Calculation of reinforcement to concrete adhesion in reinforced concrete elements

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Abstract. A model and method for calculating of reinforcement to concrete adhesion in reinforced concrete elements have been developed. The basic parameters by means of which it is possible to control interaction of reinforcement with concrete at any stage of a reinforced concrete element deformation are defined. These parameters are associated with the processes of formation and development of normal cracks. A criterion is proposed by which it is possible to determine the adhesion forces of a reinforcing rod with concrete along its conditional cylindrical surface and to estimate, thus, the degree of violation of their interaction. It is recommended to calculate the specified efforts in the simplest way: by means of average stresses of reinforcement with concrete adhesion on sites between adjacent cracks. It is statistically substantiated that the function of these stresses is nonlinear with respect to normal stresses in the reinforcement. An analytical dependence is proposed to calculate the coefficient taking into account the profile of the reinforcement (its adhesion index to concrete).

1. Introduction

The general theory of reinforcement to concrete adhesion, which would meet the basic requirements of design engineers, has not yet been built. And the current situation is due to the results of numerous studies [1-4], which show that the adhesion of reinforcement to concrete depends on a very large number of different factors. It is extremely difficult, and sometimes even impossible, to take into account their joint influence in modeling the interaction of reinforcement with concrete. Therefore, it is not surprising that the methods and algorithms for calculating reinforced concrete elements and structures regulated in domestic and foreign regulations [5, 6], almost completely ignore the interaction of reinforcement with concrete.

In general, all currently known studies of reinforcement to concrete adhesion can be divided into the following four areas:

- identification of the main parameters that most affect the strength of adhesion [2];
- study of general patterns of mutual displacements of concrete and reinforcement [1, 4];
- creation and development of a general technical theory of adhesion [4];
- modeling of reinforcement to concrete adhesion with numerical methods [7].

However, the ambiguity of the results obtained in these works and the lack of a universal theory of reinforcement to concrete adhesion encourage further research on its construction. And a special role in solving this problem should be given to a generalized model of reinforcement to concrete adhesion.

2. Analysis of recent research and publications

The results of research known today, aimed at modeling the interaction of reinforcement with concrete, not only differ significantly from each other, but also often contradict each other. This situation is quite natural and understandable, because it is due to the results of experimental studies, which were different: the shape and size of the samples for different types and classes of concrete and reinforcement; reinforcement schemes and conditions of concrete compaction, and therefore the nature of the contact layer formation; technological features of concrete care; schemes and conditions of prototypes testing; hypotheses and preconditions for theoretical research and the like.
It is indisputable that the classification of reinforcement to concrete adhesion models would allow not only to systematize the research itself, but also to organize their results in a certain way. These models could be divided into many features, the main of which should still be considered:

- scale and structure of the model;
- representations of concrete and reinforcement in the system of their contact interaction;
- test schemes and the nature of the concrete destruction at the contact boundary "concrete-reinforcement";
- mathematical solutions of reinforcement with concrete interaction schemes.

The last sign on which all models of reinforcement with concrete adhesion should be conditionally divided into analytical and numerical deserves special attention. In general, analytical models are presented in the form of mathematical equations (formulas) that characterize the functional dependence of research results on certain initial factors or parameters. By the nature of the mathematical dependences of the adhesion model can be divided into: linear (elastic), nonlinear (elastic-plastic), differentiated and variational.

Elastic models have found the widest application in researches of reinforcement with concrete adhesion. Now they represent mainly power, polynomial, exponential, fractional, logarithmic [4], trigonometric dependences, and most often spline functions [2]. But the results of experimental studies show that the diagram of the stresses of reinforcement to concrete adhesion along the area of their contact is constantly changing (Figure 1), and therefore cannot be described by a single function.

![Diagram of the change in adhesion stresses when pulling out a reinforcing bar from concrete.](image)

Differentiated models, unlike others, take into account the variability of the diagrams of reinforcement to concrete adhesion along the area of their contact in the sections of a reinforced concrete element [3, 8]. However, it is extremely difficult to assess the change in the stress-strain state of the contact interaction of reinforcement with concrete using such diagrams in practical calculations, even by numerical methods.

