Evaluation of bond between reinforcement and concrete

Olena Romashko[1], and *Vasyl* Romashko[1,*]

[1]National University of Water Management and Nature Recourses Use, Architectural Designing Bases, Constructing and Graphics Department, Soborna str. 11, 33028 Rivne, Ukraine

Abstract. The scheme of stressed state changes of the concrete contact layer and reinforcing rod during its pulling out of concrete is considered. The most important drawbacks of the known methods for evaluating the bond strength of reinforcement to concrete have been analyzed. Particular attention is focused on bond estimating by average tangential stresses. It is substantiated why the linear dependence of these stresses on normal stresses in the reinforcement cannot cover the processes of reinforcement bonding with concrete in the stage of use of reinforced concrete elements. A universal dependence of the average tangential stresses for estimating the reinforcement bond to concrete at any stage of elements deformation is proposed. Statistical evaluation of the obtained dependence was made on the basis of theoretical and experimental values of the average tangential bonding stresses comparison. The area of use of reinforcement bond with concrete average stresses dependence is defined.

1 Introduction

Concerning the reinforcement bond with concrete has always been one of the most important issues in the theory of reinforced concrete. It is well known that, together with the design measures of anchoring, the bond provides a consistent operation of reinforcement and concrete in structures, reflecting the essence of the reinforced concrete itself.

Of particular importance are the issues of reinforcement bond with concrete in the calculation of reinforced concrete elements for crack resistance, as well as in their designing for determining the length of the rods anchoring. It should be emphasized separately that the calculation of pre-stressed elements and elements with mixed reinforcement, even with simplified methods, as well as their designing, can not be realized without consideration of reinforcement bond with concrete.

In general, today numerous models, theories and methods for estimating the reinforcement bond with concrete have been proposed. However, despite the results of extensive experimental and theoretical research, the overwhelming majority of mentioned models, theories and methods [1-5] remain rather complicated and unsuitable for use in engineering calculations.

[*] Corresponding author: romashkovasyl@gmail.com

2 Analysis of recent studies and publications

Early research was mainly aimed at estimating the reinforcement bond strength with concrete that was extremely important for calculating the anchoring of reinforcing rods. The criteria for the bond strength are usually taken:

• average values of tangential stresses along the conditional cylindrical-drill surface of the reinforcing rod in the limiting deformation stage τ_{bmu} [6];

• the forces corresponding to the beginning of the displacement of the unloaded end of the rod $\sigma_{\text{sb}} A_{\text{s}}$ or the general destruction of the sample when the concrete reinforcement is pulled out $\sigma_{\text{su}} A_{\text{s}}$ [1];

• coefficient of completeness of the diagram of stresses arising in the rod along the length of its laying in concrete from the external forces action at the limiting deformation stage $\alpha = \int_0^l \sigma_{\text{s}}(x) \cdot dx / (\sigma_{\text{y}} \cdot l)$ [7];

• maximum (peak) tangential bond strain at critical displacement of reinforcement relative to concrete s_1 on the diagram $\tau_{\text{b}} - s$ [2, 8].

Although each of the above methods has its own disadvantages, one disadvantage is common for all of them – the limited use of the above criteria for coupling only for the limiting stage of deformation of reinforced concrete elements.

A noticeable extension of modern studies of reinforcement bond with concrete is largely associated with the crack resistance of reinforced concrete elements in general and with the cracks formation levels in them in particular [4, 9]. In such circumstances, there is a need to estimate the reinforcement bond with concrete not only in the limit, but also in the operational stages of reinforced concrete elements deformation. The overwhelming majority of researchers propose to solve a similar problem with the help of the diagram "tangential bond stresses – displacement of reinforcement relative to concrete" [4, 5]. However, the description of this diagram as the only analytical function remains rather problematic.

The attempts by individual researchers to estimate the reinforcement bond with concrete by average tangential bond stresses along the surface of the reinforcing rod at any stage of reinforced concrete element deformation are also known [9]. However, the linear function proposed for the calculation of these stresses causes a series of warnings:

• in the absence of normal stresses in the reinforcing rod ($\sigma_{\text{si}} = 0$), the average tangential bond stresses does not equal zero ($\tau_{\text{bmi}} \neq 0$);

• dependence cannot describe the bonding processes to the crack formation and after the shift of the reinforcing rod unloaded end;

• the function is purely empirical and cannot reflect the essence of the physical patterns of reinforcement bond with concrete at intermediate stages of reinforced concrete element deformation.

