A review of bond behavior of steel and GFRP bars to concrete

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ABSTRACT

The bond behavior of steel and GFRP bars in concrete is one of the most important issues in reinforced concrete structures and depends on several factors, such as the structural characteristics, bar and concrete properties. Glass fiber-reinforced polymer (GFRP) reinforcements are taken as an alternative solution for the deterioration of civil infrastructures. GFRP bars have received increasing attention due to low cost compared to steel bars. Bond characteristic of GFRP bars in concrete is the most critical parameter for implementation of the material to the corrosion-free concrete structures. This paper offers an extensive discussion of the bond performance of reinforcement bars (steel and GFRP) with concrete, considering the bond mechanism, parameters affecting bond strength, and bond test methodologies. Finally, a comprehensive review is presented about a previous study that was conducted to investigate the bond behavior of steel and GFRP bars embedded in concrete.

Keywords: Bond Behavior, Pullout Test, GFRP Bar, Slip

1. Introduction

Reinforced concrete can be described as a composite element in which concrete is combined with reinforcement to withstand stresses[1]. The reinforcements, including mesh, or bars, withstand bending and shear loads and increase the compression of the concrete. Although concrete does not offer sufficient resistance to tensile or shear stresses. Consequently, concrete is regarded as inadequate for the majority of construction purposes. But, concrete is an efficient material for withstanding compressive pressures [2]. Therefore, the durability of reinforced concrete results from concrete's significant compressive strength and steel resistance tensile stresses. Thus, a composite activity ensures transmission loads between reinforcement and adjacent concrete. Load transmission activity is defined as a shear bond stress acting parallel to the reinforcement bar, it has been commonly known as a shear force for the unit contact surface area of the reinforcement bar [1]

2. Bond mechanism

A bond between the concrete and the reinforcement is required to ensure the combined action of the two materials. This action represents force transmission between the reinforcing bar and concrete. The bond activity resulted from three elements, Fig. 1.

- Chemical adhesion between the surrounding concrete and the reinforcement bar.

- Friction resistance.
- Bearing of lugs against the concrete (mechanical interlock).

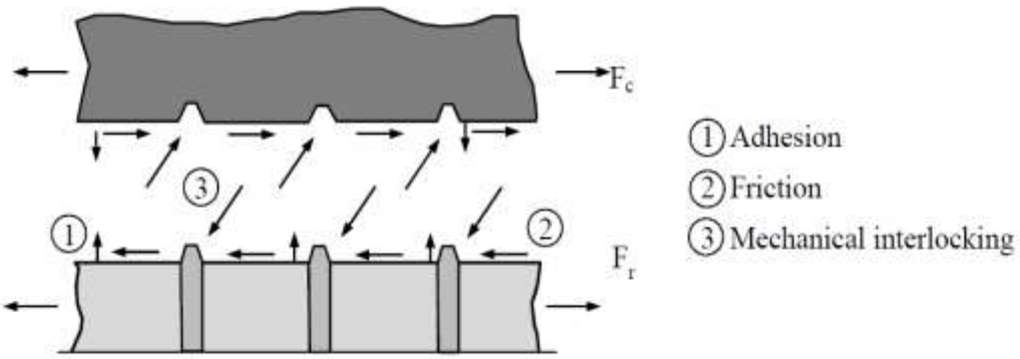


Figure 1. Force transfer mechanism [3].

also, the bond mechanism of FRP bars is based on the same three components as that of steel bars. The chemical adhesion is the first component, followed by the resistance resulting from friction. Finally, interlocking control on bond activity is based on the surface nature of bars[4][5]. In the first stages of loading, chemical adhesion seems to be dominant. When applied loads are increased, there is a gradual decrease he adhesion resistance. After that, friction is prevent FRP bars from slipping under tensile stresses, then mechanical interlocking is the controlled component of bond activity [6]. Furthermore, it was reported that chemical adhesion resistance was very low, where friction and mechanical interlock were essential in transfer loads between concrete and FRP bars. Unlike plain steel bars, friction and adhesion are dominant elements, whereas deformed reinforcing steel bars are highly dependent on mechanical interlocking[6]. Since GFRP reinforcing bars' surface deformations lack the same characteristics as steel reinforcement bars, such as sufficient shear strength, high stiffness, and deformation configuration, which provide adequate confinement to concrete, some researchers [7] [8] reached the conclusion that adhesion and friction governed the bond strength of GFRP bars.

3. Shear lag

The core and top layer of the GFRP reinforcing bar will move relative to one another when the bar is dragged due to applied tensile force, thus an unequal distribution of stresses across the bar's cross-sections[9]. Furthermore, it was indicated that fibers near the core of the bar are not as heavily stressed as fibers near the top layer [10]. The idealized distribution of stress is shown in Fig. 2.

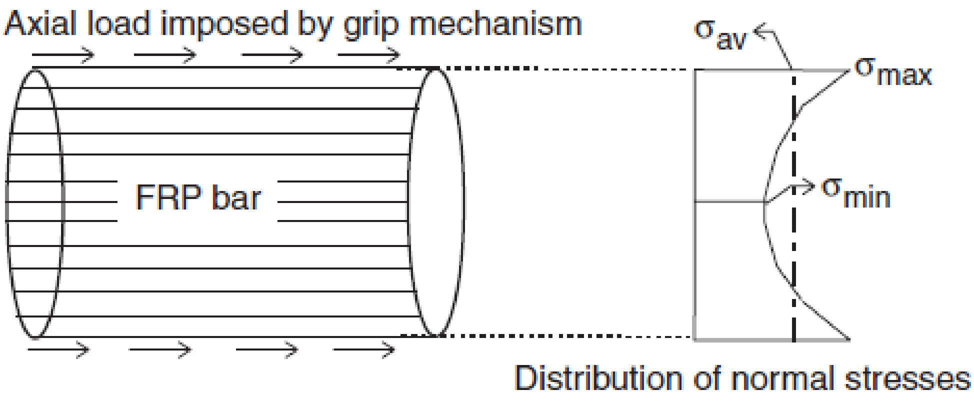


Figure 2. Normal stress distribution of FRP bar cross-section undergoes axial tensile force [11].