In variational models [9], concrete around the reinforcement is divided into three characteristic zones, which makes it possible to fairly accurately simulate its stress-strain state based on the solution of the symmetric-axial volumetric problem of a deformable solid mechanics. However, given the complexity of determining the mechanical characteristics of concrete in each zone, these models have not found practical application even in calculations using the finite element method.

In numerical models, studies are always carried out using specific numerical characteristics - finite elements, depending on the selected shape of the relief (profile) of the reinforcement. The contact layer of concrete is modeled, starting from the ideal adhesion scheme to the scheme of elastic-plastic damaged material [7]. The solution of the problems of reinforcement to concrete adhesion according to the given schemes is so complicated that it can be done only with the help of special computer programs. Among the latter, the most widely used software systems are ABAQUS, ANSYS, DIANA,
NASTRAN and others. All of them are endowed with rather broad functional capabilities, but for the overwhelming majority of them, the description of SSS in the zone of reinforcement to concrete adhesion remains rather complicated, which noticeably limits their widespread use in practical calculations when solving contact problems in reinforced concrete.

3. The purpose and objectives of research
These studies are aimed at developing a generalized model of reinforcement to concrete adhesion, which would be valid for any stage of reinforced concrete elements deformation and would satisfy the basic requirements of design engineers. It is appropriate to base such a model on the function of a universal parameter - the forces of the reinforcement to concrete adhesion along its conditional cylindrical surface. In this case, the main task of these studies is to obtain the specified function, taking into account the nonlinear relationship of the average bond stresses from the normal stresses in the reinforcement.

These studies are based on mathematical modeling of the deformation processes of reinforced concrete elements and structures in general, as well as analytical and numerical methods of mathematical analysis of reinforcement to concrete adhesion parameters (forces, stresses) along its conditional cylindrical surface in particular.

4. Results and discussion
It should be noted right away that the generalized model of reinforcement to concrete adhesion is based on the basic relationships of solid mechanics (SDM), expressed by the well-known system of static, geometric and physical relationships (equations) [10, 11]. The defining elements of the developed model will be considered:
• the main modeling parameter, with the help of which it would be possible to reliably estimate the reinforcement to concrete adhesion;
• the main criterion by which it would be possible to fix violations of the reinforcement to concrete adhesion;
• the most important parameters by which it would be possible to monitor the reinforcement to concrete adhesion at any stage of a reinforced concrete element deformation.

The main parameter by which it is possible to fairly easily evaluate the adhesion of reinforcement to concrete is the adhesion force $N_{bd}$. According to the numerous results of experimental studies, it can be argued that they cannot exceed the forces in tensile concrete $N_{ct}$. That is, violation of the condition

$$N_{ct} = N_{bd},$$

(1)

responds not only to the appearance of the first crack, but also to all others without exception.

The appearance of the first crack does not directly depend on the adhesion of the reinforcement to the concrete. Therefore, its occurrence in a reinforced concrete element can be determined by the ultimate deformations of tensile concrete $\varepsilon_{cu}$, which are fixed by the extreme criterion of its bearing strength $dM_{ct} / d(1/r) = 0$ ($dN_{ct} / d\varepsilon_{ct} = 0$). Compliance with the current norms [5, 6], they can even be taken equal $\varepsilon_{cu} = 2f_{cd}/E_{ct}$. The application of the criterion $dM_{ct} / d\varepsilon = 0$ for determining the moment of the cracks appearance [12] is somewhat incorrect, since only the tensioned concrete loses its bearing strength, and not the element as a whole. In addition, the expression $dM / d\varepsilon = 0$ is not endowed with some kind of physical content, so it cannot serve as a criterion at all. The Fermat criterion $dM / d(1/r) = 0$ is endowed with a similar content, since they characterize the rigidity ($EA$ - for centrally loaded concrete and reinforced concrete elements, $EI$ - for bending and eccentrically loaded elements), at which these elements lose their bearing strength.
When any new crack appears, the ultimate bond force $N_{bd,cr}$ in the section between the cracks according to (1) will remain unchanged and equal to the ultimate force in tensile concrete $N_{ct,cr}$ (Figure 2). Then, for an element stretched in the center, we can write the equality

$$\tau_{bmi} \cdot s_{r1} = \tau_{bm2} \cdot s_{r2},$$

(2)

where $s_{r1}$ and $s_{r2}$ are the distances between the cracks of the first and second levels, respectively; $\tau_{bmi}$ and $\tau_{bm2}$ - average adhesion stresses in areas between cracks of the same levels, respectively.

