting Concrete, Reykjavik, Iceland.

[69] Collepardi, M., Borsoi, A., Collepardi, S., and Troli, R. (2005), “Strength, Shrinkage and Creep of SCC and Flowing Concrete”, in Proceedings of Second North American Conference on the Design and Use of Self-Consolidating Concrete and Fourth International RILEM Symposium on Self-Compacting Concrete.

[70] Daoud, A., Daoud, A., Lorrain, M., and Elgonnouni, I.M. (2002), “Pull-Out Behaviour of Reinforcement Embedded in Self-Compacting Concrete”, Materials and Structures/R6sistance/l I’arrachement d’armatures ancrdes dans du béton autoplagant. https://www.researchgate.net/publication/319143772

[71] Atef, D., Michel, L., and Christian, L. (2003.), “Anchorage and Cracking Behaviour of Self-Compacting Concrete”.

[72] Schiessl, A., and Zilch, K. (2001), “The Effect of the Modified Composition of SCC on Shear and Bond Behavior”, in Proceedings of the 2nd International Symposium on Self-Compacting Concrete, Tokyo, Japan.

[73] König, G., Holschemacher, K., Dehn, F., and Weibe, D. (2001), “Self-Compacting Concrete–Time Development of Material Properties and Bond Behavior”, in Proceedings of the 2nd International Symposium on Self-Compacting Concrete.

[74] König, G., Holschemacher, K., Dehn, F., and Weiße, D. (2003), “Bond of Reinforcement in Self-Compacting Concrete (SCC) under Monotonic and Cyclic Loading”, in Proceedings of the 3rd International Symposium on Self-Compacting Concrete, Reykjavik, Iceland.

[75] Almeida Filho, F.M., De Nardin, S., and El Debs, A. (2005), "Evaluation of the Bond Strength of Self-Compacting Concrete in Pull-Out Tests", in Proceedings of Second North American Conference On The Design And Use Of Self-Consolidating Concrete And Fourth International Rilem Symposium On Self-Compacting Concrete, Chicago.

[76] Abed, M.A., Alkurdi, Z., Fořt, J., Černý, R., and Solyom, S. (2022), "Bond Behavior of FRP Bars in Lightweight SCC under Direct Pull-Out Conditions: Experimental and Numerical Investigation",Materials, **15**(10), doi: 10.3390/ma15103555.

[77] Wang, Y., Wu, L., Guo, X., Chen, H., Ba, Y., and Liu, Z. (2025), "Numerical Simulation of Bonding Performance Between GFRP and Lightweight Aggregate Concrete," Engineering Research Express, **7**(1).