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Review Article

A REVIEW OF BOND BEHAVIOR OF GLASS FIBER REINFORCED POLYMER BARS WITH CONCRETE

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Abstract: One of the most serious problems of reinforced concrete structures is corrosion of embedded reinforcing steel bars especially in aggressive environments. To control steel corrosion, several approaches have been followed but do not introduce 100% corrosion resistance and guaranteed long-term performance. Glass Fiber Reinforced Polymer (GFRP) bars are considered to be an ideal alternative to overcome corrosion problem in steel bars because of their high corrosion resistance. This paper discusses the main topics related to the use of GFRP bars as reinforcement in structural reinforced concrete applications and presents an overview to the available literature especially in GFRP bond behavior. The main conclusions are: standardizing the manufacturing process of GFRP bars are needed in order to limit the contradictory results of their performances due to the high differences in the products characteristics, and that the available design guidelines have much conservative equations, so they are recommended to be revised to be more practical.

Keywords: *Glass Fiber Reinforced Polymer, Bond Behavior, pullout test, Beam test.*

عرض لسلوك الربط لقضبان البوليمر المسلح بالياف الزجاج مع الخرسانة

الخلاصة: واحدة من اهم المشاكل الخطيرة للمنشات الخرسانية المسلحة هي تاكل قضبان حديد التسليح داخل الخرسانة و خصوصا في البيئات العدوانية لها. للسيطرة على تاكل الحديد تم اتباع عدة وسائل الا انها لا توفر مقاومة تاكل بنسبة 100% و لا تضمن الاداء بعيد المدى. لقد اعتبرت قضبان البوليمر المسلح بالياف الزجاج (GFRP) بديلا مثاليا لتجاوز مشكلة التاكل في القضبان الحديدية بسبب مقاومتها العالية للتاكل. هذا البحث يناقش المواضيع الرئيسية المتعلقة باستخدام قضبان (GFRP) كتسليح في التطبيقات الانشائية للخرسانة المسلحة كما يقدم نظرة عامة للادبيات المتاحة خصوصا في سلوك الربط لقضبان (GFRP). ان الاستنتاجات الرئيسية هي: هناك حاجة لتقييس عملية تصنيع قضبان (GFRP) لتقليل النتائج المتعارضة لاداءات هذه القضبان بسبب الاختلافات الكبيرة في خصائص المنتجات، و ان الدلائل الارشادية المتاحة للتصميم تحتوي معادلات متحفظة جدا لذلك يوصى بمراجعتها لتكون اكثر عملية.

1. Introduction

Reinforcing steel bars are successfully used with concrete members to provide tensile strength since concrete has negligible tensile strength. This composite behavior of reinforced concrete depends on the compatibility (adequate bond) of the two materials (concrete and steel) to act together in order to resist the external loads.

One of the most serious problems of reinforced concrete structures is corrosion of embedded reinforcing steel bars especially in aggressive environments. With time,

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corrosion results in a severe loss of bar cross section and leads to lower bond strength and consequently failure of reinforcing steel to do its function.

To control steel corrosion, several approaches have been followed such as using epoxy-coating or stainless steel bars and improving concrete permeability using additives and admixtures. However, such approaches do not introduce 100% corrosion resistance and still susceptible to concerns about their long-term performance[1, 2].

Glass Fiber Reinforced Polymer (GFRP) bars are considered to be an ideal alternative to overcome corrosion problem in steel bars because of their high corrosion resistance [3].

2. Characteristics of GFRP Bars

Wide use of Fiber Reinforced Polymers (FRPs) began after World War 2 because of an increase in demand for light-weight, high-strength materials. The first applications were in the aerospace and defense industries. During the 1990s, a massive research regarding the application of FRPs in the construction industry was performed due to the high costs of maintenance of corroded steel in reinforced concrete structures [4].

Currently, hundreds structural applications such as bridge decks, marine structures and parking garages have been constructed using GFRP bars as concrete reinforcement around the world. Figure (1) shows two bridges (wotton bridge in Canada and US highway 151 bridge in USA) that GFRP bars were used in the construction of their decks [5].

Fiber Reinforced Polymer (FRP) is a composite material consisting of carbon (CFRP), aramid (AFRP) and glass (GFRP) fibers embedded in a polymeric (resin) matrix to form various types of products such as bars, structural sections, plates and sheets [6,7,8].

