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Bond behaviour of FRP rebars – parameter study

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ABSTRACT: Application of fibre reinforced polymers (FRP) reached increasing significance over the last decades for strengthening reinforced concrete (RC) structures. However, the growth in the use of FRP reinforcement as internal reinforcement is less impressive. There are few reasons of this, the most important ones are: the relatively high price of the FRP rebar and the lack of recognition of the national standards of this relatively new construction material. Until the bond of FRP rebars in concrete is completely understood, the recognition in national standards is not possible. However, the bond behaviour of FRP rebars in concrete is affected by several parameters.

Participating in **endure** (European Network for Durable Reinforcement and Rehabilitation Solutions) project the main aim of the authors is to create an up-to-date overall database of bond tests results and complete it with experimental data in case of those parameters which cause many debates among researchers. Furthermore, to develop an analytical model that can capture material-related properties as well as loading rate of applied force, loading conditions and service temperature.

This paper contains a short summary of an extensive literature review. Results highlight which effects were not studied deep enough or generates disagreement among researchers. Present study is mainly based on literature data.

Keywords: bond, FRP, bond tests, bond behaviour, material properties, loading conditions

1 INTRODUCTION

Steel rebars are widely used in concrete structures due to their efficiency and economic benefit. These rebars are normally ductile and strong, which makes them appropriate for reinforcing concrete. Although steel reinforcement has a high number of advantages (similar coefficient of thermal expansion to the concrete, ductile behaviour, high tensile strength, bendability etc.) it presents some disadvantages too, being the most significant one is that the steel reinforcement is susceptible to corrosion, when the concrete structure is exposed to chloride rich environments, for instance in case of structures close to seawater or subjected to frequent use of de-icing salts.

Several solutions have been studied to prevent the corrosion of steel rebars, such as introduction of additives to make the concrete less permeable, use of stainless steel reinforcement and epoxy coated steel rebars, but no reliable long-term solutions, to avoid corrosion of steel rebars, has been found (Won et al., 2008; Sólyom et al., 2015).

A recent approach to solve this problem is to replace steel reinforcing bars with Fibre Reinforced Polymer (FRP) rebars (Balázs et al, 2000).

FRP rebars are manufactured from different fibres (glass, carbon, aramid or basalt) bound together with various resins (polyester, vinyl ester or epoxy). They have mechanical properties and surface characteristics which are considerably different from that of the conventional steel reinforcements, and provide excellent resistance to environmental factors such as freeze-thaw cycles, chemical attack etc.

Tensile strengths and Young's moduli of FRP rebars depend mainly on type of fibre and resin, volumetric ratio of fibres (usually 60-70 V%), angle between the fibres and the longitudinal axis of rebar, shape and size of the cross section of the rebar (*fib*, 2007). The most significant differences between FRP and steel rebars are their linear elastic behaviour up to failure without any plasticity and considerable release of elastic energy at failure. A major advantage of FRP rebars is that they can be engineered to have the desired mechanical and physical properties.

In this article the authors intend to summarize the parameters which have an effect on bond of FRP rebars, highlight the ones where further research is needed due to disagreement among existing results or due to lack of experimental data.

2 BOND MECHANISM OF FRP REBARS IN CONCRETE

To enable the faster acceptance and wider application of FRP materials by the construction industry new design guidelines including FRP materials are needed. Nevertheless, to prepare guidelines to design reinforced concrete elements with FRP rebars, better understanding of the composite action of FRP rebar and reinforced concrete is essential. Bond between concrete and FRP rebars is crucial to develop the composite action of FRP reinforced concrete. To achieve composite behaviour, proper bond must be activated between reinforcement and concrete for the successful transfer of forces from one to the other (*fib*, 2007; Sólyom et al., 2015).

Due to the different material characteristics, manufacturing processes and surface treatments bond of FRP rebars differ from that of steel rebars in many ways. The most fundamental differences between the two reinforcing materials are that steel is isotropic, homogeneous and elasto-plastic material, whereas FRP is anisotropic, non-homogeneous and linear elastic. However, there are also similarities, despite of the many differences, in bond mechanisms of FRP and steel rebars. A decrease in rebar diameter or a decrease in embedment length results in an increase in bond strength. Moreover, the position of rebar during casting has the same effect in both cases.