![Figure 2. Changes in the adhesion forces of reinforcement to concrete with multilevel formation of normal cracks in a reinforced concrete element.](image)

The adhesion stress of the reinforcement to the stretched concrete in the area between the cracks of the first level can be calculated by a fairly simple expression [13, 14]

$$\tau_{bmi} = \eta_1 \cdot \eta_2 \cdot f_{ck} \cdot (\sigma_{sl} / \sigma_{s,max})^{1-1/\eta_1},$$

(3)

where $\sigma_{sl}$ is the greatest stresses in the reinforcement at the site of its active adhesion to the stretched concrete at a certain stage of the reinforced concrete element deformation; $\sigma_{s,max}$ - the maximum possible stresses in the stretched reinforcement on a site of its active adhesion with the stretched concrete, cannot exceed limit values ($\sigma_{s,max} \leq f_{yk}$); $\eta_2$ - the coefficient taking into account the influence of the reinforcement diameter can be taken according to current regulations [5, 6]; $\eta_1$ is the coefficient characterizing the profile of the reinforcing bar according to the adhesion index $f_R$ (Figure 3), can be taken by the expression [15]

$$\eta_1 = 1 + 35 \cdot f_R - (12 \cdot f_R)^2,$$

(4)

which at the confidence interval in $2\sigma$ ($\sigma$ - standard deviation) takes the form [16]

$$\eta_1 = 1 + 29 \cdot f_R - 120 \cdot f_R^2.$$

(5)
Figure 3. Relationship of the coefficient $\eta_1$ with the index of adhesion of reinforcement to concrete $f_R$.

Analysis of the experimental studies results by various authors [19-22] showed that the dependence of the average adhesion stresses on the stresses in the reinforcement itself is closer to the nonlinear function (3).

This is evidenced by the results of a corresponding comparison of experimental and theoretical values of the average adhesion stresses (Table 1), calculated including by the linear function (6) [12]

$$\tau_{m,i} = f_{emin} \cdot ((\eta_1 \cdot \eta_2 - 0.4) \cdot \sigma_{si} / f_{yd} + 0.4).$$

Table 1. Comparison of theoretical and experimental values of reinforcement to concrete adhesion average stresses.

| Authors    | Rebar profile and diameter, mm | Deviation from experimental data by formula |
|------------|--------------------------------|--------------------------------------------|
|            |                                | $\Delta$ | $\sigma$ | $\nu$,% | $\Delta$ | $\sigma$ | $\nu$,% |
| Colner V [19] | Periodic 20                   | 1.00   | 1.73    | 1.73     | 1.08 | 5.27   | 4.88     |
| Adrouche K [20] | Periodic 16                  | 0.995  | 2.00    | 2.01     | 1.01 | 2.32   | 2.30     |
| Rashedul K [21] | Periodic 20                  | 0.994  | 2.29    | 2.30     | 1.051| 4.48   | 4.26     |
| Samoshkin A [22] | Periodic 16                 | 0.998  | 2.28    | 2.29     | 1.023| 2.76   | 2.70     |

$\Delta$ - mean deviation.
$\sigma$ - standard deviation.
$\nu$ - coefficient of variation.

Similarly, the average adhesion stresses are determined in the areas between cracks of all subsequent levels. As the results of experimental studies show, their number for the operational stage of deformation can be limited to two levels [23].

It should be noted that equality (2) is in the form

$$\tau_{bm2,1} \cdot S_{r2,1} = \tau_{bm2,2} \cdot S_{r2,2}$$

remains valid for bending elements (Figure 4).
5. Conclusions

According to the obtained results, it is recommended to model the reinforcement with concrete interaction with the help of adhesion forces, as their limit values remain unchanged in the process of the reinforced concrete element deformation. Adhesion forces are suggested to be calculated in the simplest way - by means of average adhesion stresses. The function of the average adhesion stresses is nonlinear with respect to the stresses in the valve itself. It is expedient to regulate the crack formation processes in reinforced concrete elements by the parameters of reinforcement adhesion with concrete [14, 24], which will contribute to the construction of an adhesion universal theory within the generalized deformation-force model of reinforced concrete elements and structures resistance to force.

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