GFRP bars (which is the least expensive among other types of FRP) has numerous well-defined properties such as high strength-to-weight ratios (10 to 15 times than steel), high tensile strength, excellent fatigue behavior, impact resistance, non-magnetization and non-conductivity [4, 6, 8, 9, 10].

However, the modulus of elasticity of GFRP bars (40-55 GPa) is lower than that of steel bars which lead to larger deflections and crack widths than steel reinforced concrete (RC) members, this is why GFRP bars are not typically used as compression reinforcement [4,8,11,12,13,14]. Also, GFRP bars do not yield and behave elastically until sudden brittle rupture so it is recommended to avoid under reinforced design of GFRP reinforced concrete members [4,10,13,15].

GFRP bars are anisotropic material with strong longitudinal axis governed by fibers and weak or moderate transverse axis governed by resin that binds fibers, Figure (2) [16,17]. As a result, GFRP bars have different coefficient of thermal expansion in the longitudinal direction (approaches concrete) from that in the transverse direction (3-6 times of concrete) [18,19]. This leads to producing bursting stresses within concrete under increasing temperature [20].

(a)Wotton Bridge, Canada.

(b)US highway 151 bridge, USA

Figure (1) Examples of practical applications of GFRP bars [5].

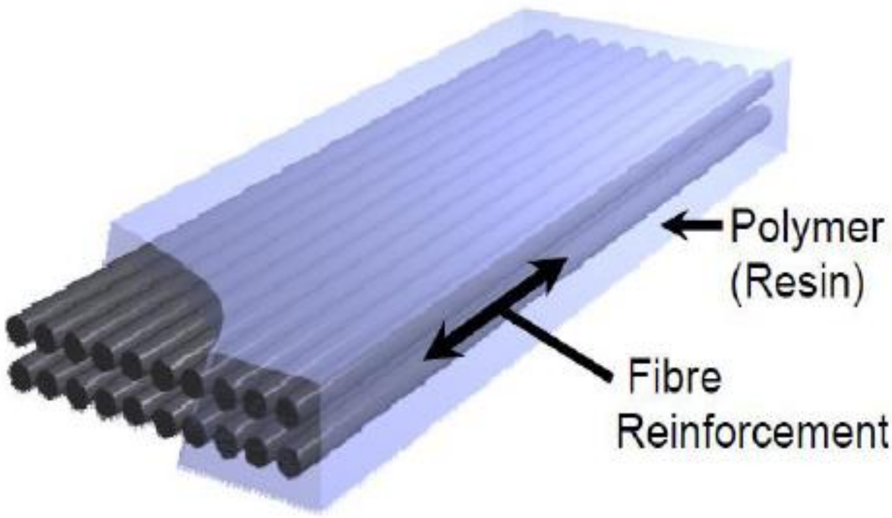

Figure (2) GFRP components [17]

Several manufacturers throughout the world have produced different GFRP bars that are significantly different in their composition, strength, surface characteristics and size due to lack of standardization of the manufacturing process which results in different, or even contradictory, bond performances.

3. Factors Affecting Bond Strength

The primary factors that affect the bond strength and consequently the development length of steel bars are bar position within concrete, surface condition (coated or not), concrete strength and bar diameter. Bars with a large depth of concrete below it have a weaker bond with surrounding concrete because of settlement of wet concrete below the bar, which reduces confining effects and needs higher development length. Using epoxy coating as corrosion protection negatively affect bond strength due to the smooth surface of coated bars. The quality (strength) of concrete affect development length since high quality allows for a higher bond stress tolerance and reduces the development length. Larger bar diameters requires longer development lengths because of the increase in localized stresses in the surrounding concrete [14].

Secondary factors that affect bond strength are presence of transverse reinforcement, position of near bars and bar yield strength. Presence of transverse reinforcement increases confining effect and hence reduces the required development length. Closely located reinforcing bars allow for the superposition of stresses between the bars and this requires longer development length. Higher yield strength requires higher development length [14].

It should be mentioned here that surface conditions of GFRP bars are different from steel bars and they have significantly higher tensile strength. Also, GFRP does not yield and behaves as a linear elastic nonductile material until rupture with lower modulus of elasticity [21].

