Investigation on bond performance between different types of FRP-reinforced rebars and concrete

A I Komarov\textsuperscript{1}, N V Makarova\textsuperscript{1,2} and V G Tsuprik\textsuperscript{1}

\textsuperscript{1} Engineering School, Far Eastern Federal University, 8 Sukhanova St., Vladivostok 690090, Russia
\textsuperscript{2} Institute of Automation and Control Processes Far Eastern Branch of the Russian Academy of Sciences, 5, Radio st., Vladivostok, 690041, Russia

The corresponding author’s e-mail address: maknat@bk.ru

Abstract. In this paper the test results of a study on the bond behaviour of FRP bars to fine-grained concrete are presented. Five series of concrete cylinders reinforced with basalt-reinforced polymer (BFRP) and glass fiber-reinforced polymer (GFRP) bars are tested in direct pullout conditions. As well as two series with steel bars are tested for comparison. For each specimen, the bond failure mode, the average bond strength, the initial bond stiffness, and the load–strain relationship curves and bar relative extension were analysed. Test results demonstrate the promise of using the FRP bars as an alternative to the steel bars in reinforcing concrete elements.

1. Introduction
Recently, the use of FRP rebar has increased, due to their unique properties. Their attractiveness is caused by such qualities as durability, corrosion resistance, electromagnetically transparency, etc. [1-5]. FRP rods are used as reinforcement for concrete structures such as bridges, foundations and marine structures, where the corrosion of steel reinforcement typically led to significant deterioration and rehabilitation needs [6]. The commonly used fiber material are glass, aramid and carbon. The increasing use of FRP bars encourages utilizing new materials, such as basalt fibers [7]. An extensive experimental investigations is being conducted to evaluate their physical, mechanical and other technological characteristics [8]. Standard test methods have been developed to determine the FRP rods characteristics for the design and manufacture of reinforced concrete structures [9].

However, the adhesion between reinforcing bars and concrete is still poorly understood due to the variety of materials and surface types [10]. Many factors such as surface deformation, mechanical interlock, chemical adhesion, embedment length, diameter, environmental and loading conditions [2-9], must be considered to fully understand the bond effects.

In the most previous studies, the geometric shape of the surface and its composition were concluded to have the greatest influence on the adhesion strength. In work [11], it is was suggested to divide all FRP reinforcing bars into three groups in accordance with the method used for establishing a bond between the core of the bars and concrete. The effects of structural fibers on the bonding mechanism changes in interface between GFRP bar and concrete were studied in work [12]. It was determined that bond failure modes largely depend on the interfacial property with the rebar. The experimental results of 180 pullout tests conducted on GFRP bars embedded into high
strength concrete blocks [13] showed that, the bond stress is inversely proportional to the embedment length and bar. Similar study [14] showed the influence of various parameters that affect bond strength such as the embedment length, type, shape, surface characteristics, and diameter of the bar. The results of an experimental study on the bond behavior of GFRP ribbed rebars with different specially designed rib geometries to the concrete are presented in work [15]. It was shown that, in normal strength concrete, the bond strength and bond-slip performance of these ribbed rebars varies with the combinations of rib spacing and rib height.

As a matter of fact, many experimental and analytical studies showed the effectiveness of FRP-based bars for reinforced concrete. Nevertheless, technological standards and design guide-lines norms cannot take into account all diversity of materials and surface shapes by different manufacturers. Therefore, the main objective of this study is to investigate the effect of different materials and surface parameters for the bond strength between FRP rebars and concrete. In addition, to understand the failure mechanism during the loading, the relative extension of the bars is measured.

2. Experimental details

2.1. Materials

Five types of rebars, manufactured in the Primorsky krai, were tested in this study. Four GFRP rebar types with different profile texture were investigated, including one type of bar containing basalt fibers in surface and one type with sand. BFRP rebars was also tested. As well as two series with steel bars were tested for comparison. Nominal diameter of all bars was 4 mm. The properties of rebars tested in this study are presented in Table 1.

Table 1. Properties of bars.

| Type | Material  | Profile | Rib height (mm) | Rib spacing (mm) | Tensile strength (MPa) | Tensile modulus (GPa) | Transverse shear strength (MPa) |
|------|-----------|---------|-----------------|------------------|------------------------|-----------------------|----------------------------------|
| 1    | GFRP      | ribbed  | 0.5–0.7         | 8                | 1070                   | 54.20                 | 221.70                           |
| 2    | GFRP      | ribbed  | 0.5             | 7                | 1162                   | 55.00                 | 194.00                           |
| 3    | GFRP      | ribbed  | 0.3             | 20               | 1016                   | 67.82                 | 202.00                           |
| 4    | Steel     | ribbed  | 0.25            | 3                | 710                    | 200.00                | 210.00                           |
| 5    | Steel     | plain   | –               | –                | 710                    | 200.00                | 210.00                           |
| 6    | BFRP      | ribbed  | 0.5–0.7         | 15               | 1085                   | 50.00                 | 150.00                           |
| 7    | GFRP      | sand    | –               | –                | 800                    | 50.00                 | 150.00                           |

The samples were cylindrical in diameter 55 mm, height 65 mm. In the exit points of the rods, notches were made to exclude surface cracking of the concrete (Fig. 1). The concrete used for making samples was fine-grained at the age of 28 days; the uniaxial compression strength was 26.4 MPa. The bonded length L for all the tests is taken as 45±mm chosen to be sufficiently representative of rebar deformations [16].

