Collaboration of polymer composite reinforcement and cement concrete

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Abstract. The results of experimental study of bond strength of cement concrete of different types with fiber reinforcing polymer (FRP) bars are reported. The reinforcing bars were manufactured of glass fibers and had a rebar with different types of the surface relief formed by winding a thin strip impregnated with a binder or by “sanding”. The pullout tests were carried out simultaneously for the steel reinforcing ribbed bars A400. The impact of friction, adhesion and mechanical bond on the strength of bonds between FRP and concrete was studied. The influence of the concrete strength and different operation factors on the bond strength of concrete was evaluated.

1. Introduction
In the recent years, in addition to the conventional steel reinforcing bars, polymer composite reinforcement (FRP) is increasingly used in the construction industry. FRP is manufactured from basalt, glass or carbon fibers and polymer binders based on epoxy and (less frequently) vinyl-ether resins. At that, a difference in molding techniques translates into the surface relief of FRP bar and exerts a direct impact on its bond strength with concrete.

The recently published investigations have revealed specific characteristics of FRP interaction with cement concrete; the influence of anchorage length, bar diameter, and strength of concrete on the bond strength value has been studied. The majority of experiments have been carried out for rebar specimens with a “sandy” coating, helically-deformed (depressed) profile or machined annular “grooves” on the surface. At the same time, FRP manufactured by the needle-trusion method is popular in Russia because of simplicity of the technique. This FRP bar has a spirally wound roving which is pasted on the surface and impregnated by the same binder; this is an imitation of a periodical profile of steel reinforcing bars (ribbed bars).

In the present work, we report the data on the bond strength between FRP with different type of the surface profile and the cement concrete, which were obtained by the direct pullout test method under different operational conditions. The bond stress distributions were determined; the character of stress distribution along the rebar was described.

2. Materials and Methods
The FRP specimens of four types with a diameter ranging from 7.5 to 8 mm, which had different surface profiles (confinement), were studied. All samples were manufactured from glass fibers and epoxy binder. To compare the results, the tests were carried out for the A400-class steel rebar together with FRP specimens.
| No. | Type of fiber and surface relief | Geometry of rod, dimensions (mm) | External view of specimens (photograph) |
|-----|---------------------------------|----------------------------------|----------------------------------------|
| 1   | Fiber – glass; Rebar surface is helically deformed by depressed winding (strip) | ![Diagram](image1.png) | ![Photograph](image2.png) |
| 2   | Fiber – glass; Double helical roving is pasted on the rebar surface | ![Diagram](image3.png) | ![Photograph](image4.png) |
| 3   | Fiber – glass; Single helical roving is pasted on the rebar surface | ![Diagram](image5.png) | ![Photograph](image6.png) |
| 4   | Fiber – glass; Surface is coated by quartz sand (sandy) | ![Diagram](image7.png) | ![Photograph](image8.png) |
|     | Steel A400                      |                                  | ![Photograph](image9.png) |

A fine-grained concrete with the strength compression of 30 MPa was used to fabricate the samples. The molding of concrete cylinders (110 mm in diameter and 100 mm in length) was carried out in a polyethylene molding matrix with a FRP bar embedded coaxially. The embedment length (length of the contact between a rebar and concrete) was 50 mm. The solidification of specimens proceeded under typical conditions (20°C and 100% humidity) within 28 days; and one experiment was carried out upon the steam curing processing (SCP) (2 + 6 + 2 hours)
Figure 1. “Adhesion-slip” curves ($\tau - \Delta$) of FRP and steel specimens obtained in the reference tests.

The method of direct pulling out of the rebar from concrete was applied. The slip of rebar tips in concrete under the load of 200 kg-sec was determined from the tracer displacement. The loads that caused 0.1, 0.3 mm and the maximum displacement of the unloaded end were considered as the reference values. To evaluate the external technological and exploitation factors, which are related to adhesion, the tests were conducted under the conditions described in table 1.