Description of the bond between rebar and concrete is presented in *fib* Bulletin 10 (2000). Bond action of plain FRP rebars is attributed only to the adhesion at zero slip. As soon as the adhesion breaks down, owing to the plain surface of the rebar, bond slip occurs. Due to the surface characteristics, no tensile cracking is likely to occur and splitting bond forces are unlikely to develop. Plain rebars (smooth rebars without any surface treatment) are allowed as internal reinforcements only if they are used together with other anchoring solutions such as bends, hooks and transverse rebars. In case of surface treated smooth rebars, bond stress has two main components: adhesion at zero slip and friction as slip is developed. When deformed rebars are considered, there is a third component: mechanical interlock (also known as bearing), playing the most important role in developing high bond strength. In this article authors will study only surface treated and deformed FRP rebars.

3 INFLUENCING FACTORS OF BOND OF FRP REBARS IN CONCRETE

The interaction between FRP rebar and concrete is affected by many factors. Some factors have been studied by many researchers and the effects of them on the bond behaviour of FRP rebars are well understood. However, the effects of a few parameters are still not obvious from the available researches. The effect of these parameters should be investigated more, in order to better understand the bond behaviour of FRP rebars in concrete.

According to *fib* Bulletin 10 (*fib*, 2000) the bond behaviour of FRP rebars in concrete depends mostly on the following parameters: shape of the rebar cross section, rebar deformations, elastic modulus in axial direction, elastic modulus in transverse direction, transverse pressure, Poisson effect, position of the rebar in the cross section, wedging effect, bends in anchored rebars, concrete cover, distances between parallel rebars, coefficient of thermal expansion, environmental influences, rebar diameter, concrete strength, transverse reinforcement.

Further parameters are: embedment length of FRP bar, loading rate, cyclic loading, fibre/resin type, concrete density, service and elevated temperature, type of surface etc.

3.1 Type of rebar surface

The effect of rebar surface on bond strength is a complex phenomenon, because the rebar can have various surface configurations. Unlike steel reinforcement, no standard surface configuration has been set for FRP rebars. Different surface configurations lead to difference in bond behaviour. The bond stress of the FRP rebar with sand coating drops rapidly after attaining the maximum bond stress, whereas FRP rebars with helical wrapping and sand coating exhibit a more gradual reduction of the bond stress. The failure modes of bond of steel and FRP rebars can significantly differ also.

According to the Eq. (1) developed by Wambeke et al (2006) after a comprehensive study of an extensive database the influence of surface characteristics was not included as a parameter. Only concrete compressive strength, concrete cover (and the distance between two adjacent rebars), rebar diameter and embedment length are taken as bond strength influencing parameters. For SI units, it has the following form:

$$\frac{\tau_{b,max}}{0.083\sqrt{f_c}} = 4.0 + 0.3\frac{c}{\varnothing_b} + 100\frac{\varnothing_b}{l_b} \quad (1)$$

However, according to Guadagnini et al. (2005), Baena et al. (2009), Wang et al (2010) and many others the bond strength developed by the rebars appears to be greatly influenced by the type of surface treatment on the embedded rebars.

CSA S806-02 (2002) takes also into consideration the effect of surface characteristics of FRP rebars by applying a modification factor. A modification factor of 1.0 is assigned to sand coated or braided surfaces; 1.05 is assigned to spiral pattern or ribbed surfaces; 1.80 is assigned to indented surfaces. It can be observed, that according to CSA S806-02 (2002) indented surfaces present the weakest bond strength.

Lin et al (2013) studied the flexural and bond–slip behaviour of FRP-reinforced concrete beams by experimental studies and numerical modelling. Experiments were conducted on beam specimens reinforced with CFRP, GFRP and BFRP rebars. FRP rebars with grain-covered surfaces had better bond behaviour in concrete than other (i.e. smooth, ribbed, wrapped) rebar surfaces. Same lengths, cross-sectional dimensions and loading conditions were applied in all experiments. FRP-reinforced concrete beams with ribbed or wrapped rebar surfaces exhibit similar flexural and bond–slip behaviour. Very poor structural performance and bond strength are observed in the FRP-reinforced concrete beam with smooth rebar surface (Figure 1).

It can be observed, from the above discussion, that no definite trend has been established so far for the effect of rebar surface on bond strength. As a consequence, there is need for more experimental data and a general equation for bond stress should be developed with the help of this data which can take into account the effect of surface characteristics. Surface patterns of available FRP bars are shown in Figure 2.

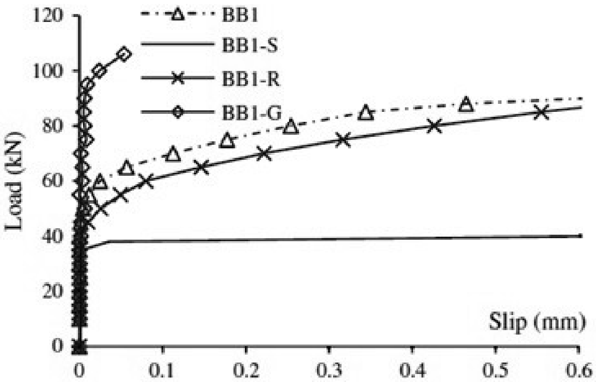

Figure 1. Load–slip relationships of BFRP reinforced concrete beams with different rebar surfaces (BB1 - wrapped, BB1-S - smooth, BB1-R - ribbed and BB1-G - grain-covered; Lin et al, 2013).