4. Bond Mechanisms

Forces are transferred from the reinforcing bar to the concrete through three bond mechanisms: chemical adhesion, friction and mechanical interlock, Figure (3). Chemical adhesion, which is the chemical interaction between the concrete interface and the bar, is considered to contribute marginally to bond strength for steel as well as GFRP bars. This is why smooth bars are avoided in practice [16]. However, unlike steel bars, GFRP bars are less sensitive to chemical attacks, hence; chemical treatments of GFRP bars may improve their chemical adhesion.

Friction is developed between surfaces by deformations or sand coating. Mechanical interlock is caused by bearing of the bar ribs on the concrete. Bond failure of conventional steel bars is a result of bearing which cause side splitting or shearing of concrete. In contrast, bearing stresses in GFRP bars can exceed the shear strength between the bar core and the surface deformation resulting in a bond failure at this interface [16].

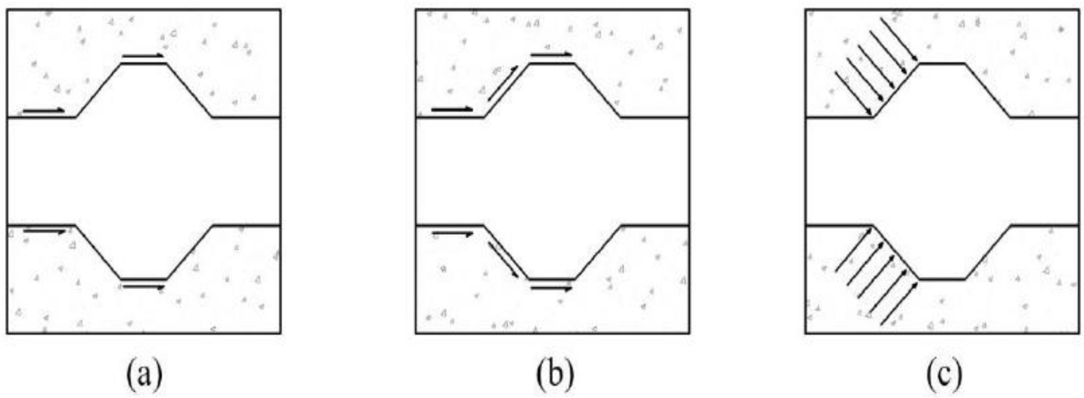

Figure (3) Bond Mechanisms (a) chemical adhesion, (b) friction, and (c) mechanical interlock [16]

5. Bond Stress-Bar Slip Relationship

Typically, bond behavior is represented by an average bond stress – bar slip curve, Figure (4), where bond stress is the shear stress along the bar-concrete interface, and bar slip is the relative displacement of the bar to the undisturbed concrete [22].

During the pre-peak portion, chemical adhesion is lost, internal transverse cracks are formed and the mechanical interlock between bar deformations and concrete begins to cause splitting cracks. Ultimate bond failure happens when the splitting cracks reach the concrete surface or there is shearing of the concrete or bar deformations.

Then the bar pulls out and large slips are observed. In the post peak portion, residual bond stresses exist because of the remaining interface friction causing the smooth descending curve as shown in Figure (4) [16].

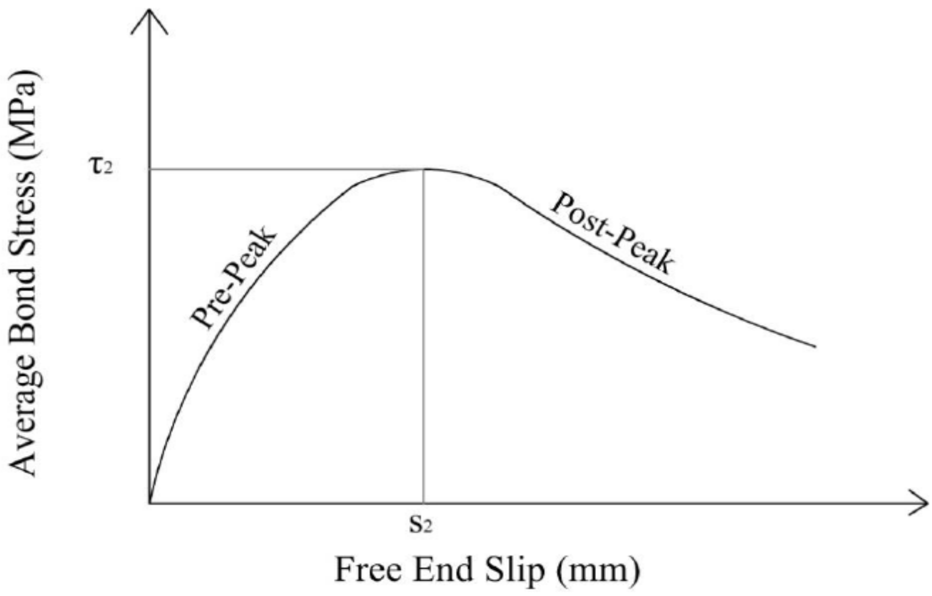

Figure (4) Typical bond stress versus bar slip relationship for steel and GFRP bars [16].