4. Bond failure modes

Pull-out and splitting failures are the two main modes of failure seen in bond test methodologies. Following is an illustration of these modes.

4.1 Pull-out failure mode

Pullout mode is defined as pulling the reinforcement bar from the surrounding concrete without any cracks surrounding concrete. This mode can be caused by the shearing of the interface between the reinforcing bar of the surrounding concrete. Pull-out failure arises if the perpendicular forces that spread out from a bar under tension are less than the strength of the concrete around it, but the parallel forces are stronger than what the concrete can resist, as shown in Fig.3. According to previous studies, pull-out failure often occurs at the interface between concrete and deformations at the bar surface or between the bar core and the outer surface in the case of GFRP bars.

Benmokrane [12] broke GFRP pullout specimen after failing to explore the nature of the failure, thus reached that pull-out failure happens due to deterioration of the bar surface. This deterioration was because the shear strength of the concrete was higher than the strength between the bar core and the bar surface. Bond failures are mostly influenced by concrete strength, bar size, transverse reinforcement, bond length, and concrete cover. For example, Okelo and Yuan (2005) [13] reported that shorter embedment length specimens with weak concrete strengths fail by pull-out mode. Yan et al. 2016 [14] observed that a greater cover provides additional bond strength between concrete and bar, thus reducing the probability of arising cracks, thus pull-out mode occurs. Also, the researcher aforementioned showed that bars with smaller diameters mostly fail by pull-out mode. Pilakoutas and Achillides (2004)[9] observed that pullout GFRP failure occurred when the concrete compression strength exceeded (30 MPa), whereas concrete cracks occurred if the compressive strength of concrete was less than 30 MPa (about 20 MPa).

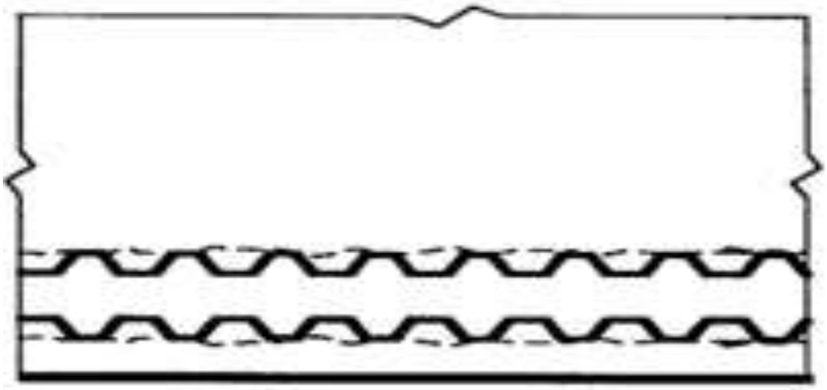


Figure 3. Crushing of concrete that surrounds reinforcement bar [15].

4.2 Splitting failure mode

Splitting mode occurs in the cover of concrete that surrounds the reinforcing bar under tension. The bars generate radial forces on the surrounding concrete when they are loaded. If the concrete and transverse reinforcement are insufficient to withstand these radial forces, cracks arise near the surface of the embedded bar towards the concrete cover, as shown in Fig.4.On the other hand, splitting is a result of tensile stresses greater than concrete tensile strength.

Ehsani et al. (1996) [16] noted that specimens of GFRP bars with a small concrete cover split because the concrete cover did not withstand the tensile stresses, but with greater embedded lengths with adequate cover failed by bar rupture as a result of tensile stresses inside the bar exceeding its tensile stress. ACI-408R (2003) [15] states that splitting is caused if the concrete cover is sufficient, and also reported that embedded length also influences bond failure. Longer embedment lengths lead to failure by splitting, while shorter embedment lengths result in failure by pull-out.

Yan et al. 2016 [14] reported that the presence of stirrups increases confinement to the concrete, thus delaying or preventing a split failure, and the probability of a splitting failure will be reduced and stated that the likelihood of splitting failures increases as the diameter of the bar increases.

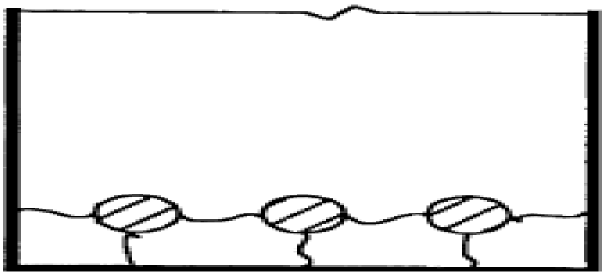


Figure 4. Radial splitting cracks towards concrete cover.