As a part of study, the following tests were carried out:

- tests of reference samples;
- tests after steam curing processing;
- tests with regard to high (+40°C/+80°C) and low (−40°C) temperatures;
- tests after temperature oscillations;
- tests after exposure in water;
- tests after exposure in alkaline medium;
- pullout tests with concrete specimens of different strength.

3. Results

The results of investigations are listed in table 2; the results of pullout tests for the reference samples (most typical) are represented as “stress-slip” ($\tau - \Delta$) curves.

The plots in figure 1 show that the character of variations in the tangent stress “$\tau$” on the interfacial “FRP-concrete” boundary in the course of the pullout tests carried out for the reference samples significantly depends on the type of FRP surface profile. The growth of “$\tau$” up to the values about 15 MPa was observed for a FRP#1 specimen with depressed winding (deformed bar) at a FRP slip of less than 0.3 mm after which the FRP slip in concrete attained 1–3 mm upon a slight growth in “$\tau$” attaining the maximum values $\approx$ 20 MPa and was characterized by an inflection of the “$\tau - \Delta$” curves in the figures. Then, the rebar occurred to
Table 2. Test results.

| Test                         | Cohesion strength, MPa, for different samples | at the reference values |
|------------------------------|-----------------------------------------------|-------------------------|
|                              | FRP#1 at 0.1 mm | FRP#2 at 0.1 mm | FRP#3 at 0.1 mm | FRP#4 at 0.1 mm | Steel at 0.1 mm |
| Reference samples            | 10.8            | 9.6            | 10.1            | 19.01           | 19.7            |
| Samples after SCP            | 10.9            | 9.4            | 8.8             | 20.6            |
| Temperature action upon tests| Heating up to +40°C | 10.8            | 10.9            | 10.6            | 21.7            | 18.8 |
|                              | Heating up to +80°C | 10.2            | 5.9             | 4.8             | 16.6            | 17.6 |
|                              | Cooling down to −40°C | 94.4%            | 97.9%           | 87.1%           | 108.4%          |
| Thermal cycling oscillations | 20 cycles       | 13.8            | 9               | 10.2            | 16.2            | 22.2 |
|                              | 40 cycles       | 127.8%          | 93.8%           | 101.0%          | 85.2%           | 112.7%          |
| Exposure in water            | 30 cycles       | 117.6%          | 109.4%          | 113.2%          | 101.5%          | 115.2%          |
|                              | 60 cycles       | 12.6            | 10.4            | 10.8            | 18.1            | 21.9 |
| Exposure in alkaline medium  | Exposure in concrete | 11.5            | 10.5            | 6               | 18.9            |
|                              | Exposure of rods | 106.5%          | 109.4%          | 59.4%           | 99.4%           | 4.1 |
| Influence of the strength of concrete | B12.5 | 12.7            | 10.5            | 11.43           | 19.3            | 22.7 |
|                              | 90.7%           | 84.0%           | 84.7%           | 83.9%           | 112.4%          |
|                              | 12.6            | 10.4            | 10.8            | 18.1            | 21.9 |
|                              | 90.0%           | 83.2%           | 80.0%           | 78.7%           | 108.4%          |
|                              | 12.7            | 10.5            | 11.43           | 19.3            | 22.7 |
|                              | 102.4%          | 102.9%          | 106.9%          | 89.4%           | 111.3%          |
|                              | 12.6            | 10.4            | 10.8            | 18.1            | 21.9 |
|                              | 101.6%          | 102.0%          | 101.0%          | 83.8%           | 107.4%          |
|                              | 12.7            | 10.5            | 11.43           | 19.3            | 22.7 |
|                              | 100.8%          | 101.0%          | 105.8%          | 106.6%          | 103.7%          |

be pulled out that was accompanied by a consequential wave-like decrease and increase in the load caused by inclusion of coils distant from the loaded end of FRP into the collaboration work. The pulled out FRP bars had partial surface damage between the depressed winding (cut-off of external layers of epoxy coating) and, generally, the destruction pattern at the boundary could be assessed as cohesion (via the material of the FRP bar).