Some authors developed analytical bond stress-slip relationships namely: Bretero-Eligehausen-Popov (BEP) model (1983) [23], Cosenza-Manfredi-Realfonzo (CMR) model (1997) [24], modified BEP model (2000) [22]. Other models were proposed by Pecce et al (2001) [25], Tastani and Pantazopoulou (2006) [26] and Mazaheripour et al (2012) [27].

The modified BEP model, which is often used to predict GFRP bond stress-slip behavior [16], considers three branches: ascending (up to the peak bond stress), softening descending (modeling residual stresses) and horizontal (friction bond mechanism) as shown in Figure (5).

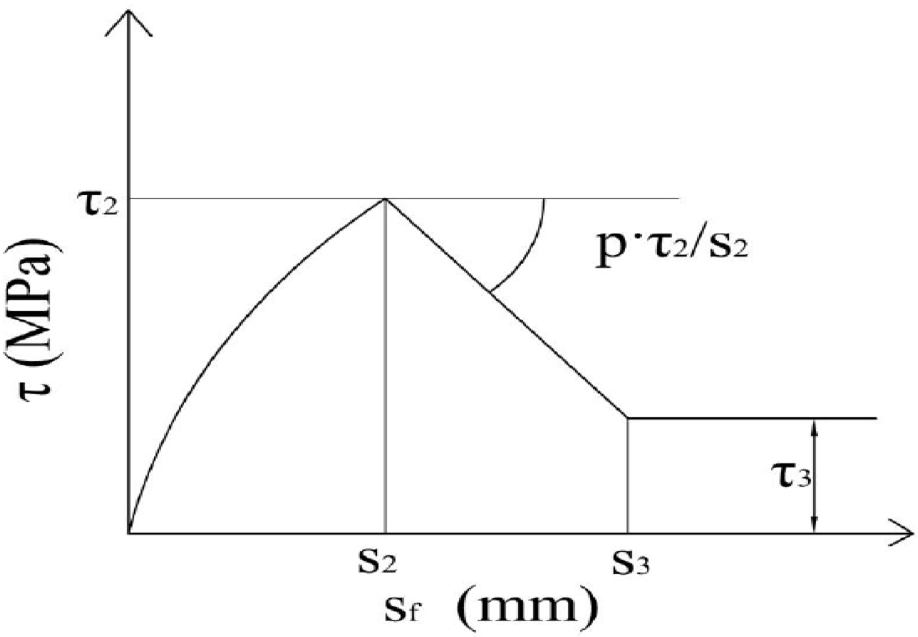

Figure (5) Modified BEP model for bond stress-slip relationship [16].

These three branches are represented by Equation (1):

$$\frac{\tau}{\tau_2} = \left(\frac{s}{s_2}\right)^{\alpha_1} \qquad for\ s \leq s_2 \qquad (1.1)$$

$$\frac{\tau}{\tau_2} = 1 - p\left(\frac{s}{s_2} - 1\right) \qquad for\ s_2 \leq s \leq s_3 \qquad (1.2)$$

$$\tau = \tau_3 \qquad for\ s \geq s_3 \qquad (1.3)$$

where:
$\tau_2$is the maximum average bond stress,
$s_2$is the slip atτ_2,
α is parameter of curve fitting (0-1),
p is parameter of curve fitting,
$\tau_3$is the constant residual bond stress, and
$s_3$is the slip when residual stress just reach τ_3

6. Bond Failure Modes

Bond failure primarily occurs in two modes: concrete splitting and bar pull out. Concrete side splitting causes nearly all bond failures except when high degree of confinement is provided. Splitting occurs when the hoop stresses exceed the concrete tensile strength. Geometry of the member affect splitting where greater cover is preferred to delay or prevent splitting [16].