3 Issues not solved within the common problem

In the theory and practice of calculation of the reinforced concrete elements the reinforcement bond with concrete is proposed to be evaluated by complex mathematical dependencies $\tau_{\text{b}} - s$, the determining parameters of which, however, need to be installed experimentally. However, in most cases, neither type of fittings, nor geometric characteristics of its section, nor the type of concrete, etc., are taken into account. In addition, the models, theories and laws, methods and techniques for assessing the reinforcement bond with concrete proposed by the researchers, differ from each other, not only functionally, but formally. This is due to both subjective and objective reasons, including the influence of a large number of powers, deformation, structural and technological factors on the patterns of reinforcement bond with concrete. In other words, the evaluation of reinforcement bond with concrete due to the inevitable integration of dependence $\tau_{\mathrm{b}} - s$ along the laying area of reinforcing rod remains a rather difficult task even with the use of special software.

The linear function of the reinforcement bond with concrete average stresses, proposed in [9], due to the above-mentioned disadvantages, can not be recommended for engineering calculations. It is obvious that only a nonlinear function of the reinforcement bond with concrete average stresses can cover all the stages of reinforced concrete element deformation.

4 Purpose and objectives of the study

The purpose of the study is developing an engineering method for estimating the reinforcement bond with concrete at any stage of reinforced concrete elements deformation. Of all the above-mentioned methods for estimating the reinforcement bond with concrete, the advantage is given by the average tangential bond stresses along the conditional cylindrical surface of the reinforcing rod. The main task of the study is obtaining a universal nonlinear dependence of these stresses from normal stresses in the reinforcement when squeezing it out of concrete.

5 Results and discussion

Each of the aforementioned methods for estimating the reinforcement bond with concrete has its own disadvantages, by which they mainly differ. However, the common to these methods is that they are all one way or another aimed at determining the effort of reinforcement bond with concrete at a certain stage of reinforced concrete element deformation.

Undoubtedly, the most simple bond effort can be determined at any stage of deformation, if the function of the average tangential stresses of reinforcement bond with concrete is known. To establish its character we consider the change scheme and the features of the stressed state of the concrete contact layer and reinforcing rod when it is removed from concrete (Fig. 1).

I – conditionally elastic stage. With a little effort, the concrete and reinforcement are deformed almost elastically: the diagram of normal stresses in the rod is close to the triangular, the maximum tangential bond stresses τ_{bmax^2} arise near the loaded end of the concrete sample, and their average values can be assumed to be approximately equal $\tau_{\mathrm{bm}^2} = \tau_{\mathrm{bmax}^2} / 2$.

II – elastic-plastic stage. The appearance of noticeable plastic deformations in concrete leads to distortion the reinforcement normal stresses pattern, the maximum tangential bond stresses τ_{bmaxI^2} remain close to the loaded end of the concrete sample, but the completeness coefficient of the diagram of the specified stresses $\tau_{\mathrm{bm}^2} / \tau_{\mathrm{bmax}^2\mathrm{I}}$ begins to grow.

III – offset stage. At significant displacements of the rod loaded end may occur not only plastic concrete deformation under its projections, but also partial concrete destruction in the contact layer. Maximum tangential bond stresses τ_{bmaxII^2} gradually shifted to the concrete sample unloaded end with constant growth of the diagram completeness coefficient of the specified stresses $\tau_{bm^2} / \tau_{bmax^2II}$.

IV – destruction stage. The slightest increase in effort is accompanied by the slipping of the reinforcing rod throughout its length.