5. Parameters influence bond performance

5.1 Embedded length

Embedded length important parameter that affects the bonding strength of reinforcement bars. Bond strength decreases as embedded length increase ,This is due to the non-linear distribution of bond stresses over the bond length [9]. This behavior was approved by a number of investigations using pull-out and beam tests [9][17][5]. The non-linear- distribution of bond stresses becomes more observable as embedded length increases, leading to a reduction in the average bond strength. Achillides et. al. 2004 [9] found that the embedded length has a notable effect on the bond strength of GFRP bars, as embedded length increases initial bond stiffness decreases. Hossain et al. 2014 [18] investigated the bond behavior of GFRP bars with 75 MPa compressive strength and variable embedded length (three, five, seven, and ten times bar diameter) ,the result proved that as the embedded length increased, bond strength decreased, also Tekle et al. 2016 [19] determined that an increase in the embedment length of GFRP with compressive strength (43MPa) lead to decreasing in the bond strength.

5.2 Bar diameter

Similar to steel reinforcement, it has been determined from earlier studies that increasing the diameter of FRP bars reduces the average maximum bond stress [20] [21] [22] [9] [13]. Tigiouart et al. 1998 [8] and Hao et al. 2007 [23] found that a greater diameter developed less bond strength than a lesser diameter as a result of the bleed the water below the large diameters thus forming the voids, which reduces the adhesion or contact surface between reinforcement and the concrete thereby reduces bond strength. Whereas Achiillides [9] attribute the decrease in bond strength in larger diameters due to many parameters: embedment length, shear lag, besides Poisson effect which are discussed in sufficient explanation below.

To achieve reasonable bond stresses of larger diameters, the embedment lengths are required to be longer. As was previously stated the longer bond lengths lead to less bond strength. The longitudinal strain might cause a little reduction in bar diameter as a consequence of the Poisson effect. This decrease might result in a reduction in friction and mechanical interlocking stresses as the bar diameter increases. Shear lag is primarily governed by the toughness of the resin and the shear resistance of the resin-fiber contact. When tensile forces are applied to the GFRP or steel bars, relative movement arises between surface and the core of the bar. As a consequence, stresses will be unequally distributed between bar core and top layer bar, as shown in the Figure 2. Shear lag causes highest stresses near the surface, which govern bond strength, and low average normal stresses throughout bar core. Large diameters have a larger variance between stresses in top layer and core , which reduces bond strength[9][24].

5.3 Compressive strength of concrete

Compression and tensile concrete strengths affect the bond strength of FRP bars. Xue et al. (2008) [6] demonstrated that increased compressive strength of concrete resulted in a better bonding for FRP bars. Achilliides et.al 2004 studied the influence of compressive strength on the bond behavior of GFRP bar, compression strength (15 - 49 MPa). The outcomes stated that compression strength of concrete influenced mode of failure, with strength above 30 MPa failing via pull-out failure. For concrete strength 15 MPa, bond failure occurred in concrete so they concluded that bond strength increased as concrete strength increase. This behavior confirmed by the by Baena 2009 [20] with strength is about 30 MPa, failure happens in concrete. They discovered that a lesser compression strength of 30 MPa caused less damage to the bar surface and greater damage to the concrete, and vice versa for 50 MPa concrete compressive strengths. Lee et al. (2017) [25] also studied the concrete compression strength as a variable (20 to 60 MPa) on the bond behavior of GFRP bars. The experimental results revealed a negligible improvement in bond strength when concrete strength increased from 40 to 60 MPa. Lee et al. 2008 [26] found that the bond strength of GFRP increased with increasing compressive concrete and this enhancement in bond strength was better in steel rebar than that in GFRP bars. Lee et al. (2012) [27] studied the influence of concrete compressive strengths (25 to 70 MPa) on GFRP bars, The findings revealed that bond strength improved with concrete strength and slip decreased with a greater concrete compressive strength due to damage to the exterior surface of the bar.

5.4 Concrete cover

The bond strength between both the FRP bars and the concrete is greatly influenced by the concrete as the concrete cover lead to increase the degree of confinement, which in turn leads to an enhancement in the bond strength[28]. ACI 440.1R-15 noted that splitting failure will occur if there is an insufficient concrete cover. If the reinforced concrete beam has a sufficient concrete cover, pullout failure will result from shear along the surface of the bar at the top of the ribs surrounding the bars. The mechanism of bond failure is mostly determined by the cover of concrete and the degree of confinement. Pullout failure occurs when the concrete cover is more than two times the diameter of the bar. While splitting failure develops with concrete cover is equal to the diameter of the reinforcing bar[29]. Veljkovic et al.[30] (2017) evaluated the influence of different concrete covers on the bond between GFRP and concrete bars,in this investigation, three concrete covers were utilized and they found that increasing the cover (10 mm to 20 mm) enhanced the bond strength by about 20%,both specimens with 10 mm and 20 mm cover failed by splitting.

5.6 Transversal reinforcement

Stirrups are supplied along longitudinal reinforcing bars in order to improve the shear strength. Several authors have researched the significance of transversal reinforcement on bond strength in concrete members. Aly (2005) [31] and Harajli et.al (2010) [29] both concluded that transversal reinforcement improved the bond strength of spliced bars in concrete. In beam specimens reinforced with GFRP bars, increasing transverse reinforcement throughout the splice length improved bond strength ,these outcome was comparable to that observed for steel bar by Darwin (1996)[21].

6. Bond test methods

The pullout test and the beam test are the two most common methods to evaluate the bond strength between reinforcing bar and concrete.

6.1 pullout test

The pull-out test is the most popular method since it is simple to fabricate test specimens and easy to carry out the test. The test is carried out by holding the concrete in place and providing pullout force to the reinforcement bar till failure. This is less reliable for determining the real bond behavior; thus, it should only be employed for comparison reasons.