Pull out failure occurs when heavy confinement is present or a minimum concrete cover (three times bar diameter) is provided. In this case, the bond strength is a function of mechanical interlock between bar deformations and the surrounding concrete [28].

7. Bond Testing Methods

Pullout test is the simplest testing method, where a single bar is embedded within a concrete cylinder or prism and after concrete hardening, a direct tension force is applied to pull the bar out of the concrete as shown in Figure (6) [29].

The pullout test does not give accurate data about bond behavior of bars in members subjected to bending, shear, etc. because the loading pad induces compression stresses in the concrete which cause a higher bond stress than in practice where concrete is subjected to tension [30]. Therefore, pullout tests are mostly used to investigate the effects of different parameters such as bar diameter, concrete cover, and concrete strength [31].

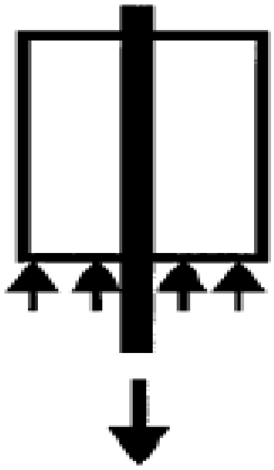

Figure (6) Pullout test [29].

Beam-bond tests, Figure (7), are an alternative to pullout tests that give results more comparable to practical applications because the surrounding concrete is in tension and transverse cracks are free to develop [14]. Generally, ultimate bond stresses obtained from beam tests are much lower than pullout tests and can be used to develop design criteria [16].

Beam tests are much more suitable for measuring the bond strength and development length of bars serves as flexural reinforcement, but these tests are relatively difficult and time-consuming to conduct when compared to pullout tests.

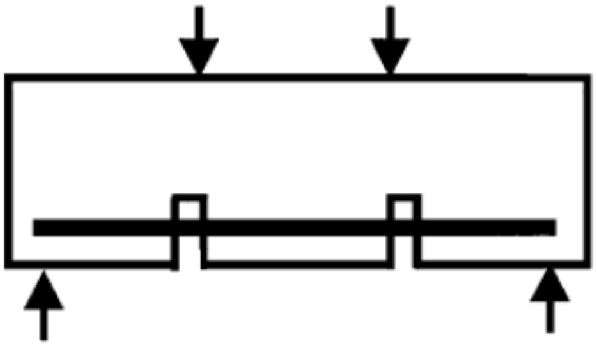

Figure (7) Beam-bond test [29].

Little researchhas been doneto find a relationship between the results of pullout test and those of beam-bond test. Establishing such reliable relationship (through comparative studies) will be greatly useful and enables to make advantage of the simplicity of pullout test as well as the more practical representation of beam-bond test results.

8. Bond Properties of GFRP Bars

Trends of the available literature show that the average bond strength of GFRP bars is approximately 55-90% of that for steel bars of the same diameter. This trend is observed in both beam and pullout tests [16]. The difference in bond behavior of the two materials can be attributed to the differences in surface deformations, thermal properties and stiffness.

In the case of deformed steel bars, the bond strength is proportional to the concrete strength where the complete bond failure is always caused by crushing of the concrete in front of the ribs and shearing of the concrete between the ribs. This is because that bond stresses are mainly transferred by mechanical interlock (bearing stresses) between the ribs and the surrounding concrete, and shear stresses in the concrete between ribs [32].

Figure (8) shows three common method of surface treatment of GFRP bars to enhance their bond performance which is ribs, sand coating and helical wrapping [4]. However, these deformations are made of resin which do not have the high compressive and shear strengths and high rigidity that are common to steel bars. As a result, lower bond strength and higher slip may be expected due to the failure of the ribs (or other surface deformations) where bond strength is controlled by the shear strength of the resin that holds these surface deformations [14,33].