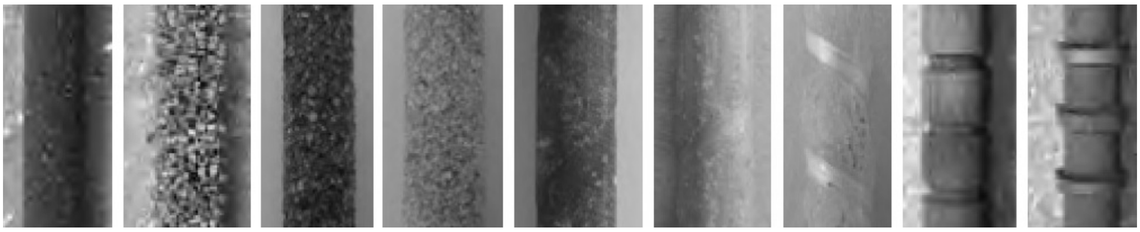

Figure 2. FRP bars with different surface characteristics. From left to right: plain surface; three different sand coated surface; texture surface; helical wrapping; helical wrapping and sand coated; two different indented surfaces (Al-Mahmoud et al., 2007; Baena et al., 2010).

3.2 Type of fibres

As discussed in the previous chapter the bond strength of FRP rebars seems to not depend on the fibre type neither. This was also confirmed (in case of glass and carbon fibres) by Achillides et al (2004), who found that GFRP and CFRP rebars developed 72% of bond strength of the steel rebar.

Design guidelines CSA S6-06 (2006) and JSCE (1997) do not distinguish between different types of fibres in the determination of bond strength, while the CSA S806-02 (2002) design code does take into consideration the effect of fibres. According to CSA S806-02 (2002), CFRP and GFRP gives the same bond strength, but AFRP shows lower bond strength in comparison to CFRP and GFRP. Modification factor with a value of 1.0 is assigned to CFRP and GFRP rebars, whereas a modification factor of 1.25 is assigned to AFRP rebars in the determination of the average bond strength (modification factor is inversely proportional to the bond strength).

According to *fib* Bulletin 10 (*fib*, 2000) in case of normal (and high) strength concrete the resin type, rather than the fibre type, controls the bond strength.

Similar observation was made by Nanni et al. (1995). Carbon-epoxy (fibre/resin configuration) FRP rebars developed much higher bond strength than glass-vinyl ester and carbon-vinyl ester FRP rebars.

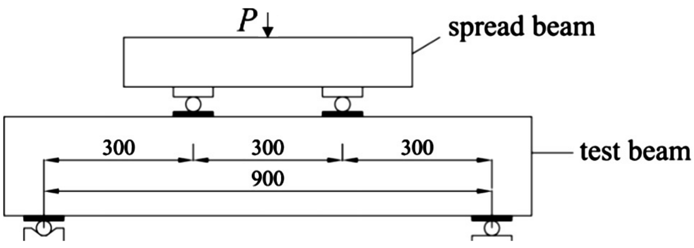

Figure 3. Beam test setup used by Lin et al (2013).

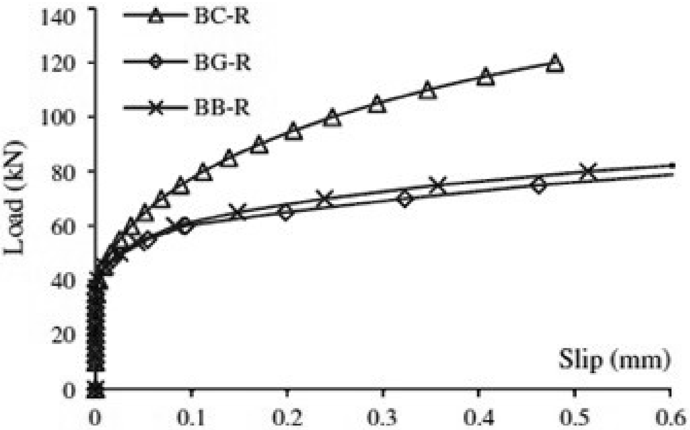

Figure 4. Load–slip relationships of concrete beams reinforced with different types of FRP rebars with ribbed surfaces (C - carbon, G – glass and B - basalt; Lin et al, 2013).