Similarly to the previous samples, for the FRP#2 and 3 with roving pasted on the core, the
main growth of “τ” up to 12–13 MPa was observed at a insignificant slip of 0.3 mm, then the growth of stresses up to 14–15 MPa was accompanied by FRP bond failure in concrete and the significant slip attained 2 mm (for FRP#2) and 4.5 mm (for FRP#3). The load dramatically dropped after it attained the maximal value, and the sample was pulled out of concrete by the minimal efforts caused only by friction of the rebar core on the concrete surface. Figures 2b and 2c show the fracture pattern of the FRP#2 and 3 specimens. Only the core could be seen in the FRP specimens which were pulled out of the concrete cylinders, the roving were cut away and partially remained in concrete (that is clearly seen in figure 2c).

Upon the tests on the reference samples, the FRP#4 samples with sandy surface demonstrated the following features of the pullout: the growth of the tangent stresses up to the maximal values $\approx 16–20$ MPa occurred without any slip, after which the stresses dramatically decreased and the rebar was pulled out at minimal efforts. As figure 2d shows, the pulled out rebar were partially cut off including the sandy coating and external layers of epoxy binder over an area up to 50% of the contact zone, the cut of concrete on the rest of the area was fixed by the grains of sandy coating. No splitting of any concrete cylinders was observed upon the pullout test on FRP#4.

During the pullout test on the steel rebar, the tangent stresses “τ” increased up to $\approx 20$ MPa almost without any slip; afterwards the “τ − ∆” plot bent and a gradual slip of the rebar began.

Figure 2. Cross-sections of concrete cylinder after the pullout test on FRP#1 (a), FRP#2 (b), FRP#3 (c), and FRP#4 (d).
The maximal values of “τ” attained ≈ 22–26 MPa upon the slip on the free end of rebar of 0.3–0.5 mm; then the rebar specimens were gradually pulled out of the concrete cylinder, which was accompanied by a reduction in the tangent stresses. The rebar specimens, which were pulled out of concrete, showed no damage: both the rebar itself and the crescent-shaped coils remained undamaged; the bond failed at the “rebar-concrete” interfacial boundary due to the cut-off of concrete between the coils.

The strongly pronounced dynamics of the increase in the bond strength with an increase in the strength of concrete was established on the basis of the test results on the rebar specimens. However, this tendency developed differently for the specimens with unequal type of the surface relief.

For the FRP specimens with helically-deformed profile (depressed winding) — FRP#1, as the strength of concrete increased from 20.3 to 46.7 MPa, the maximal bond strength increased from 12.6 to 21.7 MPa (72.2%), but the further increase in the strength of concrete up to 98.9 MPa resulted in the maximal bond strength for FRP of only 24.7 MPa (an increase by 13.8%).

A similar tendency was found for the variations in the bond strength in the FRP#4 specimen with sandy surface: the main growth of the maximal bond strength from 14.3 to 22.7 MPa (increase by 58.7%) was observed when the strength of concrete increased from 20.3 to 46.7 MPa. The further increase in the strength of concrete up to 98.9 MPa led to the growth of the bond strength only by 14%.

The FRP#3 specimen with the winding pasted on the main bar showed an increase in the bond strength up to 59.2 MPa: the bond strength increased from 10.8 to 21.2 MPa (increase by 96.3%). A significant growth in the bond strength from 11.3 to 19.5 MPa was observed for the samples with winding (FRP#2) when the strength of concrete increased up to 79.5 MPa.

The maximal bond strength of the steel rebar varied directly with the strength of concrete. For example, when the class of concrete changed from B15 to B80, the maximal bond strength for the steel rebar increased from 19.4 to 35.7 MPa (increase by 84%).

The destruction pattern of FRP specimens also varied with the changes in the class of concrete. The minimal damages of the surface of specimens were observed when they were pulled out of concrete of B15 class and even B25: the sandy specimens were pulled out with the cut-off of concrete between the sand grains, the samples #1 with depressed winding also were pulled out without any damage with cut-off of concrete between the coils. The tests on the FRP#2 samples resulted in the cut-off of the lowest coils (distant from the plane of loading).

