Numerical modeling of composite reinforcement with concrete

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Abstract. Composite reinforcement is a good alternative to metal, for its high tensile strength, but its scope is limited due to its low deformation modulus and adhesion to concrete. The aim of the work is to propose a numerical model of the interaction of composite reinforcement with concrete in order to be able to simulate the operation of plastic-concrete (polymer-composite) structures of transport structures. During the study, the authors conducted a series of experiments to assess the strength of adhesion to concrete, the results of which were used to construct the “pulling force – reinforcement slippage relative to concrete” relationship. To approximate this relationship, a linear piecewise function was proposed, which was later used to implement a numerical model based on linear constraints with finite rigidity.

1. Introduction

Composite rebar takes an increasingly strong position in modern construction. This is due to indicators such as high strength, high corrosion resistance, low thermal conductivity and other useful properties of the valve. Enumerating the advantages and disadvantages. The main disadvantage of composite reinforcement is the low deformation modulus, which is closer to concrete than to steel, which slows down the inclusion of composite reinforcement in operation.

Another serious drawback is poor adhesion between concrete molecules and composite reinforcement, which reduces adhesion between materials [1]. To solve these problems, today a wide range of composite reinforcement has been created, where roving with fiberglass, basalt-plastic and carbon-plastic fibers, the creation of various types of artificial irregularities on the surface of the reinforcement, such as various types of windings or a sand layer of quartz sand, are used to bond concrete to reinforcement [1].

It is known that the interaction of concrete and reinforcement, as a whole, occurs due to three factors [2]: mechanical fixation of reinforcement to concrete, in the presence of irregularities on the surface of the reinforcement, friction between concrete and reinforcement, molecular interaction (adhesion). The description of complex multi-parametric interaction of concrete and composite reinforcement is characterized by the curve of “tension of adhesion - slippage of reinforcement relative to concrete”, or alternative dependence “pulling force - slippage of reinforcement relative to concrete” [3, 4, 5]. Such a curve can be constructed using the experimental method of pulling the rod out of the cube (Pull-out test) according to RILEM/CEB/FIB [3,6].
2. Conduct an experiment

The authors conducted an experiment on 5 samples of fiberglass “sandy” reinforcement (FG) with a diameter of 6 mm on a test facility (Figure 1). The installation is a movable and fixed platform, the pulling force is generated by a hydraulic jack with a smoothness of 1 mm per minute, and the movement of the reinforcement is recorded using dial gauges. During the preparation of the experiment, specimens with dimensions 100x100x100 mm of fine-grained concrete of class B30 were poured, the FG has a length of adhesion area with concrete $5d = 30$ mm. The test results of the samples are shown in Table 1 and in Figure 2 as graph 1.

![Figure 1. Test facility. 1 - fixed platform; 2 - mobile platform; 3 - sample for testing; 4 - two indicators with a scale of 0.01 mm; 5 - traction device](image)

| Sample Number | Tangential stresses $\tau$, MPa | Maximum displacement of the rod before pulling out $\Delta$, mm | Pulling force $F$, kN |
|---------------|-------------------------------|-------------------------------------------------------------|----------------------|
| 1             | 11.85                         | 0.4                                                         | 6.70                 |
| 2             | 10.70                         | 0.45                                                        | 6.05                 |
| 3             | 11.50                         | 0.46                                                        | 6.50                 |
| 4             | 10.61                         | 0.38                                                        | 6.00                 |
| 5             | 11.23                         | 0.45                                                        | 6.35                 |
| The average   | 11.178                        | 0.428                                                       | 6.32                 |