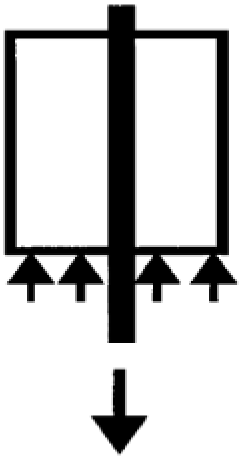


Figure 5. Pull-out test method [32]

6.2 Beam test

Fig.6. shows several kinds of beam tests that evaluate the bond performance of reinforcing bars implanted in the concrete (ACl 440,3R, 2012, ACI-408R, 2003).

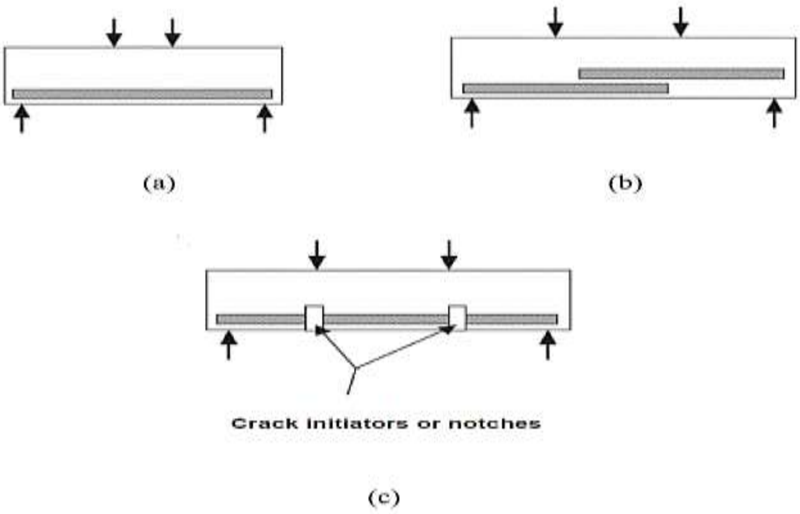
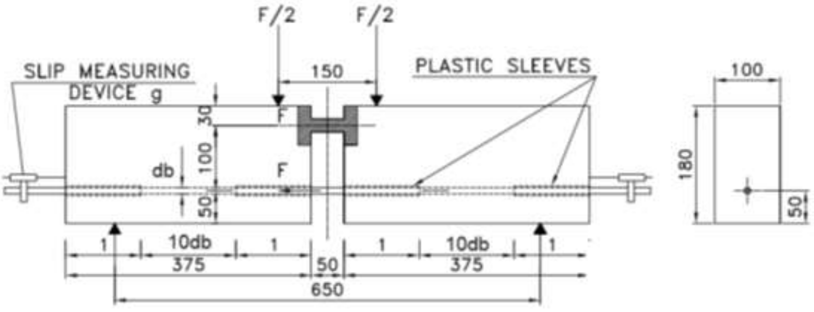
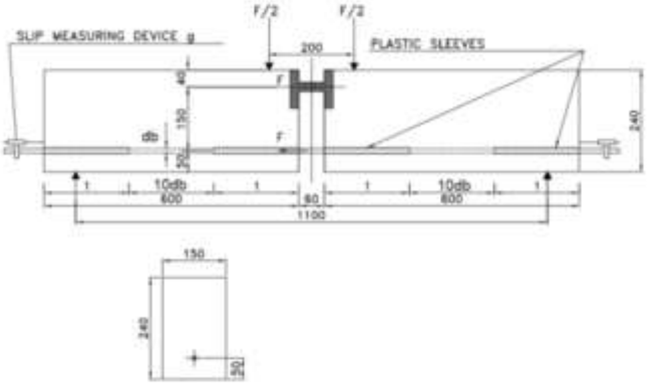


Figure 7. Different types of beam test (a) simple beam specimen (b) splice specimen (c) nothed beam specimen [33] [32].

This investigation will look into the bond characteristics of steel and GFRP bars using a hinged beam test. The RILEM standards [34]show the design for the hinged beam test, as illustrated in Fig.8. This methodology was first constructed to explore the bond behavior of steel bars.



Type (A)



Type (B)

Figure 8. hinged beam test-type A and B (Rilem recommendation) [34].

Szczech and Kotynia, 2018 [35] modified a hinged beam to evaluate the bond performance of steel and GFRP bars, as seen in Fig.9. Each beam is made up of two parallel reinforced concrete blocks that are attached at the top by a steel hinge and the bottom by the tested bar (steel or GFRP). It is loaded by two-point forces. When loading, which must continue till the bond fails. Szczech and Kotynia distinguished from other researchers that they investigated bond performance of steel and GFRP bars together in the same section by using hinged beam test so that in this study use the same modified hinged beam to study the bond behavior of steel and GFRP bars embedded high volume fly ash concrete (HVFAC).

