



EVALUATION OF CONCRETE STRUCTURES REINFORCED WITH FIBER REINFORCED POLYMERS BARS: A REVIEW



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ABSTRACT

Article History

Received: 26 April 2017

Revised: 23 May 2017

Accepted: 31 May 2017

Published: 2 June 2017

Keywords

Reinforced concrete
Corrosion resistance
Fiber reinforced polymer
Tensile strength
Modulus of elasticity
Numerical study

The behavior of concrete members reinforced with fiber reinforced polymer (FRP) bars has been the focus of many studies in recent years due to their excellent corrosion resistance, high tensile strength, and good non-magnetization properties. However, the low modulus of elasticity of the FRP materials and their non-yielding characteristics results in large deflection and wide cracks in FRP reinforced concrete members. This review was focusing in different behavior of FRP bars in reinforced concrete (RC) structures. Data and information collected in this review were gathered from the experimental, numerical and analytical studies from previous researches.

Contribution/ Originality: This study contributes in the existing literature by investigate the behavior of FRP bars in reinforced concrete (RC) structures. Due to the increased use of FRP bars in concrete structures, the performance of FRP bars has been an important research topic in recent years.

1. INTRODUCTION

Concrete structures are conventionally reinforced with steel bars and stirrups. Deterioration of RC structures due to corrosion of reinforcing steel bars is a major concern [1]. The corrosion problem of steel bar is the greatest factor in limiting the life expectancy of RC structures. Many environmental conditions accelerate the corrosion process of steel bar; thereby resulting in steady deterioration that decreases the life expectancy of these structures. In the last decade, considerable efforts have been made to apply FRP composites in the construction industry, and recently, structural applications of FRP composites started to appear in civil infrastructure systems [2]. FRP composite materials have been used as internal and external reinforcement in the field of civil engineering constructions [3]. Considerable research efforts have contributed to the understanding of concrete members internally reinforced with FRP bars [4]. These efforts, greatly improving our knowledge of how concrete members reinforced with FRP bars should be analyzed and designed in flexure and shear.

In recent years, significant research efforts have shown that FRP materials can be effectively used to reinforce RC structures [5-7]. FRP reinforcement is made from high tensile strength fibers such as; aramid, carbon, and

glass embedded in polymeric matrices and produced in the form of bars, grids, and tubes in a wide variety of shapes and characteristics. The main Advantages and disadvantages of FRP reinforcement against steel are shown in Table 1 [8].

Table-1. Main advantages and disadvantages of FRP reinforcement

Advantages of FRP reinforcement	disadvantages of FRP reinforcement
High longitudinal tensile strength (varies with sign and direction of loading relative to fibers)	No yielding before brittle rupture
Corrosion resistance (not dependent on a coating)	Low transverse strength (varies with sign and direction of loading relative to fibers)
Nonmagnetic	Low modulus of elasticity (varies with type of reinforcing fiber)
High fatigue endurance (varies with type of reinforcing fiber)	Susceptibility of damage to polymeric resins and fibers under ultraviolet radiation exposure
Lightweight (about 1/5 to 1/4 the density of steel)	Low durability of glass fibers in a moist environment
Low thermal and electric conductivity (for glass and aramid fibers)	Low durability of some glass and aramid fibers in an alkaline environment
	High coefficient of thermal expansion perpendicular to the fibers, relative to concrete
	May be susceptible to fire depending on matrix type and concrete cover thickness

Source: Tastani and Pantazopoulou [8]

This review was focusing in different behavior of FRP bars in reinforced concrete structures. Data and information collected in this review were gathered from the experimental, numerical and analytical studies from previous researches. Nowadays, several codes and design guidelines are available for the design of concrete structures reinforced with FRP bars under flexural and shear loads. Meanwhile, limited research work has been conducted to examine the behavior of RC structures with FRP bars. The review hoped to be a good reference and guidelines for all engineers and researches in fields of composites material especially fiber-reinforced polymer to enhance the application of FRP for new construction or rehabilitation of existing structure.