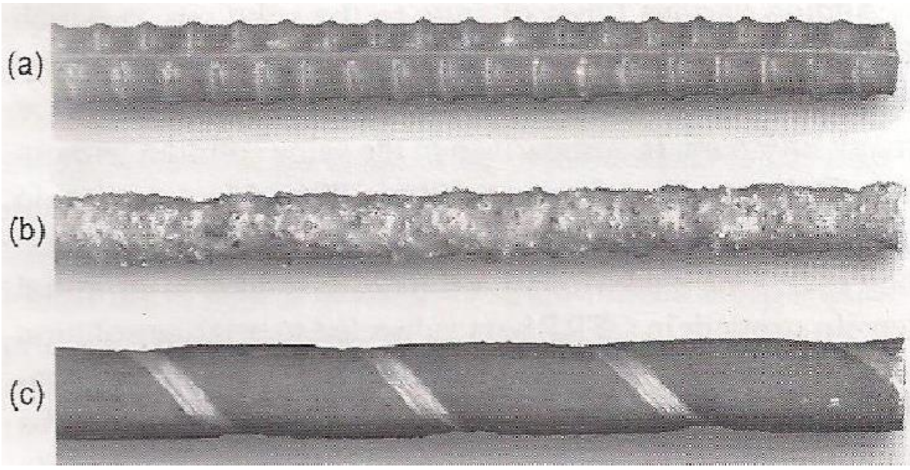

Figure (8) Methods of surface treatment of GFRP bars (a) ribbed, (b) sand coated, and (c) helical wrapping [4].

Unlike steel bars, bond stresses and slip of GFRP bars are not constant throughout the embedment length, instead they vary (by decreasing) from the loaded end to the free end. This is because the relatively low longitudinal modulus of elasticity and the fact that shear and transverse properties of GFRP bars are governed by the resin which cause additional slip [16, 25].

9. Bond Behavior of GFRP Reinforcement

A survey of the available literature regarding the experimental data on bond behavior of GFRP bars in concrete will be presented in this section.

Many researchers performed a number of investigations to study the bond behavior of GFRP bars embedded in concrete using pullout tests:

Nanni et al (1995) [34] concluded that the contribution of mechanical interlock to bond strength highly exceeds the contribution of chemical adhesion and frictional components, furthermore, the choice of surface geometry of the bar can enhance the bond performance.

Katz et al (1999) [35] performed an investigation to study the effects of high temperature on bond performance of FRP and noticed a significant decrease in bond strength with an increase in temperature due to polymer degradation. Similar observations were reported by Galati et al (2006) [18].

Lee et al (2008) [36] observed that initially, an increase in concrete compressive strength results in an enhancement of bond performance of FRP bars. As concrete strength continues to increase, the failure mode changes from crushing of the concrete to shear failure at the fiber-resin interface within the bar.

Davalos et al (2008) [37] recommended the importance of preventing resin degradation in FRP bars and concluded that exposure of FRP bars to thermal cycles not only damages the resin but also decreases bond strength more by causing micro-cracking in the concrete.

Hao et al (2009) [38] conducted an investigation into the effects of surface texture on the bond behavior of GFRP bars and found that ribbed bars with rib spacing equivalent to the bar diameter and rib height of 6% the bar diameter showed superior bond performance.

Esfandeh et al (2009) [39] concluded that surface deformations of GFRP bars in the form of a combination of helical wrapping and sand coating, as well as a relatively long embedment length significantly enhances the bond performance.

Goraya et al (2011) [40] found that bond strength of smooth GFRP can be increased by 17-58% by using sand coating, which also changes the mode of failure from pullout to splitting, the same mechanism when using ribbed bars.

Soong et al (2011) [41] concluded that the majority of the pullout resistance of GFRP bar is due to the frictional and the interlock components of the bond strength.

Vint (2012) [16] found that during the post-peak phase, GFRP bars that are both sand coated and helically wrapped experience more ductile bond failure with approximately 65% residual stresses. In contrast, sand coated or ribbed bars exhibit more brittle failure with 33% and 42% residual stresses, respectively.

Chen et al (2012) [42] concluded that acidic environment have the most negative effect on the bond performance of both steel and GFRP reinforced concrete.

Makhmalbaf (2015) [14] found that the actual bond stress distribution along the embedment length has a parabolic form and the assumption of the average uniform bond stress underestimates the bond stress development.

Beam-bond tests were used by other researchers to investigate the bond behavior of GFRP bars under various conditions.

Daniali (1992) [43] stated that for concrete beams reinforced with FRP bars to develop the ultimate strength of the bars before bond failure, it is beneficial to use stirrups along the span of the beam. Also, sudden bond failure may occur under sustained loadings even if the FRP bars did not reach their ultimate bond strength.

Benmokrane et al (1996) [44] reported that pullout tests give bond strength values higher than those obtained using beam-bond tests.