When the samples with winding were pulled out of concrete of B35 and B45, the cut-off was observed on the whole contact length. The damage of the surface epoxy coating was found for specimens with depressed winding (FRP#1). The pullout test on the FRP#4 specimen with sandy coating revealed the bond failure over an area up to 50% in the form of cut-off of the surface layer of epoxy and sand coatings, concrete was cut off between the sand grains. No damage was found after the pullout tests on the steel rebar. Upon the pullout tests for concrete of B60 and B80 classes, the rebar with depressed winding were extensively damaged; there was a cut-off of the epoxy coating and some segments with surface fibers. After the pullout tests, the specimens with sandy coating moved out with significant (up to 100%) damages (cut-off) of the sandy coating and surface layer of epoxy coating. The damage of the FRP#2 and 3 with winding has “classical” form — with the total cut-off of coils of the winding.

The tests on the steel rebar revealed an almost proportional growth of the bond strength with the strength of concrete. The damage of all specimens was in the form of the cut-off of concrete between the coils of rebar.

Thus, a limiting factor for the bond strength between concrete and FRP is the resistance to shear of the FRP surface profile, and, in the end, the resistance to shear of epoxy binder. This factor also determines the tensile strength of the polymer composite reinforcement.
4. Analysis of data on the pullout tests

It is well known that the bond between a rebar and concrete is a continuous binding over the entire surface contact between them. It has been recently established that three factors are responsible for the bond of the composite rebar with concrete:

- adhesion (pasting) of cement to the FRP surface ($F_d$);
- mechanical interaction between the rebar surface relief and concrete ($F_b$);
- friction ($F_f$).

The adhesion factor and mechanical bond work at the initial stage of loading, and after the slip starts (in our experiments, a slit of 0.1 mm at the unloaded end of a polymer composite rebar was considered as a criteria of the adhesion failure), the adhesion failed, and the resistance against pulling out is provided by friction and mechanical bond of the rebar profile.

Adhesion (pasting) of cement to the FRP surface ($F_d$) arises during the set and hardening of concrete and is determined by chemical and physical processes which lead to intermolecular (physical) bonds on the “cement–epoxy polymer” interfacial surface. The adhesion forces are inoperative at relatively inconsiderable bond stresses and displacements of a rebar. It is known that these (physical) bonds cause the polymer susceptibility to higher temperatures and its susceptibility to aggressive liquids.

Mechanical bond strength of the rebar with concrete ($F_b$) is determined by the protruding elements of rebar profile: coils and sandy coverage.

In the case of the rebar with a deformed profile (depressed winding), the value of mechanical bond strength is taken as the minimal value: the cut-off of concrete between the raised grooves of the rebar and bearing (cut-off) of spiral “oval” ribs, and can be described by the equations

$$F_b = R_{sh} \frac{\pi dbn}{\sin \alpha}, \quad (1)$$
$$F_b = f_{sh} \frac{\pi dsn}{\sin \alpha}, \quad (2)$$

where $R_{sh}$ is the shear resistance of concrete, $d$ is the rebar diameter, $b$ is the distance between the coils “in the clear”, $n$ is the number of coils along the contact length of the rebar in concrete, $f_{sh}$ is the shear strength of epoxy polymer, $s$ is the width of winding, and $\alpha$ is the angle of slope of coils to the longitudinal axis of the rebar.
Figure 5. Fragment of the FRP specimen with depressed profile.

Figure 6. Fragment of the FRP specimen with sandy coating.

Figure 7. Fragment of the FRP specimen with winding pasted on the rebar core.

In the pullout tests on specimens with sandy coverage, the bond failure resulted from the cut-off of cement (C) between the sand grains or of epoxy coating together with the sand grains. Upon the pullout of specimens with sandy coating, the destruction resulted from the cut-off of cement between the sand grains or of the epoxy coverage with sand grains. Therefore, the contribution from mechanical bond for the sandy rebar is taken as the minimal value of the shear strength of epoxy coating and cement between the sand grains (or a sum of two unequal values), that is approximated by the equations

\[ F_b = R_{sh} \frac{\pi dl}{2}, \]  
\[ F_b = f_{sh} \pi dl, \]  

where \( R_{sh} \) is the shear strength of concrete, \( d \) is the rebar diameter, \( l \) is the contact length (contact between a rebar and concrete), and \( f_{sh} \) is the shear strength of epoxy polymer.