2. HISTORY OF USE

Fiber materials with higher strength, higher stiffness, and lower density, such as boron, carbon and aramid, were commercialized to meet the higher performance challenges of space exploration and air travel in the 1960s and 1970s. FRP products has been use since 1940s but only recently has won the attention of engineers involved in the construction of civil structures [9]. At first, composites made with these higher performing fibres were too expensive to make much impact beyond niche applications in the aerospace and defense industries. In the 1970s, work hard was begun to lower the cost of high performance FRPs and promote substantial marketing opportunities in sporting goods [10]. By the late 1980s and early 1990s, increased importance was placed by fiber and FRP manufacturers on cost reduction for the continued growth of the FRP industry as the defense market waned [11]. As the cost of FRP materials continued to decrease and the need for aggressive infrastructure renewal becomes increasingly evident in the developed country, pressure has mounted for the use of these new materials to meet higher public expectations in terms of infrastructure functionality [12]. Aided by the growth in research and demonstration projects funded by industries and governments around the world during the late 1980s and throughout the 1990s, FRP materials are now finding wider acceptance in the characteristically conservative infrastructure construction industry [13]. Since nowadays it has won the attention of engineers in the construction, research aimed at developing innovative and appropriate applications of FRP has been encouraged for sustainable construction. It has relatively large impact to cost ratio where few resources are engaged to result in a significant

structural benefit. FRP products can take the form of bars, cables, two- and three dimensional grids, sheet materials, fabrics and laminates as shown in Figure 1 [14-16].

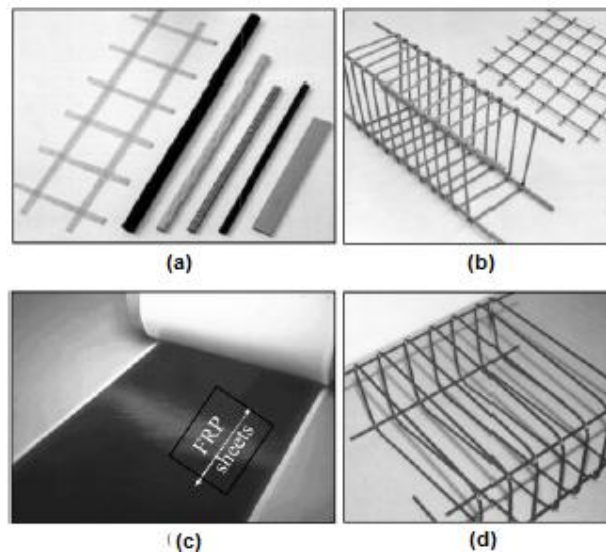


Figure-1. Different FRP products
Source: Mutalib and Hao [15]

3. FIBRE REINFORCED POLYMER COMPOSITE MATERIAL

A composite is defined as the assembly of two or more distinct materials to achieve new material whose overall performance is higher than the individual ingredients [17]. FRP are composites that consist of two components: the fibres, which are the load carrying elements, and the matrix, which ensures the cohesion of the fibres, the retransmission of applied loads to the fibres, and the protection of fibres from the external environment. The matrix, such as a cured resin-like epoxy, polyester, vinyl ester, or other matrix acts as a binder and holds the fibres in the intended position, giving the composite material its structural integrity by providing shear transfer capability. Figure 2 shows the concept of FRP composite. The benefits of using composites are: light weight, high tensile strength, and durability if compared to traditional steel reinforcing rebars [18].

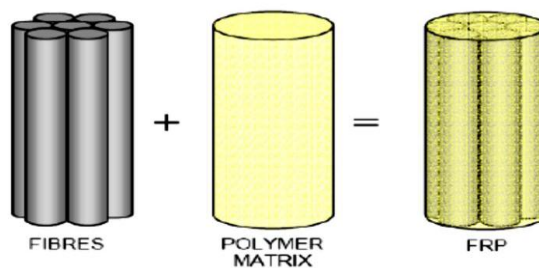


Figure-2. Basic material components of FRP composite
Source: Nacer [18]

Aramid, Carbon, and Glass are the most common types of fibres used in civil engineering applications. Table 2 shows typical values of the physical and mechanical properties of these fibres. Aramid fibres are characterized by their good fatigue resistance. However, they are susceptible to damage by ultraviolet radiation. Carbon fibres are known by their high longitudinal tensile strength, their high modulus of elasticity, and their excellent fatigue resistance.