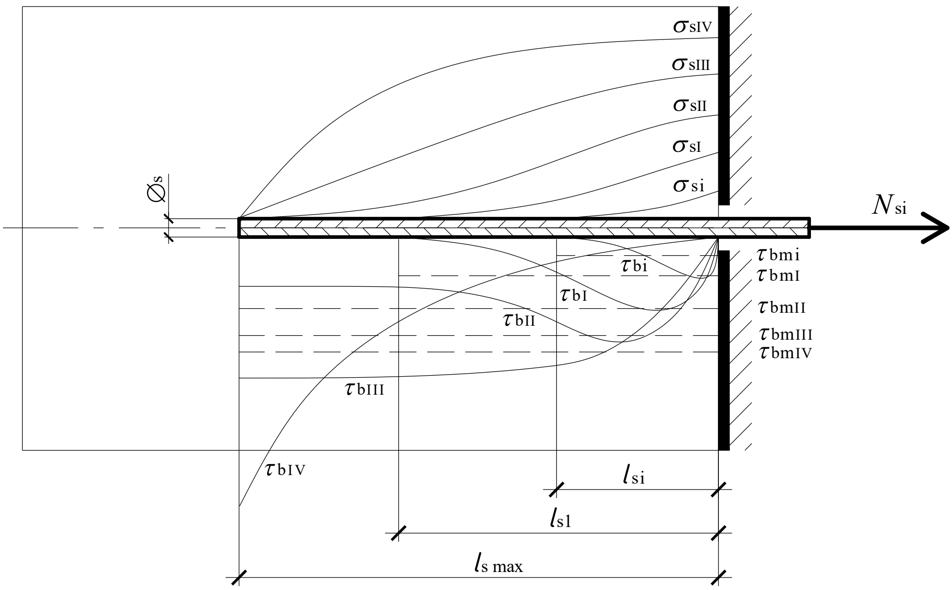

Fig. 1. Scheme of stressed state change of the concrete contact layer and reinforcing rod when it is removed from concrete.

The considered scheme is typical for a case where the reinforcement deformations remain elastic to the destruction of the concrete sample without the appearance of cracks in it. Deformation of reinforced concrete elements with cracks (with stretched concrete) takes place under a slightly different scheme. For them, the main is the second multilevel stage of cracks formation with a certain approach to the third stage only at the last level of their development.

Taking into account the above, the average tangential stresses of reinforcement bond with concrete at intermediate stages τ_{bm} will be described similarly to the limit stage f_{bd} according to the known formula

$$\tau_{bm} = \sigma_s \cdot \varnothing_s /(4 \cdot l_i), \tag{1}$$

where σ_s – the greatest stresses in the reinforcement on the area of its bond to concrete; $\varnothing_s$ – diameter of the reinforcing rod; l_i – area of reinforcement active bond with concrete.

It is easy to notice that the level of the average tangential bond stresses

$$\tau_{bm} / f_{bd} = \sigma_s / \sigma_y \cdot l_s / l_i, \tag{2}$$

depends not only on the level of the boundary stresses in the reinforcement, but also on the relative area of active bond, which, by the results of processing of experimental data [5, 7, 8, 10-14], is recommended to calculate the expression

$$l_i / l_s \approx (\sigma_s / \sigma_y)^{1/\eta_s}, \tag{3}$$

where σ_y – extreme stresses in reinforcement ($\sigma_y = f_y$); l_s – area of reinforcement active bond with concrete at the limit stage; $1/\eta_s$ – bond intensity parameter.

According to the results of processing the experimental data, shown in Fig. 2 and Fig. 3, coefficient η_s is recommended to take equal: η_1 – for fittings of periodic profile and $6 \cdot \eta_1$ – for fittings of smooth profile.

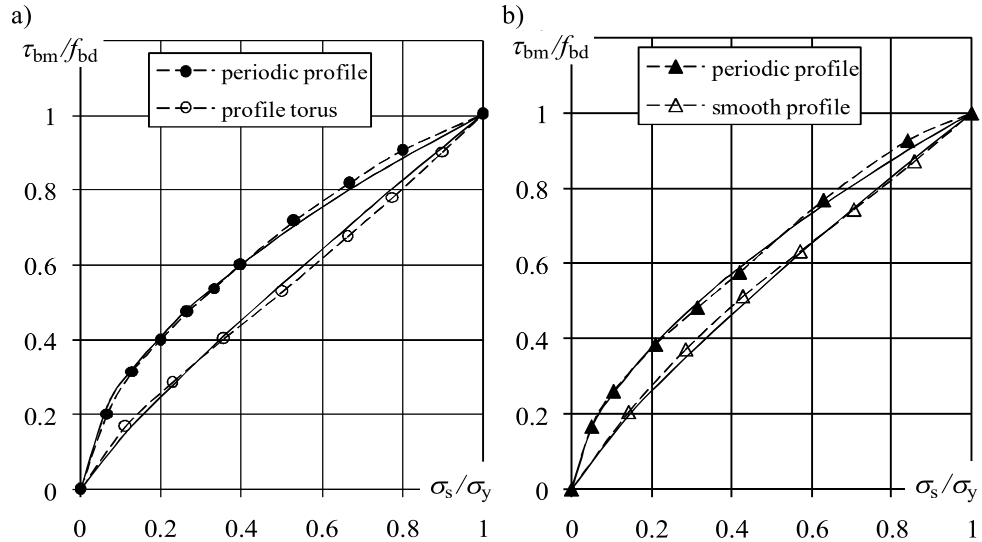

Fig. 2. Theoretical (——) and experimental (– – –) dependencies of average tangential bond stresses from normal stresses in reinforcement for experiments: (a) – Amstutz E. [11]; (b) – Bernander K. [12].