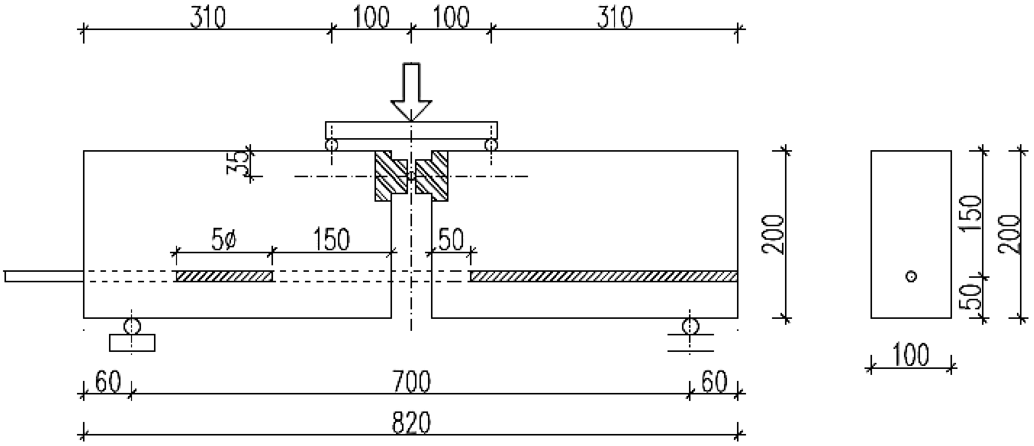


Figure 9. Hinged beam test (Szczech and Kotynia, 2018) [35].

7. Previous works

7.1 Prior works utilizing pullout specimens

Katz et al. (1999) [36] looked into the influence of high temperature ,max. 300°C. on the bond strength of FRP bars and compared their findings with steel bars. with constant bar diameter. The test samples were cylinders with 150 mm in diameter, 300 mm in height, embedded length (5Ø), and 35 MPa compression strength. The testing included heating the cylinders to a required temperature before the test. The researchers found that all of the reinforcing bars showed decreasing in bond as temperature increased, however, there was a clear difference between the failing modes of steel and FRP bars. Steel bars showed a drop in bond with rising temperature, and their failure mode was concrete crushing, while FRP bars displayed polymer deteriorations. FRP bars with polymer lug deformations showed significantly lower bonding performance than FRPs with glass fiber helical wraps. Finally, testing findings revealed that the bond strength of FRP bars at room temperature is not only comparable to steel but greater for steel bars. Also, at high temperatures ranging from 180 to 250°C, the bond strength of steel and FRP bars is reduced, with the FRP bars suffering high reduction.

Al-Owaisy, 2001[37] evaluated the residual bond strength after exposure to high temperatures. The test results showed that bond strength deteriorates at high temperatures, and the residual bond strength-temperature relationship was similar to that of the concrete compressive strength-temperature relationship. Also, test results showed that bond strength increases as bar diameter increases. Also the researcher indicated that the use of ties increases bond strength significantly.

Al Ukaily et al. 2005 [38] investigated the influence of compressive strength, bar diameter, and cover on bonding strength. In this investigation, prism specimens were used. prism length is fifteen bar in diameter, whereas the prism width is 304 mm, the thickness is determined by cover. The prisms are reinforced by the central reinforcing bar with a length that is five times the diameter of the bar. The test findings indicate that bond strength increased when the concrete cover and compressive strength increase, but decreases as bar diameter increases. In addition, the results of his tests showed that an increase in compressive strength minimizes the need for a wide cover.

Taha 2007 [39] studied the bond strength of SCC and conventional concrete (CC) with steel reinforcement has been carried out by pull-out prisms specimens tests for different compressive strengths and bar diameters (10, 12, 20, and 25 mm) with constant concrete cover (40mm). The prism length is determined based on bar diameter, (15db). while (300) mm width and the depth is determined based on the bar diameter (db+2×cover). The specimens are reinforced by central bar with a bond length determined based on the bar diameter (Lb=5db). The results showed that bond strength is highest for the smallest bar diameter

(SCC specimen with compressive strength of 40MPa and db=10mm bond strength is higher than SCC specimen with compressive strength of 40MPa and db=25mm by 51.15%) and bonding strength rises with the increasing of compressive strength. (SCC specimen with compressive strength of 100MPa and db=10mm bond strength is higher than SCC specimen with compressive strength of 15MPa and db=10mm by 37.5%.

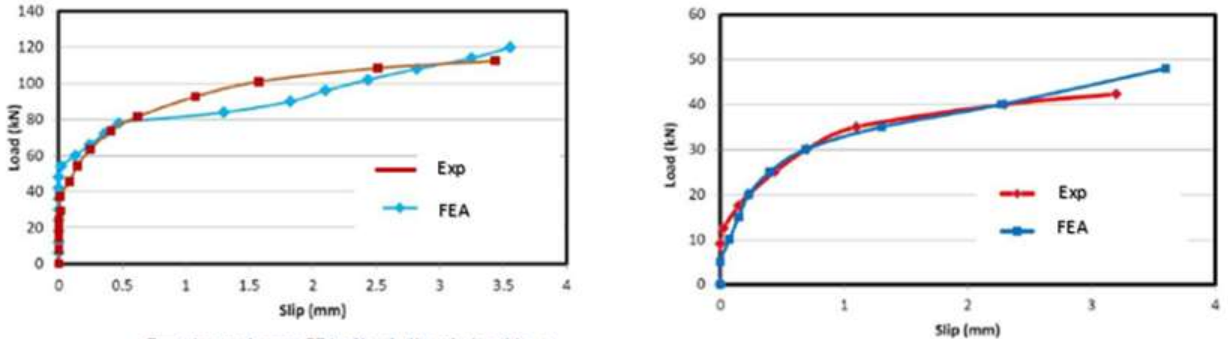
Lee et al. (2008) [26]compared the bond strength of conventional steel and GFRP reinforcing bars with various compression strengths (25.6, 35.3, 40.6, 56.3, 75.7, and 92.4 MPa). Nine specimens (every compression strength) consisting of 150 mm cubes with a bond length four times of bar diameter, with a constant diameter of 12 mm. The researchers reached many conclusions about the bond performance of FRP and steel in concrete of varied compressive strength. First, bond strength improves in both reinforcement types when concrete compressive strength increases, but the increase is more for reinforcing steel than for GFRP bars. As concrete strength increases, steel bars tend to fail at the concrete-bar contact due to crushing concrete on the bar surface. In normal concrete, GFRP showed the same concrete crushing behavior at the concrete-bar interface in high compressive strengths, GFRP failure mode is due to the damage of resin and fibers.