Table-2. Typical properties of fibres

	Carbon	S-Glass	Aramid	E-Glass
Tensile strength(MPa)	3500~6000	4020~4650	2900~3400	3100~3800
Elastic Modulus (GPa)	79.3~93.4	83~86	70~140	72.5~75.5
Elongation at break (%)	1.5~2	5.3	2.8~3.6	4.7
Diameter of filament (mμ)	5~15	6~21	-	6~21
Temperature of application (°C)	-50~+700	-50~+300	-50~+290	-50~+380

Source: ISIS [17]

Matrix, or resin, is the bonding agent of FRP composites. There are essentially two types of resins: thermoplastic and thermosetting polymers. The choice of resins during the manufacturing process is crucial because it affects the mechanical properties of composites. Thermoplastic polymers are not used in civil engineering purposes because of their low thermal and creep resistances. However, thermosetting resins, such as epoxies, polyesters and vinyl esters, which are the most used resins, have “good thermal stability and chemical resistance and undergo low creep and stress relaxation” as stated by ISIS Design Manual 2007 and shown in Table 3.

Table-3. Properties of thermosetting resins

Resin	Tensile Strength (MPa)	Tensile Modulus (GPa)	Specific Gravity	Cure Shrinkage (%)
Vinyl Ester	73-81	3-3.35	1.12-1.32	5.4-10.3
Epoxy	55-130	2.75-4.1	1.2-1.3	1-5
Polyster	34.5-103.5	2.1-3.45	1.1-1.4	5-12

Source: ISIS [17]

4. MECHANICAL PROPERTIES OF FRP REINFORCING BARS

FRP composites are used in a wide variety of applications. The mechanical properties of FRP bars are typically quite different from those of steel bars. A key element in evaluation of FRP properties is the characterization of the relative volume and/or mass content of the various constituent materials. FRP reinforcing bars in concrete structures is strongly influenced by their physical and mechanical properties. Their mechanical properties provide unique benefits to the product they are fabricated into. This section presents testing methods and mechanical properties of bars such as:

- Axial tensile strength.
- Compressive strength.
- Shear strength.
- Bond strength.
- Bend portion strength

4.1. Axial Tensile Strength

Axial tension testing of high strength unidirectional composites is often a challenge because load should be transmitted from the testing apparatus to the specimen via shear, and the shear strength of a unidirectional composite is typically much lower than its axial tensile strength. Further, shear gripping will load the external fibers more than the internal ones causing shear lag and progressive fiber failure. To avoid these problems, end tabs are required when testing flat laminates. Special anchors are required for testing FRP rods and bars by inserting their ends into steel cylinders that are subsequently filled with either a polymer resin or a cement-based grout as described in ACI 440.1R-06 [19]. Also, CSA S807-10 [20] specified ASTM D7205/D7205M-06 [21] standard method to get the bar tensile properties. Table 4 to Table 7 represents axial tensile strength and modulus of

elasticity for FRP bars as provided in the North American codes and design guidelines and as produced by different companies.

Table-4. Typical mechanical properties of FRP bars [22]

Trade Name	Minimum Specified Tensile Strength (MPa)	Modulus of Elasticity E (GPa)		
		Grade I	Grade II	Grade III
Carbon	1100-1300	80.0	110.0	140.0
Glass	600-750	40.0	50.0	60.0

Source: Aiello and Ombres [23]

Table-5. Typical mechanical properties of FRP bars [24]

Fiber Type	Tensile Strength (MPa)	Modulus of Elasticity (GPa)
Steel	483-690	200
AFRP	1720 -2540	41-125
CFRP	600-3690	120-580
GFRP	483-1600	35-51

Source: Harajli and Abouniaj [24]

Table-6. Typical mechanical properties of ASLAN FRP bars manufactured by Hughes Brothers Inc

Trade Name	Tensile Strength (MPa)	Modulus of Elasticity (GPa)	Ultimate Tensile Strain
CFRP Aslan 200	2068-2241	124	0.0167 – 0.0181
GFRP Aslan 100	620-827	46	0.0134 – 0.0179

Source: ACI [19]

Table-7. Typical mechanical properties of ComBAR GFRP bars manufactured by Schock Inc.