2.2. Test method

The pullout-test developed in [17] was carried out using a universal testing machine (Shimazu AGS-X 10 kN). The concrete specimens were placed in to the rigid device, as shown in Figure 2. The loading rate was 0.1 kN/min. The values of the full pulling force of bar (inclusion of friction forces into work) were measured. In addition the relative extension of the bars was also measured during the loading by used the extensometer fixed on the bar.
3. Result and discussion

3.1. Bond strength

Bond strength is calculated using the value on the maximum pullout load $P_{\text{max}}$, assuming a uniform bond stress distribution along the embedded length $L$ of the rod in the concrete. The average maximum pull-out load and bond strength of all experimental programs are presented in Table 2. The bond strength was calculated using the nominal rod diameter 4 mm.

| Type series | Average maximum bond stress (MPa) | Strain (mm) | Bar relative extension (%) |
|-------------|---------------------------------|-------------|----------------------------|
| 1           | 9.44±0.53                       | 5.32±1.28   | 1.09±0.32                  |
| 2           | 8.08±0.04                       | 5.23±1.64   | 1.18±0.30                  |
| 3           | 14.18±1.43                      | 7.48±2.15   | 1.30±0.24                  |
| 4           | 5.82±0.94                       | 2.27±0.18   | 0.10±0.02                  |
| 5           | 2.78±0.51                       | 0.99±0.37   | 0.06±0.005                 |
| 6           | 12.68±1.54                      | 5.04±0.11   | 1.40±0.26                  |
| 7           | 6.17±0.73                       | 1.70±0.42   | 0.44±0.08                  |

GFRP rebars with basalt ribs in surface (Type 3) show higher bond strength (14.18 MPa). BFRP rebars (Type 6) show high bond strength too (12.68 MPa). But the concrete of several specimens of this types was broken, this is characteristic of brittle fracture. The obtained average bond stress for the GFRP rebars of Type 1 and Type 2 was 9.44 MPa and 8.08 MPa respectively. For BFRP rebars with sand in surface (Type 7), the average bond stress obtained was 6.17 MPa.

Comparing the test results of the bars with the ribs on the surface showed that the main factor is the spacing of the ribs. The highest bond values were obtained on GFRP and BFRP bars with the spacing of the ribs 20 mm (Type 3) and 15 mm (Type 2). The effect of spacing is presented in the histogram shown in Figure 3. But on the basic of results, presented in [15], it was obtained that bond behavior of ribbed rebars would improve with a decrease in rib spacing. However, this conclusion needs further more investigations to validate.
Two types of steel bars were tested, having a rough (Type 4) and a plain surface (Type 5). The average bond stress obtained was 5.82 MPa for the bar with a rough surface and 2.78 MPa for the bar with a plain surface. Also, the bond strength in all types of FRP bars is greater than the corresponding steel rebars.

3.2. Load-strain curves
There are measured total load-strain curves (a) and local load-strain curves (b) only for the bar for every specimen of seven series. The examples of the typical curves are presented in figures 4–7.

The section of the curve to the peak characterizes the stiffness of the bond as the ratio between the load and the deformation. First of all, this provides a mechanism for the combined action of reinforcement and concrete in structures. The bond behaviour of all types of rebars before peak is linear at early section. After 60% - 80% of the maximum load up to the peak, the curves become non-linear (Figure 4a, 5a, 6a, 7a). For all types of bars, before peak load level, the relative extension strains are elastic and the curve is linear (Figure 4b, 5b, 6b, 7b).

When the load reaches their maximum value Pmax, the loose deboning zone forms between the concrete and the bar. The post-peak section of the load-strain curve characterizes the frictional shear strength in this debonding zone. After the maximum pull-out load of GFRP bar (Type 1), the debonding of the bar decreases the load to about 40% and then immediately increases to the maximum load to about 20%. The decreasing curve commencing after this is the result of frictional resistance (Figure 4a), as well as for BFRP bar with sand (Type 7) and ribbed steel bar (Type 4) (Figure 6a). For these two types of bars, after peak load level, the relative extension strains are not elastic and the curve is not linear (Figure 4b, 6b).