According to the test results, it was established that the destruction of all samples under the action of pulling force occurs along the boundary layer between concrete and reinforcement. As a result, concrete is destroyed, due to the limited operation of concrete for shear and stretching, and partly sandy sprinkling of fiberglass reinforcement, due to the weak bond between sand particles and fiberglass. The stress distribution over the adhesion surface is not uniform, due to the work of the composite reinforcement binder and the non-uniform distribution of sand over the reinforcement surface. When two materials come into contact in small areas, zones of large tangential stresses are formed that exceed the allowable ones, which leads to cutting off the most prominent sand particles from the plane of the rod and leads to local slippage of the rod [7, 8]. This phenomenon was recorded during testing of samples, as a result of which the indicator readings did not change smoothly, but in steps.
The diagram “pulling force - slippage of reinforcement relative to concrete”, obtained as a result of the experiment is shown in graph 1 (fig. 2). In the curvilinear dependence of the movement of fiberglass reinforcement $\Delta$ on the pulling force, three zones can be clearly identified. The first zone is a linear section of the graph $F(\Delta)$, when at small values of the pulling effort in concrete elastic deformations of the concrete occur, when the load is removed, the reinforcement returns to its original position. With a further increase in force $F$, shear cracks and areas with local slippage appear, which increases the speed of movement of reinforcement relative to concrete in zone 2. Zone 3 exhaustion of the bearing capacity of concrete, reinforcement still has adhesion to concrete due to non-damaged areas and friction forces [2]. It should be noted that similar studies of reinforcement have already been conducted by the authors [1] and the results as a whole, with some discrepancies due to different manufacturers of reinforcement, are consistent with previous experiments.

![Graph of displacement of fiberglass reinforcement](image)

**Figure 2.** Graphs of the displacement of fiberglass reinforcement $\Delta$ from the pulling force $F$, 1 - according to test results; 2 - for numerical simulation

### 3. Constitutive equations

The paper proposes a numerical model of the adhesion of concrete with composite reinforcement (FG) based on the finite-element method, for further use in the analysis and prediction of the stress-strain state of various (polymer-composite) structures of transport facilities. Therefore, it will be necessary to compare and analyze already developed models of interaction between concrete and metal reinforcement and to propose a numerical model for fiberglass reinforcement, which most closely agrees with the empirical data obtained as a result of the experiment and is available for use in more complex structures.

There are 7 classes of models of adhesion of concrete and reinforcement [2]:
- the model of ideal adhesion of reinforcement and concrete;
- the model with the addition of an additional layer with a reduced deformation modulus;
- the model using links with finite stiffness;
- the model with shutdown of destroyed items from work;
- the model taking into account microcracking;
- the model of elastic-damaged material;
- the model with elastic - plastic - damaged material.
The most common are the first three models, the other models require high-level software packages, like ANSYS, Nastran, ABAQUS, and others. The model of ideal adhesion of reinforcement and concrete does not take into account the discontinuity of the medium and microcracking, however, it is widely and widely used in numerical calculations of reinforced concrete elements, since the loss of the bearing capacity of reinforcement is achieved faster than the adhesion between reinforcement and concrete is lost. It is easy to prove, if we equate the pulling force to the bearing capacity of the reinforcing bar - then we get the expression:

\[ \tau \cdot C_b \cdot l = R_f \cdot A_f, \]

where \( \tau \) is the average bond stress, \( C_b \) is the equivalent circumference of the rod from the FG, \( l \) is the length of the embedment in concrete, \( A_f \) is the area of the reinforcement, \( R_f \) is the calculated resistance of the composite reinforcement to tensile. The moment of loss of bearing capacity of a composite rod with a diameter of 6 mm and a seeding depth of 15 sm as a result of loss of adhesion will occur with the bearing capacity of the reinforcement \( R_f \)

\[ R_f = \frac{\tau \cdot C_b \cdot l}{A_f} = 1200 \text{ MPa}, \]

which is more resistance to stretching, obtained as a result of an experiment of 1100 MPa. Therefore, this model is consistent in assessing the strength of the structure, but is unacceptable in assessing the deformation of structures.

The model with the addition of an additional layer with a reduced initial modulus of deformation requires a more detailed discretization of the computational model, namely, the use of bulk finite elements with a small grid breakdown for concrete, reinforcement and the boundary layer itself, which is not allowed for calculating complex computational schemes, as it will require large time costs.

The model based on the use of bonds with finite stiffness is considered the most logical, and also has the greatest consistency with the experimental and theoretical results of adhesion of metal reinforcement to concrete [2]. This model allows to take into account non-linear displacements of reinforcement relative to concrete in the process of destruction of cohesion bonds. For the numerical description of the model, it is required to introduce additional elements with finite stiffness or otherwise flexible connections. The authors of [2] proposed to use nonlinear springs, the properties of which are described according to the diagrams of adhesion between reinforcement and concrete. This type of CE is not available in all design complexes; therefore, it is necessary to simplify the model, namely, nonlinear springs should be replaced with linear springs with a limiting force for tension or compression. Then, to approximate the nonlinear diagram of reinforcement adhesion with concrete, presented in graph 1 (Fig.2), it is proposed to use the piecewise linear function shown in graph 2 (Fig.2), which is described by the formula:

\[
S(F) = \begin{cases} 
\frac{F}{\Delta} & \text{at } F < F_{\text{pref}} \\
0 & \text{at } F \geq F_{\text{pref}} 
\end{cases}
\]