Trade Name	Tensile Strength (MPa)	Modulus of Elasticity (GPa)	Ultimate Tensile Strain
GFRP	> 1000	> 60	0.0261

Source: ACI [19]

4.2. Compressive Strength

There is no standard axial compression test for FRP composites because there are many different failure modes [19]. The mode of failure is buckling, ranging from buckling of the entire specimen cross section or local micro buckling of individual fibers. Thus, the greater resistance to buckling the test fixture provides, the higher the compressive strength values obtained. For flat laminate FRP composites, many axial compression test methods in current use are some variation of the Celanese compression test as in ASTM D3410 [21]. This test uses a thin, straight-sided specimen that looks very much like an axial tension specimen except that the distance between tabs is much smaller. Testing of FRP bars in compression is typically complicated by the occurrence of fibre micro-buckling due to the anisotropic and non-homogeneous nature of the FRP material, and can lead to inaccurate measurements. Therefore, standard test methods are not established yet. For the case of FRP bars, reductions in the compressive strength by 50% must be considered.

4.3. Shear Strength

Most FRP bar composites are relatively weak in inter-laminar shear where layers of unreinforced resin lie between layers of fibers. Because there is usually no reinforcement across layers, the inter-laminar shear strength is governed by the relatively weak polymer matrix. On the other hand, interface problem between vinyl ester resin and

carbon fiber appeared and results very low inter-laminar shear strength compared to glass fiber. In addition to, carbon fibers are more brittle than glass fiber with ultimate elongation 1.32% and 1.56% for carbon and glass fibers, respectively. Also, orientation of the fibers in an off-axis direction across the layers of fiber will increase the shear resistance, depending upon the degree of offset. For FRP bars this can be accomplished by braiding or winding fibers transverse to the main fibers. Off-axis fibers can also be placed in the pultrusion process by introducing a continuous strand mat in the roving/mat creel.

4.4. Bond Strength (Pull-out Test)

The bond properties of FRP bars have been extensively investigated by numerous researchers through different types of tests, such as pull-out tests, splice tests, and cantilever beams, to determine an empirical equation for embedment length [12]. The bond stress of a particular FRP bar should be based on test data provided by the manufacturer using standard test procedures that are still under development at this time. ACI 440.1R-06 [19] specified a standard test method for bond strength of FRP bars as shown in Figure 3.

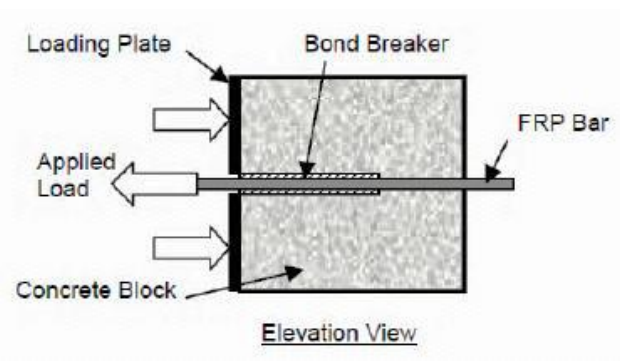


Figure-3. Schematic drawing of pull-out test
Source: Benmokrane and Tighiouart [12]

Bond failure between steel or FRP reinforcing bars and concrete occurs predominantly in two modes: pull-out and splitting. If the concrete around the bars is well confined, or the concrete cover is large, or the bar embedment length is small, bond failure occurs in pullout mode. On the other hand, if the concrete cover is relatively small, and/or the concrete is unconfined, bond failure occurs in splitting mode. For most practical applications of steel reinforced concrete, bond failure occurs by splitting. For pull-out mode of bond failure, the bond strength of steel bars with short embedment lengths (less than $7 db$) called local bond strength is mainly dependent on the concrete compressive strength f_c . As the development or embedment length of the bar increases, the bar force at bond failure increases but because the bond stress distribution along the embedment length becomes non-uniform, the average pullout bond strength at bond failure decreases.