Davalos et al. (2008) [40] studied the bond strength of GFRP (with diameters of 12.7 mm and 9.5 mm) bars in concrete compressive strength (57 - 63 MPa) exposed to a variety of environmental conditions, including immersion in tap water at room temperature as well as at 60°C for ninety days and exposed to repetitive thermal cycles (20,60°C) for thirty days. The researchers concluded that failure in high-strength reinforcing was due to GFRP deterioration. Furthermore, under environmental conditions, there was a drop in GFRP bond strength and an increment in the slip of the deteriorated bars under loading. The environmental condition that used tap water at 60 °C shows better bond strength compared to repetitive thermal cycles. Finally, heat cycles lead to micro-cracking in concrete, which produces an increase in slip, in addition to bar degradation.

Hao et al. (2009) [41] performed comprehensive research into the influence of the geometry of GFRP bars on the bond strength of reinforced concrete by testing ninety pullout specimens. The GFRP bars all had the same tensile strength of 710 MPa and elastic modulus of 41 GPa, with the main differences in nominal diameter, rib spacing, and rib height. The nominal diameters were 8, 10, or 12 mm, the rib spacing ranged from between 0.5 and 3 times the bar dimeter, and the rib heights ranged (3% - 9%) of the normal GFRP dimeter. The concrete utilized in all of the tests had a compressive strength of around 30 MPa. According to the research, the GFRP with the best bond performance had a rib spacing equal to the bar diameter and a rib height of around 6% of the bar diameter. Furthermore, an important result of this study was the conclusion that decreases in rib spacing are undesirable because the concrete between the ribs becomes not able to provide enough bearing action. Finally, they found that raising rib height enhances rib bearing area and improves bond performance; however, as rib height increases, the use of cross-sectional area drops, and there is a specific height over which bond capacity begins to reduce.

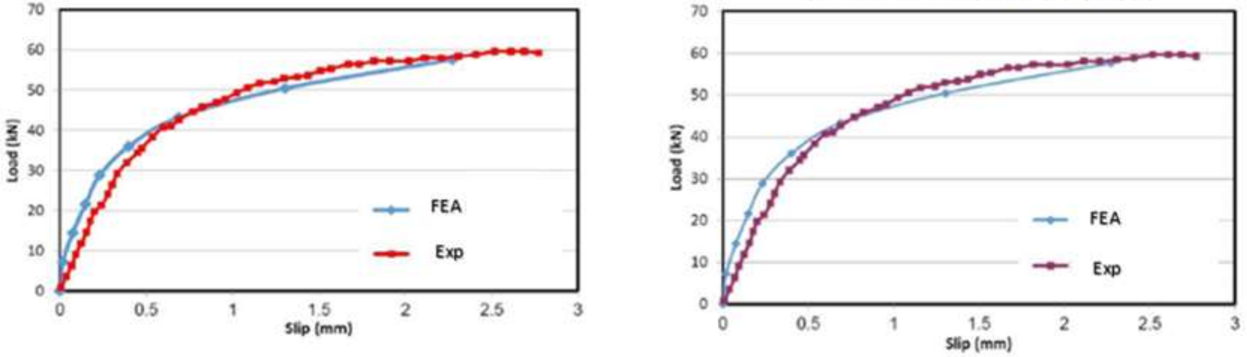
Al-Dulaime (2010) [42] conducted an experimental investigation to evaluate residual bond strength for steel reinforcement when embedded in different types of concrete (lightweight concrete LWAC and high-strength concrete HSC) after exposing it to different temperature levels. The experimental program consists of the fabrication and testing of 120 pull-out cylinder specimens (60 pull-out specimens of HSC and 60 pull-out specimens of LWAC), where every 60 pull-out specimens are classified into four groups with three variables: compressive strength, steel bar diameter, and the effect of type cooling (i.e. air or water), under four levels of temperature (150, 250, 400, 500C°) and at the room temperature. After casting and curing, the test is done after 28 days, the pull-out specimens are tested in a specially fabricated frame. The test results for all types of concrete showed that bond deteriorates at high temperatures. The results show that the bond strength increased with increasing compressive strength of unheated specimens. But, for heated specimens, the residual bond strength decreased with the increase of compressive strength, where the residual bond strength at 500C^{o} of nominal compressive strengths 60 and 70MPa were about 54% and 52% respectively for HSC. For the LWAC, the residual bond strength at 500C^{o} of nominal compressive strengths 25 and 30 MPa were about 65% and 63% respectively. The result shows also that the bond strength decreases with the increase in the diameter of the bar. Another result shows, that cooling in water after heating causes more reduction in bond strength than cooling in the air which is about 21% for HSC and 12% for LWAC at the temperature of 500C^{o}.