For the rebar specimens with the pasted single- and double-helical winding, the value of mechanical bond is limited by the strength of pasting of winding and described by the equation

\[ F_b = f_{sh} \frac{\pi dsn}{\sin \alpha}, \]  

where \( d \) is the rebar diameter, \( n \) is the number of coils in the zone of embedment, \( f_{sh} \) is the shear strength of epoxy polymer, \( s \) is the width of winding, and \( \alpha \) is the angle of slope of coils to the longitudinal axis of the rebar.

The above-mentioned equations indicate that the mechanical bond for the FRP#1 and #4 with developed surface profile and sandy coating depends on both the strength of concrete and the shear strength of epoxy coating. For the FRP#2 and 3 with winding, the mechanical bond is constant and depends only on how firmly the winding is pasted to the core, but for low strength of pasting, the mechanical bond strength calculated by Eq. (5) is insignificant, and it can be neglected.

Friction \( (F_f) \) between the FRP surface and concrete. Several authors divide the friction into the static and dynamic terms. In our studies, due to low values of static friction, we include only the dynamic sliding friction in adhesion. The dynamic sliding friction arises after the failure of adhesion component at the moment of initiation of the rebar specimen slip in concrete.

The friction can be described by the equation

\[ F_f = \pi dl \mu N, \]  

where \( \mu \) is the friction coefficient for “epoxy coating–concrete” or “concrete–concrete” contacts, \( d \) is the diameter of rebar, \( l \) is the length of embedment, and \( N \) is the edging draft of the rebar specimen during the test.
Figure 8. Scheme of changes in stresses upon the pullout of FRP#1, 2, and 3.

Figure 9. Scheme of changes in stresses upon the pullout of FRP#4 and steel reinforcement.

It should be noted that, upon friction, the normal pressure on the rebar remains constant in reciprocal friction as against the mechanical bond at which the normal stresses from the arising thrust turn out to be alternating quantities which depend on the type of profile.

The bond stress $\tau$ is determined as a sum of three above-mentioned factors:

\[ F_p = F_d + F_b + F_f. \]  

Therefore, the changes in the tangent stresses, which were determined in the testing procedures, are attributed to the changes of one of the factors $F_d$, $F_b$, and $F_f$.

Summarizing the above results, the contribution of each factor throughout all stages of the pullout of FRP from concrete can be represented as the following plots shown in figures 8 and 9.

The foregoing plots can be fitted using the equations, which have been recently suggested
\[ \frac{\tau}{\tau_u} = B_1 \frac{s}{s_u} + B_2 \left( \frac{s}{s_u} \right)^2, \]
\[ \tau = \frac{P_1 s - P - 2}{s_u} \quad (s_u < s \leq s_r), \]
\[ \tau = \tau_r \quad (s > s_r), \]

where \( B_1 \) and \( B_2 \) are the coefficients determined from the results of tests for each type of FRP; \( P_1 \) and \( P_2 \) are the coefficients calculated from the equations

\[ P_1 = \frac{s_u \tau_r - s_r \tau_u}{\tau_u \tau_r (s_u - s_r)}, \quad P_2 = \frac{\tau_r - \tau_u}{s_u - s_r} \frac{s_u s_r}{\tau_r \tau_u}. \]

5. Estimation of the tangent stress distributions over the embedment length

In our work, we carried out the numerical simulations using an ANSYS software in order to assess the irregularity degree of tangent stress distribution along the embedment length and to examine the stresses arising both in the concrete sample and rebar. The obtained results showed that the tangent stress distribution along the embedment length is irregular to a wide extent. Therefore, the internal stresses in the embedded part of the rebar are also irregularly distributed depending on the stage of loading and the bond, which transmits the load from the bar to concrete. The analysis of pullout test results enabled us to indicate three main stages of stress strain behavior at the “FRP–concrete cylinder” contact:

1st stage (figure 10): elastic state in which the deformation of the loaded rebar is proportional to the applied force and, mainly, reversible. The stresses in the rebar decrease rapidly with distance from the loaded end, as well as the bond stresses whose maximal value is observed near the loaded end of the rebar over the sections no more than 30 mm with relatively low bond strength elsewhere. At this stage, the bond strength is determined by adhesion and mechanical bond.