5. BOND BETWEEN FRP BARS AND CONCRETE

As far as the structural performance of RC members is concerned, bond between FRP reinforcement and concrete is the most significant aspect that controls the structure's capacity, ductility, and serviceability. In this aspect, bond of GFRP and CFRP bars to concrete has been widely investigated, which resulted in a significant amount of experimental data on their bond performance [8, 19, 24-26]. It was established that parameters such as concrete strength, bar diameter, embedment length, and concrete confinement significantly affect the bond performance of FRP bars to concrete [5, 27-29]. Bond development is strongly dependent on the mechanical and physical properties of the surface of the FRP bar and the constituents of the FRP material. It varies widely between different FRP bars due to the unique properties of each bar. In the following sections, the parameters influencing the bond performance of FRP bars to concrete are highlighted.

5.1. Surface Treatment

Nowadays, many types of FRP bars having different surface treatments and characteristics are available. The FRP bar surface may vary between deformations (ribbed, braided, or indented), or sand coating, or a combination of both. Cosenza [1, 30] tested GFRP bars with various surface deformations (Figure 4) to compare their bond performance to concrete. The bond strength for the ribbed and indented FRP bars was found to be 11.6 MPa and 10.2 MPa, respectively. These values of bond strength were comparable to those obtained for deformed steel bars (11.9 MPa) but were much lower than the bond strength of sand-coated bars (17.7 MPa). The authors concluded that sand grains glued to the bar surface enhanced its bond strength and that the surface deformation play an important role in developing bond between concrete and the bar's interface.



Figure-4. Different FRP bars surfaces used

Source: Cosenza, et al. [1]

Chaallal and Benmokrane [31] compared the bond strength of wrapped sand-coated GFRP and steel bars embedded in 150 x 300 mm concrete cylinders. The authors reported that bond strength of GFRP varied between 11.1 MPa and 15.1 MPa representing 62% to 84% of the bond strength of deformed steel bars. In order to evaluate the bond performance of GFRP in tension, Harajli used thread wrapped and ribbed bars embedded vertically in concrete cylinders of 150 x 300 mm with an embedded length of 7 d, where d is the bar diameter [24]. The results showed that ribbed bars developed larger average bond strength at failure than the thread wrapped bars. The authors concluded that surface deformations of FRP bars significantly affect their bond strength to concrete and their mode of failure at ultimate limit stat. Similar conclusions were reported by [23, 32] who studied the bond performance of various types of FRP bars in pullout tests. A total of 24 prismatic concrete cubes (250 mm) reinforced with AFRP, CFRP and GFRP bars were tested. Ribbed, fine-sanded, coarse-sanded, and bars with spirals wound with fibres were used in addition to traditional smooth and ribbed steel bars. Results showed that the maximum bond stress of CFRPsw (spiral wound) was four times larger than that of both fine and coarse sanded CFRP bars.

Davalos, et al. [5] tested 12 cylinders (150 x 150 mm) to investigate the effect of FRP bar degradation on the interfacial bond to high strength concrete (60 MPa). Different types of GFRP bars (wrapped GFRP 1, slightly sand-coated GFRP 2, and sand-coated GFRP 3, and sandblasted CFRP) were used in the study (Figure 5). The bars were vertically embedded in concrete for a length of 5 d. The results showed that the sand-coated GFRP3 bars exhibited the highest bond strength (23.42 MPa) compared to the wrapped GFRP1 (19.61 MPa) and the slightly sanded GFRP2 bars (21.38 MPa). CFRP bars exhibited average bond strength of 22.26 MPa. The authors reported that the surface characteristics of FRP bars not only affect their bond strength to concrete but also affects the post-peak bond stress attained.