Lin et al (2013) concluded, that the concrete beam (Figure 3) reinforced with CFRP rebars performs better than those reinforced with GFRP and BFRP rebars (with the same rebar surface, Figure 4).

Due to the lack of experimental data in case of AFRP and CFRP rebars, further experiments are needed in order to understand the effect of rebar type on bond strength of FRP rebars.

3.3 Service and elevated temperature

The surfaces of the FRP rebars are rich in matrix. The glass transition temperature (Tg) of matrices are between +60 ºC and +180 ºC. When the temperature reaches the glass transition temperature, the modulus of elasticity and strength of matrices reduces rapidly. As a consequence, the FRP rebars are more affected by the service temperature than the steel rebars (Lublóy et al., 2005).
Borosnyói (2015) studied the effect of the service temperature on bond behaviour. According to this study the bond strength of FRP rebars depends not only on the compressive strength of concrete (which itself is also temperature dependent), but on the temperature dependent behaviour of the resin matrix as well. In the study 5 mm in diameter CFRP wires (sand coated) were used. Higher stiffness of surface layers of the resin results higher bond strength at low temperature and the softening of the surface layers of the resin results lower bond strength at elevated temperature (Figure 5). In the diagrams the bond stress is plotted against the loaded end slip. Specimens with three different concrete grades (C20, C40 and C60) were studied. Highest strength concrete governs the failure at all temperatures: FRP surface fails in pull-out in these cases. In case of lower strength concretes the surface failure of FRP is less pronounced in pull-out. However, reduction in bond strength is clearly visible in Figure 5 also in those cases where the reduction is not of high magnitude. Mixed mode of failure is the reason of the observations.

Galati et al. (2006) concluded that in most cases the thermal treatment induced a slight degradation in the bond performance in terms of ultimate load. Furthermore, the effect of the thermal treatment was more pronounced for the bond stress–slip curves in terms of slip values owing to the degradation of the resin. The highest effect of the service temperature was observed when small concrete cover was used. Such behaviour can be explained with the microcracking of the concrete due to the stresses induced during the thermal treatment.

The effect of elevated temperature on FRP rebars performance (tensile strength, modulus of elasticity, bond strength) was investigated by Alsayed et al. (2012). Bare bars and bars in concrete specimens were exposed to elevated temperatures (100 ºC, 200 ºC or 300 ºC) for different time period (1 h, 2 h or 3 h) and the results were compared. Total number of 120 specimens were tested. The SEM technique used in this investigation showed that increasing the temperature level affected the resin matrix surrounding the fibres and the bond between the fibres and the resin

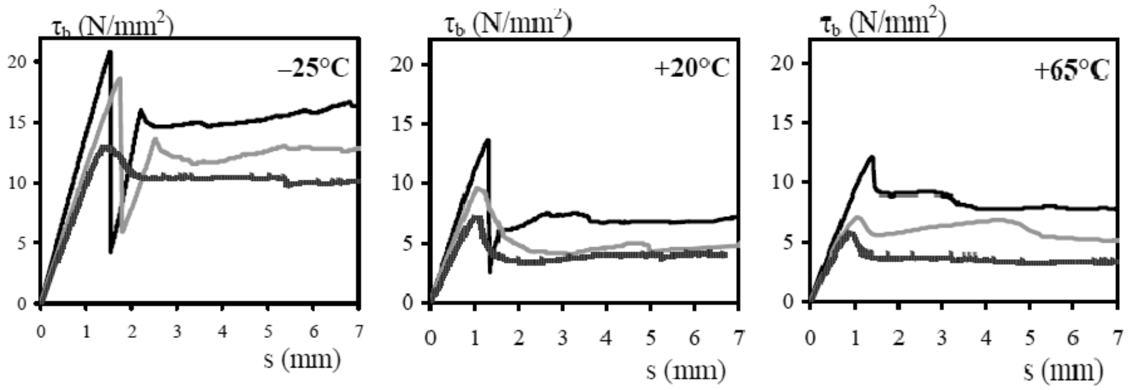

Figure 5. Testing temperature and typical bond stress (τ_b) vs. slip (s) diagrams during static pull-out testing for sand coated CFRP wires. Three different concrete grades were studied (Borosnyói, 2015).

matrix which resulted in the recorded reductions in the tensile strengths and failure strains (Alsayed et al., 2012).