Later, **Mahmoud and Ahmed 2021** [43] conducted a numerical study by ANSYS on Eight specimens made with high-strength concrete selected from the previous study **Al-Dulaime (2010)** [42] Where the temperatures (150, 250, 400, and 500 C) are studied to show the behavior between slip-bond stress compared with experimental data of **Al-Dulaime (2010)** [42], as shown in Fig.10 . The Selected Pull-out specimens are divided into 2 groups, with four specimens for every group. Group (A) deals with a pull-out test of Ø 20 mm deformed bars with a concrete cylinder 150x300mm, while group (B) deals with a pull-out test of Ø 12 mm deformed bars within a concrete cylinder 100x200m. The researchers concluded that the elevated temperature (more than 250 C^{o}). The temperature distribution still has a significant effect on the cover region, after reaching the specified temperature. Otherwise, the lack of temperatures has been rapidly affected when the temperature increases. That will need little time to affect bond behavior. The heat flux into the concrete structure was different because the higher temperature can rapidly pass through concrete, also concluded that using high compressive strength, the bond of steel reinforcement had been increased due to increasing the confining and adhesive phenomena.



Experimental verse FEA of load-slip relationship at (T = 25°C, Room Temprature)) for group (A)

Experimental verse FEA of load-slip relationship at (T = 25°C, Room Temperature) for group(B)



Experimental verse FEA of load-slip relationship at (T = 500°C) for group (A)

Experimental verse FEA of load-slip relationship at (T = 500°C) for group(B)

Figure 10. Experimental verse Finite Element Analysis FEA of load-slip relationship at different temperatures [43].

Chen et al. (2012) [44] performed a comparison experiment on the bond performance of steel and GFRP bars under varying environmental conditions. 90 specimens reinforced with steel or GFRP with diameters of 17 and 16 mm and ultimate strengths of 455 and 400 MPa, respectively. In terms of environmental circumstances, including tap water, sodium hydroxide, and sodium chloride, exposed for 30, 60, and 90 days in each environment. Before environmental conditioning, the ends of the cylindrical specimens were covered such that solution diffusion could only occur via the sides of the cylinders to replicate actual scenarios. The test specimens were 100 mm in height, and 75 mm in diameter, and the concrete compressive strength remained constant at 33.96 MPa. The bond strength of tap water specimens was greater than that of other conditions specimens, which the researchers attributed to two reasons first the excessive curing in water developed the concrete compressive strength. Furthermore, steel and GFRP reinforced specimens displayed comparable bond strengths in high humidity, alkaline, and salty conditions; however, all specimens exposed to acid conditions had a deleterious effect, especially the GFRP specimens.

Al-Sa'idi et al. 2019 [45] conducted an experimental investigation for bond performance of the dowel bars in rubberized concrete. The purpose of using dowel bars in transverse joints of concrete pavement can significantly reduce the distress of concrete pavement. These stresses involve joint lockup, faulting, and mid-span cracks. Therefore, proper design and construction of these dowels mean better load transfer across these joints and less distress. As a result, the dowel bars can be considered as a very important part of concrete due to its role in pavement structure.The research involves conducted pullout tests for steel dowel bars ith dimensions were 25 mm for the diameter and 458 mm for the length with half of it embedded in concrete contains a different percentage of The Crumb Rubber (CR) particle (2%, 4%, and 6% of total aggregate) as partial replacement to aggregate on sieves No. 16 and No. 50. Four cases of dowel bars surface were investigated. Four cases of dowel bars surface were examined as uncoated un-lubricant dowel, uncoated lubricant dowel, epoxy-coated un-lubricant dowel, and epoxy-coated lubricant dowel.The researchers reveals that .The best results of the pullout test were obtained in the case of epoxy-coated lubricant dowel bars as the least pullout loads were recorded . The pullout loads were decreased by 45%, 66%, and 83% for epoxy coated lubricant dowel bars cast in concrete pavement containing 2%, 4%, and 6% crumb rubber respectively compared with that contain 0% crumb rubber.

2.9.2 Prior works utilizing beam specimens

Moreno et. al (2006) [46] studied the bond performance of steel reinforced hinged beams with four various kinds of concrete: normal concrete, steel fiber concrete, and structural lightweight concrete, each having compression strength of 61.6 MPa, and 52.3 MPa, and 27 MPa. The investigators made ten hinged beam specimens in compliance with RILEM RC5 specifications, and the investigation used embedded lengths of 5 and 10 times the bar diameter. According to the investigation results, one beam with bond length 10 times of bar diameter failed through steel yielding with average bond stress of 15 MPa, whereas the remaining beams with bond lengths five times the bar diameter suffered pullout bond failure with an average bond strength ranging from 13 to 30 MPa.

Menezes et al. (2008) [47] constructed hinged beams and pullout specimens to assess the bonding strength of steel bars in self-compacted and vibrated concrete. For each concrete type, the researchers looked at the influence of the concrete's compressive strength (30 and 60 MPa), steel reinforcing diameter (10 and 16 mm), and concrete type. The yield strength of both steel reinforcement bar sizes was 500 MPa, and an embedment length 10 times the bar diameter was employed. The test findings revealed that pullout and hinged beam specimens made of normal-strength concrete and reinforced with 10 mm diameter bars had comparable bond-slip behavior. Furthermore, owing to the confining effects of the transverse reinforcement in the beam-bond specimens, the normal-strength concrete utilizing 16 mm diameter bars exhibited concrete splits failure in the pullout tests but not in the beam-bond tests. An examination of pullout specimens of normal-strength concrete found that self-compacting concrete SCC mixes better vibrated concrete in terms of bond strength, which the researchers attributed to the presence of fillers in SCC mixes, which contribute to the improvement of the bonding between the steel and concrete interfaces. The high-strength concrete pullout specimens showed concrete cover splitting, whereas splitting did not occur in the high-strength concrete hinged beams, due to the existence of stirrups.