Then the stiffness of each bond is assigned from the condition

\[ S(F) = F_{\text{pref}} / \Delta \cdot N, \]

where \( F_{\text{pref}} \) is the pulling effort; \( \Delta \) is the displacement of the reinforcement relative to the concrete; \( F \) is the longitudinal force in the reinforcement; \( N \) is the number of links (springs) in the design scheme. When reaching the force in the links more \( F_{\text{pref}}/N \) they are turned off from work.

Further, in the work, with the help of the proposed model, the full-scale experiment on the adhesion of SPA to concrete was recreated by numerical methods using numerical methods. The design model of the experimental sample consisted entirely of bulk finite elements, the characteristics for concrete were set for class B 30, the strain modulus for fiberglass reinforcement was 55000 MPa, the calculated compressive resistance 800 MPa with extreme relative deformations 0.0035. The problem was solved by a step method in a nonlinear formulation, with a final load of 6 kN. The modeling results, for
computational schemes with different number of input linear relationships, are presented in Figure 3, 4 and Table 2.

**Table 2. The modeling results**

| Number of links, pcs | 40  | 60  | 80  | 100 | 120 |
|----------------------|-----|-----|-----|-----|-----|
| Rebar offset relative to the upper face of the concrete cube $\Delta$, mm | 0.1345 | 0.122 | 0.1156 | 0.1114 | 0.108 |
| Deformations of concrete $\Delta_{b}$, mm | 0.0172 | 0.0128 | 0.0104 | 0.0095 | 0.0063 |
| Rebar displacement relative to deformed concrete $\Delta_{c}$, mm | 0.1173 | 0.1092 | 0.1052 | 0.1045 | 0.1017 |
| Relative deviation of the result from the field experiment, % | 34.5 | 22  | 15.6 | 11.4 | 8  |

**Figure 3.** The results of numerical modeling of the coupling of composite reinforcement with concrete: isopole displacement of reinforcement relative to concrete.

**Figure 4.** The results of numerical modeling of the coupling of composite reinforcement with concrete: isopole of adhesion stresses to concrete.
4. Discussion of the results and conclusions

Analysis of the obtained values shows that, in addition to the deformation of the bonds themselves, there are deformations of the concrete of the boundary zone, which together give the desired displacement of the composite reinforcement relative to the upper concrete face \( \Delta = \Delta b + \Delta c \) (Fig. 3, 4). The difference between the data taken in the field experiment in the form of a piecewise linear dependence and the numerical experiment differ by the value of the relative deviation from 8% to 34.5% depending on the number of bonds. That is, with an increase in the number of connections being made, it is possible, firstly, to reduce the concrete deformations \( \Delta b \), and secondly, to increase the convergence between the experimental and numerical indicator of the displacement of reinforcement relative to the upper face \( \Delta \). Therefore, when solving a specific task, it is necessary to solve test problems that will allow determining the value of the required number of bonds simulating the reinforcement adhesion to concrete with the required accuracy.

According to the results of the experiments, a “pulling force — reinforcement slipping” diagram of “sandy” composite reinforcement (FG) with a diameter of 6 mm relative to concrete was constructed on the samples. The average axial wrestling force was 6.32 kN, the friction voltage was 11.178 MPa, which is less than the standard [3].

For numerical modeling of composite reinforcement adhesion to concrete, a model is proposed based on linear relationships with extreme stiffness (springs), which showed good convergence in modeling adhesion of metal reinforcement to concrete. To describe the work of the bond under load, it is proposed to use the piecewise linear function (1) shown in graph 2 (Figure 2), and the rigidity of each bond is assigned from the condition \( S(F) = F_{pef}/\Delta \cdot N \). At achievement of effort in communications more than \( F_{pef}/N \) communications are switched off from work.

The number of links entered is directly proportional to the accuracy of a numerical experiment. To differentiate the accuracy of the tasks to be solved, it is necessary to adjust the number of links entered on test problems.

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