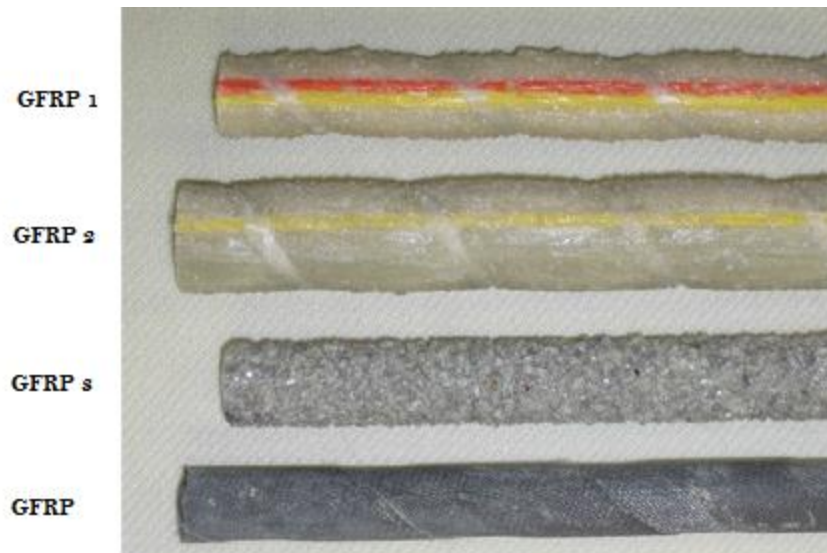


Figure-5. Different types of FRP bars

Source: Davalos, et al. [5]

Baena, et al. [33] investigated the effect of six different surface treatments on bond between FRP bars and concrete (Figure 6). The bar specimens included sand-coated GFRP and CFRP bars, textured surface CFRP bars, GFRP bars with and without helical wrapping surface and sand-coating, GFRP bars with grooved surface, and steel bars. A total of 88 concrete cubes of 200 mm with 5 d embedment length were tested. The authors concluded that the sand-coated bars had better chemical bond than other bars, which confirmed the influence of the bar surface treatment on its bond to concrete.



Figure-6. Surface deformations of FRP bars

Source: Baena, et al. [33]

5.2. Bar Diameter and Embedment Length

Many research studies have reported that bond strength of FRP bars is inversely proportional to the bar diameter [34, 35]. Sayed [36] tested 60 pullout specimens to evaluate the effect of the bar diameter on the bond of CFRP bars to ultra-high-performance fiber-reinforced concrete. Four diameters (8, 10 and 12 mm for smooth bars and 7.5 mm for sand-coated bars) were used with embedment lengths of (5, 10, 15 and 20 d). The authors concluded that specimens with shorter embedment length and smaller bar diameter developed the highest bond strength. Alvarez reported similar conclusions from testing 72 concrete cylinders (150 x 300 mm) reinforced with four different sand-coated GFRP bars [26]. Four diameters (9.5, 12.7, 15.9 and 19.1 mm) and three embedment lengths (5, 10 and 15d) were investigated under different applied temperatures (20°, 40°, and 60°C) for 4 months. It was concluded that bond strength decreased when the embedment length and the bar diameter increased.

6. CONCLUSION

A general overview of previous research in the behavior of FRP bars in reinforced concrete structures was presented in this paper. Due to the increased use of FRP bars in concrete structures, the performance of FRP bars has been an important research topic in recent years. This research investigated the material characteristics and mechanical properties of different type of FRP bars in RC structures. In current study one of the most significant aspects is to understanding the behavior of bond between FRP bars and concrete. Subsequently the main experimental, numerical and analytical studies were presented. Moreover, FRP in concrete allows engineers to increase or decrease margins of safety depending on environmental and stress conditions, generic FRP type and required design life. At the end, the proposed study is to improve the understanding of FRP bars in RC construction and this research brings new challenges for professionals and who are working in the field of structural design and strengthening of reinforced concrete structures.

Funding: The authors would like to thank Universiti Kebangsaan Malaysia for financial support under grant ERGS-1-2013-PK04-UKM-02-1 and FRGS-1-2015-TK01-UKM-02-4.

Competing Interests: The authors declare that they have no competing interests.

Contributors/Acknowledgement: All authors contributed equally to the conception and design of the study.

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