Desnerck et al. (2010)[48] tested 36 hinged beam specimens prepared according to RILEM RC5 to assess the bond strength between longitudinal steel reinforcement and concrete. Steel bars diameters ranging from 12, 20, 25, 32, and 40 mm were tested with bond length five times of bar size. The study sought to compare the properties of conventional vibrated concrete and self-compacting concrete with a compressive strength of 58 Mpa, and 65 MPa respectively. The study reached numerous results based on the analysis of bond strength on the influence of concrete type and reinforcing diameter on the shear bonding strength of steel-reinforced beams. First, when compared to conventional concrete, self-compacting concretes revealed greater bond strength with smaller diameter steel reinforcement; however, as the diameter of the steel reinforcement rose, the two types of concrete exhibited equivalent bond strength. the investigators attributed this behavior to the presence of limestone fillers that had a substantially better compressive strength, which improved the bond strength of the steel reinforcement.

Xu et al. (2011) [49] looked into the effect of freezing and thawing phases on the bonding strength of steel-reinforced beam specimens according to RILEM TC-RC5 guidelines. This study used steel bars with 20 mm diameters, 412 MPa yield stress, and 557.5 MPa ultimate strength with a bonding length 10 times the bar diameter, while the concrete had 45 MPa compressive strength. The beam specimens were first soaked in a 3 % NaCl solution for four days before being exposed to 0, 50, 100, and 200 freeze-thaw cycles. The investigators observed a significant drop in bond strength with increasing cycles, referring to microscopic concrete deterioration and internal crack development caused by multiple cycles as the main contributor. Furthermore, the researchers determined that as specimen size increased and more transverse reinforcement in the form of stirrups was incorporated, the influence of freeze and thaw cycles on the bond between reinforcement and concrete was reduced.

Szczech and Kotynia 2018 [35] studied the effect of bar diameter and bar type (steel and GFRP). The investigation program included 18 specimens with varied bar diameters (12, 16, and 18mm) with bond lengths five times of bar diameter. Whereas the GFRP bars showed excellent bond performance, the bonding strength was rather lesser than that of reinforcing steel in case of large diameters (16mm and 18mm), but GFRP bars show higher bond strength in case of small diameters (12mm), as illustrates in Fig.11.

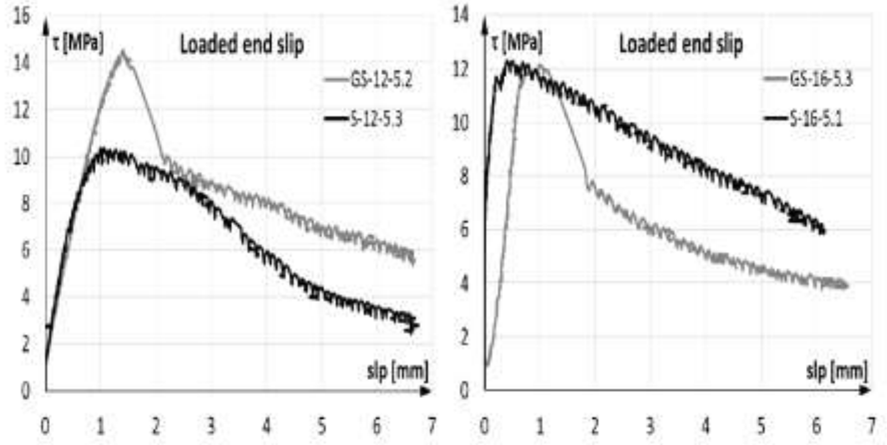


Figure .12 Effect of bar type (steel and GFRP) on bond-slip relation[35]

Al-Atharya et al. 2019 [50] condcted a series of bond tests related to reinforced concrete beams with rectangular cross section (140x150) and span of 600 mm that are provided with shear reinforcement. The specimens are tested as simply supported beams with one point load. Displacement between the steel bar and the concrete at the free end of bar has been measured. Three groups of beams have been tested to study the effect of many variables on bond strength for Self Compacting Concrete (SCC) and conventional reinforced concrete (CC). The variables are: [steel bar diameter (8, 12 and 16) mm, concrete compressive strength (30, 60) MPa and type of curing (tap water continuous curing, saline water wetting and drying, saline water continuous exposing) for a time of (90 days). The study also involves the effect of each variable on bond strength and comparison between the results of all the specimens of SCC and CC bond stress-slip relationships.The researches cocluded that the bond strength increases by decreasing the bar diameter. The bond strength for a bar diameter of 8 mm is greater than that for a bar diameter (12 and 16) mm for SCC (30,60)MPa and curing type saline water wetting and drying saline water continues.The experimental results of the bond stress for the same steel bar diameter and different concrete compressive strengths (30,60 MPa), the increase of compressive strength of concrete causes an increase in the bond strength between the concrete and the steel bar in case of tap water continuous curing and saline water continuous exposing, but in case of saline water wetting and drying curing, the increase in compressive strength of concrete, the bond strength between the concrete and the steel bar decrease because the type of curing. The results of comparison between all specimens of SCC and CC bond stress-sliprelationships show that, the CC bond strength is lower than the SCC bond strength in two cases of curing (tap water continuous, saline water continuous exposing), but in case of saline water wetting and drying exposing, the CC bond strength is higher than SCC bond strength.

Conclusions

- Most prior investigations focused on employing a pull-out test to investigate the bonding behavior of GFRP bars in concrete.
- Many variables control the bond performance of reinforcing bar in concrete. Bar size, bond length, and compressive strength of concrete.
- Bar size and bond length are inversely proportional with bond strength for reinforcing bars. The bond of reinforcing bars in concrete increases as compressive strength increases.

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