![Figure 3. Effect of rib spacing on average bond stress.](image)

![Figure 4. Specimen 1-3 (GFRP bar):a – total load-strain curve; b - local load-strain curve.](image)
After peak load of the GFRP bar (Type 3) rapid drop of the pullout load to about 80-90% of the maximum load decreases (Figure 5,a), this is characteristic of brittle fracture with a minimal contribution of the friction force. Similarly behaviours we observed for of the BFRP bar (Type 6), moreover we noticed a second increase in the load, which was due to the redistribution of stresses after peak load along of the bar (Figure 7,a).
4. Conclusions
Test results demonstrate the promise of using the FRP bars from different manufacturers as an alternative to the steel bars in reinforcing concrete elements. It should be noted that the study of deformation process during the entire loading cycle gives important results for further investigations.

In this study, the conclusions to be drawn are that there is an adhesion and friction are the most important components of bond stress in FRP reinforcing bars. The greatest strength obtained with GFRP and BFRP rods with spacing of the ribs 15 and 20 mm. However, the analysis of the load-strain curves showed the brittle fracture mechanism; it can lead to brittle cracking of the structure during operation. Samples with low bond (but more than steel bars) strength showed the plastic nature of the deformation.

Thus, further research should be carried out directly in the concrete reinforced structures. It will contribute to introducing new development in the FRP design codes.

5. References
[1] Bronnikov IV 2019 Compositereinforcement — problemsandprospectsapplicationsInt. J. of Appl. ScienceandTechn. «Integral» 3 223 (in Russian)
[2] Lapshinov A E 2015Prospects of Potential Application of Non-Metallic FRP Reinforcement in FRP-Reinforced Concrete Compressive Members as Main Longitudinal Non-Prestressed ReinforcementProc. of Moscow State University of Civil Engineering 10 96 (In Russian)
[3] Portnov G, Bakis C E, Lackey E. and Kulakov V 2013 FRP Reinforcing bars - designs and methods of manufacture (Review of Patents)Mechanics of Composite Materials 49(4) 381
[4] Teplova Z S, Kiski S S and Strizhkova Y N 2014. Fiberglass reinforcement for armouring of concrete structuresConstruction of Unique Buildings and Structures 24(9) 49 (in Russian)
[5] Behnam B and Eamon C 2013 Reliability-based design optimization of concrete flexural members reinforced with ductile FRP barsConstruction and Building Materials 47 942
[6] Benmokran B and Ahmed H A 2016Durability of FRP rebars in aggressive environments Proc. of 8th Int. Conference on Fibre-Reinforced Polymer (FRP) Composites in Civil Engineering (CICE2016)
[7] Elgabbas F, Cousin P, Ahmed E and Benmokrane B 2014 Development and characterization of basalt FRP reinforcing bars for concrete structuresProc. of the 7th International Conference on FRP Composites in Civil Engineering, International Institute for FRP in Construction (CICE) pp 20-2
[8] Monaldo E, Nerilli F and Vairo G. 2019 Basalt-based fiber-reinforced materials and structural applications in civil engineeringComposite Structures 21415 246
[9] GOST 31938-2012 Fibre-reinforced polymer bar for concrete reinforcement. General specifications (in Russian)
[10] Elgabbas F, Ahmed E A and Benmokrane B 2015 Physical and mechanical characteristics of new basalt-FRP bars for reinforcing concrete structuresConstruction and Building Materials 95 623
[11] Wang H and Belarbi A 2010 Static and Fatigue Bond Characteristics of FRP Rebars Embedded in Fiber-reinforced ConcreteJournal of Composite Materials 44(13) 1605
[12] Kim B, Doh J H; Yi C K and Lee J Y 2013 Effect of structural fibers on bonding mechanism changes in interface between GFRP bar and concreteComposites B 45 768
[13] Islam S; Afefy H M; Sennah K and Azimi H 2015Bond characteristics of straight- and headed-end, ribbed-surface, GFRP bars embedded in high-strength concreteConstruction and Building Materials 83 283
[14] Achillides Z and Pilakoutas K 2004Bond behavior of fiber reinforced polymer bars under direct pullout conditions J. of Composites for ConstructionASCE 8 (2)173
[15] Hao Q; Wang Y; He Z and Ou J 2009 Bond strength of glass fiber reinforced polymer ribbed rebar in normal strength concreteConstruction and Building Materials 23 865
[16] Cosenza E; Manfredi G; Pecce M and Realfonzo R 1999 Bond between GFRP rebars and concrete: an experimental analysis Proc. of the 4th Int.l Symp. on Fiber Reinforced Polymer
for Reinforced Concrete Structures (American Concrete Inst. Detroit) pp 347-58

[17] Makarova N V and Makarov S V 2018 Femtosecond laser nanostructuring of reinforcement bars surface for improvement of its interaction with concrete J. of Physics: Conf. Series 1092(1) 012082 (IOP Publishing)