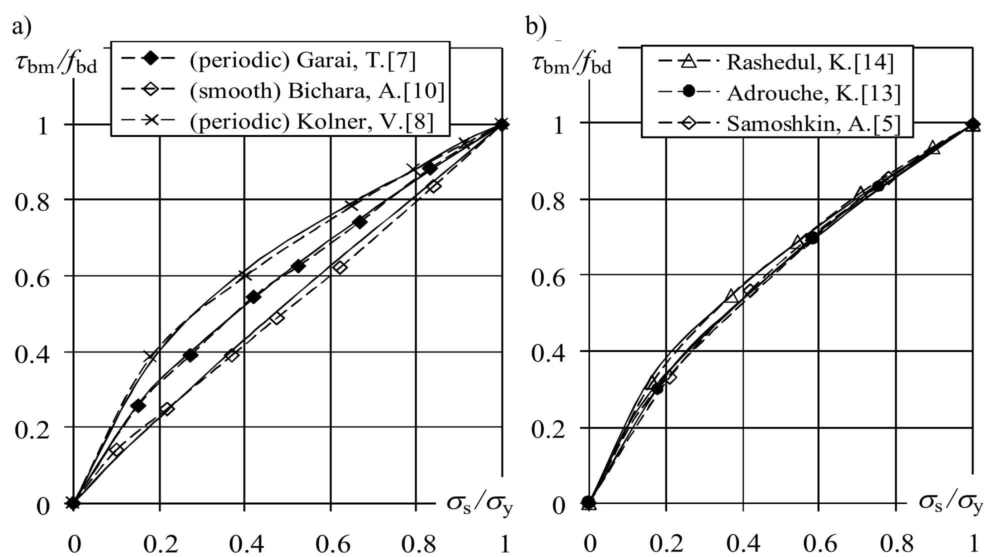

Fig. 3. Theoretical (——) and experimental (– – –) dependencies of average tangential bond stresses from normal stresses in the reinforcement: (a) - different profiles; (b) - periodic profile.

Taking into account the limit values of average bond stresses

$$f_{bd} = \eta_1 \cdot \eta_2 \cdot f_{\text{ñtk}} \quad (4)$$

the universal dependence of the average tangential stresses of the reinforcement bond with concrete will take the final form

$$\tau_{\text{bm}} = \eta_1 \cdot \eta_2 \cdot f_{\text{ñtk}} \cdot (\sigma_{\text{s}} / \sigma_{\text{y}})^{1-1/\eta_{\text{s}}}, \quad (5)$$

where η_2 – coefficient taking into account the influence of the reinforcement diameter [3].

The statistical estimation of the obtained dependence (5) on the evaluation of the reinforcement bond with concrete, shown in Table1, confirms the lawfulness of its use in practical calculations.

Table 1. Comparison of theoretical and experimental values of the average tangential stresses of reinforcement bond with concrete

The authors of the research	Year	Profile and diameter of fittings, mm	Deviation from experimental data		
			Δ	σ	v, %
Bichara, A. [10]	1951	smooth, 39	1.01	5.97	5.94
Amstutz, E. [11]	1955	torus, 30	1.00	4.71	4.71
		periodic, 30	0.99	3.22	3.25
Bernander, K. [12]	1957	smooth, 15	1.02	2.59	2.55
		periodic, 16	1.01	2.26	2.25
Garai, T. [7]	1959	periodic, 20	0.99	1.34	1.35
Kolner, V. [8]	1965	periodic, 20	1.00	1.73	1.73
Adrouche, K. [13]	1987	periodic, 16	0.995	2.00	2.01
Rashedul, K . [14]	2014	periodic, 20	0.994	2.29	2.30
Samoshkin, A. [5]	2017	periodic, 16	0.998	2.28	2.29
Notes: Δ and σ - arithmetic mean and standard deviations between experimental and calculated values, v - variance coefficient of deviations					

6 Conclusions

Proceeding from the foregoing, the estimating of the reinforcement bond with concrete in practical calculations is recommended to be performed with the help of a nonlinear function of the average tangential bond stresses. This will allow not only to clarify, but also to significantly simplify the calculation of the reinforced concrete elements crack strength [15, 16], even taking into account the levels of crack formation.

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