3.4 Fibre reinforced concrete

Bond behaviour between FRP rebars and concrete when reinforcing fibres were added to make concrete less brittle was studied by Belarbi et al (2004). In the research GFRP and CFRP rebars were used. GFRP had 12.7 and 25.4 mm diameter, wrapped with helical fibre strand to create indentations along the rebars. In addition, sand particles also were added into the surface to increase the bond strength. GFRP were 12.7 mm in diameter, with smooth surface. The fibres added to the concrete mix were commercially available polypropylene short fibres, with maximum length of 57 mm. The compression strength of concrete was 37 N/mm² in case of plain concrete and 51 N/mm² in case of fibre reinforced concrete. From test experimental data (27 pull-out specimens) it was concluded that the addition of polypropylene fibres did not increase the bond strength however, larger slips were recorded. The large slip values made the bond behaviour more ductile and the failure mode changed from splitting to pull-out.

Contradictory results were reported by Ding et al. (2014). According to this study adding macro mono fibres (steel fibres - SF; or macro-polypropylene fibres - PPA) or hybrid fibres (SF and PPA) into concrete can enhance the bond strength of GFRP rebars and also reduces the slip corresponding to the bond strength. Especially, the hybrid use of SF and PPA demonstrates a significant positive synergetic effect on the bond behaviour of GFRP rebars in concrete. The results show that the bond capacity of GFRP rebars in concrete reinforced by hybrid fibres can be equivalent to that or better than that of steel rebar in plain concrete.

The combined use of steel fibres (30 kg/m^3) and macro-polypropylene fibres (2 kg/m^3) shows greater effect on the bond capacity than the sum of the effects of PPA and of SF separately. This demonstrates great positive synergetic effect on the bond strength of GFRP rebars in concrete matrix. The fibres used in this study were 37 mm (PPA) and 35 mm (SF) long. The concrete compressive strength measured on cubes of 150 mm sides specimens varied between 43.2 and 48.8 N/mm^2 depending on fibre type and dosage. GFRP rebar had deformed surface with diameter of 12 mm, glass fibre strands were bound together with polyester resin. The steel rebar used for comparison had also 12 mm diameter.

The effect of the type and amount of fibre on the bond properties between high-strength concrete and different FRP rebars was studied also by Won et al. (2008). Three types of high strength concrete mixes (54, 74 and 94 N/mm^2 - mean values for the compressive strength of concrete, evaluated on cylindrical specimens), two types of FRP rebar (CFRP, 9 mm in diameter and GFRP, 13 mm in diameter - Both types had surface ribs that were manufactured using PVA fibre braiding technology), two different reinforcing fibres (steel and synthetic), and two reinforcing fibre volume fractions (in case of steel fibres: 20 or 40 kg/m^3; in case of synthetic fibres: 4.55 or 9.1 kg/m^3) were considered. The embedment length of the rebar was up to four times the rebar diameter. It was concluded that the bond strength of both CFRP and GFRP rebars increased significantly with the increase of the concrete strength. In addition, concrete compressive strength increased slightly as more fibre was added to the mixture. The highest bond strength improvement due to reinforcing fibre addition in concrete matrix was achieved with steel fibres.

4 CONCLUSIONS

The use of Fibre Reinforced Polymer (FRP) rebars is an effective solution to the problem of steel durability in aggressive environments and where the magnetic or electrical properties of steel are undesirable. Mechanical properties and surface characteristics of FRP rebars can be considerably different from those of steel rebars which leads to several open questions, among these is the bond behaviour of FRP rebars in concrete. Due to various constituent materials, manufacturing processes and surface treatments of FRP rebars, both bond performance and failure of bond can take place in different ways than in the case of conventional steel rebars.

Bond strength of smooth FRP rebars is constituted of only two components: the adhesion at zero slip and the friction as slip is developed. However, depending on the sand coating characteristics, bond strength values of smooth FRP rebars can be similar to that of steel deformed reinforcement. Mechanical interlock (also known as bearing), as third component of the interaction, is present in case of the deformed FRP rebars. This is the most important one among the three components of bond stress. Deformed FRP rebars can develop higher bond strength than smooth FRP rebars. Since, the modulus of elasticity of the FRP rebars are usually lower than that of steel rebars bond strength is generally reached at higher slips.

Despite the high amount of experiments carried out to understand the bond behaviour of FRP rebars, there are still parameters which effect is not obvious. Most researcher agree, that the surface characteristic of the rebar influences the bond strength, however no generally valid equation was developed which can capture this effect. This is also valid for the type of fibres. Further experimental data are needed for proper understanding the effect of the temperature on bond behaviour of FRP rebars in concrete. There are completely contradictory results reported about the effect of the fibre reinforced concrete on the bond strength of FRP rebars.

5 ACKNOWLEDGEMENTS

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