2nd stage (figure 11): partially elastic state in which the linearity and reversibility of deformation are interrupted, but no displacements of free (unloaded) end of the rebar occur. At this stage, the angle of slope of the “\( \tau - \Delta \)” curve changes abruptly. With an increase in the applied forces, the peak of maximal bond stress is shifted towards the unloaded end of the rebar, which indicates nonsimultaneous inclusion of tangent stresses into collaboration and distribution over the surface. This fact is caused by a low elastic modulus of the composite reinforcement leading to elongation of the rebar along the embedment length under tensile loading and, as a consequence, to adhesion failure.

The further increase in the loading leads to an increase in the elongation meaning the failure of physical bonds of the rebar with concrete in this section and the redistribution of tangent stresses over the next sections, which were formerly unloaded. At this stage, the mechanism of transmitting the stresses from the rebar to concrete is irregular: the elastic action of bond forces remains near the unloaded end of rebar, the concrete in the contact layer in the middle of the sample is most loaded, and the zone of contact is entirely destroyed near the loaded end.

3rd stage (figure 12): slip state when the rebar shifts relatively to concrete along the total embedment length. The maximal bond stresses are drawn towards the unloaded face of the sample. At the starting of embedment, the concrete in the contact layer is destroyed, but the particles of broken concrete still provide friction and splitting stresses. At this stage, an increase in the loads applied to the rebar leads to an intensive displacement of the loaded end. The embedment breakdown is the result of disintegration of the contact layer in concrete or epoxy binder on the FRP surface, or it occurs after the splitting of the sample.
In regard to the concrete construction subjected to bending, which is reinforced by FRP, the tangent stress distribution can be described as is shown in figure 13. In the case of concrete beams reinforced by FRP, this manifests an increase in the number of cracks and a decrease in the spaces between them for the same loading and reinforcement ratio as in steel reinforcement.
Conclusions

1. Following the results of pullout test, it was established that regardless the type of surface profile, the bond strength is most sensitive to temperature: when heating up to +80°C, the bond strength is reduced by 49%, and conversely, when it is cooled down to −40°C, the bond strength increases by 21–36%. The exposure of the rebar in the caustic solution followed by the concrete casting also results in a decrease of the bond strength. The maximal drop of the strength by 79% was observed for specimens. The effect of other operational and technological factors on the bond strength is insignificant for all types of FRP regardless the surface profile.

2. An increase in the strength of concrete provides a proportional increase in the bond strength of all types of FRP. The maximal bond strength is limited by the strength of composite material, the shear resistance of the polymer binder, and its adhesion to the fiber filler and grains of sandy coverage. Therefore, when the limiting values (different for each FRP) are attained, the increase in the strength of concrete has almost no effect on the bond strength, in contrast to the direct growth of the bond strength in steel reinforcement.

3. As a result of study, the pattern of the stressed state of concrete and FRP is suggested, as well as their contact boundary upon the rebar pulling out. It was established that the tangent stress distribution along the pulled out rods was irregular and had a pronounced peak at the length of 30 mm, which moved in loading from the loaded end of FRP to its unloaded end. This peak of stresses was attributed to the lower elastic modulus of polymer composite reinforcement compared to concrete, and, as a consequence, to significant elongations of the rebar under loading and nonuniform inclusion into their collaboration.

4. Physical models of the bond between concrete and a series of FRP of four types were theoretically represented and examined as a sum of three factors: adhesion of concrete to polymer surface, mechanical bond with protruding profile elements, and friction.

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