Oh et al (2010) [45] performed a comparative study between the bond performance of steel and GFRP reinforced concrete beam-bond specimens and concluded that

GFRP bars with adequate surface deformations can develop bond strength values similar (or even, under certain conditions, greater than) the corresponding values for steel reinforced concrete beams.

Mazaheripour et al (2013) [46] found that increasing concrete cover has positive effect on bond performance of GFRP bars, while increasing bar diameter or embedment length can cause large slippage and concrete splitting which both negatively affect bond performance.

Makhmalbaf (2015) [14] concluded that at the same GFRP bar slip value, beam-bond test produces higher bond strength than pullout test because of the confinement effect of transverse reinforcement (stirrups) in the beam-bond specimens.

Although extensive research have been performed in the last two decades as illustrated above, there still a need for more investigations to achieve a comprehensive knowledge of all factors affecting the bond performance of GFRP bars. For example, in the available literature presented here, the confining effect of GFRP transverse reinforcement (stirrups) is not investigated yet.

10. Design Guidelines for Bond Strength and Development Length of GFRP bars

A number of design guidelines for FRP reinforced concrete have been developed during the last two decades such as:

- ACI 440.1R (2006) [4] "Guide for the Design and Construction of Structural Concrete Reinforced with FRP Bars".
- CSA-S806 (2012) [47] "Design and Construction of Building Structures with Fiber-Reinforced Polymers".
- CSA-S6 (2006) [48] "Canadian Highway Bridge Design Code".
- fib Bulletin 40 (2007) [49] "FRP Reinforcement in RC Structures"
- JSCE Report No. 23 (1997) [50] "Recommendation for Design and Construction of Concrete Structures Using Continuous Fiber Reinforcing Materials"
- CNR-DT 203 (2006) [51] "Guide for the Design and Construction of Concrete Structures Reinforced with Fiber-Reinforced Polymer Bars"

Generally, these guidelines have been written based on the same classical theory of steel reinforced concrete members with making some modifications to the existing design requirements depending on the experimental data taking into account the different mechanical behavior of FRP bars especially the lower modulus of elasticity and the linear elastic behavior up to failure without yielding characteristic.

The design equations for bond strength and development length of FRP bars presented in these guidelines are highly empirical and similar to the corresponding equations for steel bars with some modifications, consequently they are more conservative and require, sometimes, unpractical (too long) development length [14].

In locations where there is a restriction to provide the required straight development length, steel bars are usually hooked (bent) to satisfy development length requirements. However, this is not the case with FRP bars because they cannot be bent in situ and only straight development length is available, so revising the more conservative requirements in the design guidelines will be highly beneficial.

11. Conclusions and Recommendations

From the discussions presented in this paper and the review of literature regarding bond behavior of GFRP bars with concrete, the following conclusions can be drawn:

1. The commercially available GFRP bars are significantly different in their composition, strength, surface characteristics and sizes produced by several manufacturers which results in different (sometimes contradictory) bond performances, so it is recommended to standardize the manufacturing process.
2. As for steel reinforcing bars, the available design guidelines have mostly conservative equations for the minimum development length should be provided for GFRP reinforcing bars leading to, sometimes, unpractical requirements (too long development length). Taking into account that, unlike steel bars, GFRP bars cannot be bent (hooked) in situ to satisfy the required development length in locations where straight development length is restricted, the conservative design guidelines are recommended to be revised.
3. Most studies and design guidelines on bond strength of GFRP bars are based on the assumption of average uniform bond stress along the embedment length which is less valid in the case of GFRP bars than steel bars because of the lower longitudinal modulus of elasticity and weaker transverse axis due to resin weakness. It is recommended to consider the actual bond stress distribution which varies along the embedment length to get better understanding and consequently more representable relationships for bond behavior of GFRP bars.
4. Although extensive research have been performed in the last two decades, there still a need for more investigations to achieve a comprehensive knowledge of all factors affecting the bond performance of GFRP bars.
5. Little literature is available concerning the relationship between the results of pullout test and those of beam-bond test. Establishing such reliable relationship (through more comparative studies) enables to make advantage of the simplicity of pullout test as well as the more practical representation of beam-bond test results.
6. The contribution of chemical adhesion of steel bars with the surrounding concrete was always neglected. However, unlike steel bars, GFRP bars are less sensitive to chemical attacks, hence, it is recommended to investigate the potential of improving the chemical adhesion of GFRP bars by means of chemical treatments, if possible.

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