doi: 10.18720/MCE.79.1

Models of direct anchoring of reinforcement in concrete

Модели прямой анкеровки арматуры в бетоне

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Key words: reinforced concrete; stress-strain state; anchoring of reinforcement; modeling and theory of elasticity

Ключевые слова: железобетон; напряженно-деформированное состояние; анкеровка арматуры; моделирование; теория упругости

Abstract. When analyzing methods for calculating the anchoring of non-tension reinforcement of reinforced concrete structures, it has been established that there are two types of destruction of concrete in the anchoring zone by shearing or cracking. They are based on the results of research of the strength the adhesion of reinforcement with concrete and testing of specimens with the same type. A new model of anchoring has been created. This model initial moment is the equality of deformations of the elements of equality deformation elements. A new anchoring model was developed. This model is based on the equality of deformations of the elements. For theoretical substantiation were used the ideas of the theory of elasticity about the action of a concentrated force at the point of half-space and the results of computer simulation of the anchoring zone of reinforcement in concrete. Modeling of reinforced concrete samples was carried out using the finite element method.

Аннотация. При анализе методов расчета анкеровки ненапрягаемой арматуры железобетонных конструкций установлено, что существуют два вида разрушения бетона в зоне анкеровки срезом или расколом. Они основаны на результатах исследования прочности сцепления арматуры с бетоном и испытаниях однотипных образцов. Разработана новая модель анкеровки, исходным моментом которой является равенство деформаций элементов. Для теоретического обоснования привлекаются задачи теории упругости о действии сосредоточенной силы в точке полупространства и результаты компьютерного моделирования зоны анкеровки арматуры в бетоне. Моделирование образцов железобетонных конструкций производилось с использованием метода конечных элементов.

1. Introduction

It is accepted that the reliability of the anchoring of non-tensioning reinforcement depends basically on the factors determining the adhesion of the reinforcement to the concrete [1]. The empirical basis of the calculated dependencies are the "pull-out" tests of the reinforcing armature bar out of prisms, fixed to the surface [2]. In the last years very often was used the scheme which was recommended in 1983 by international organizations RILEM, FIP and CEB [3].

Tear-out tests are used to determine the adhesion of reinforcement to concrete and serve to compare the adhesion strength of reinforcement bars of different profiles. The effective bond length in the test samples is only 5 diameters of the reinforcement, therefore the results of the test cannot be a confirmation of the reliability of the calculated value of the anchoring length. The dimensions of the concrete samples (200 mm > 10 d), the length of the section of the armature covered by plastic cuffs (the section with the removed coupling 5 d ≥ (200 mm – 5 d) and the loading speed are regulated.

During testing special samples according to this scheme, the destruction of anchoring occurs two ways both – by cutting the concrete surrounding the armature bar and by developing cracks along the reinforcement, with followed cracking of the concrete. Accordingly, the exhaustion of the anchoring strength in the test samples is accompanied by a controlled displacement of the unloaded end of the reinforcement (up to 3 mm) or destruction of the concrete.

The theoretical model of the interaction of the reinforcement with concrete, which was realized with the destruction of the anchoring by shear, was placed in the basis of the technical theory of adhesion at VNIIZhilezobeton with a number of several of simplifying assumptions. One of the assumptions is linked to the neglect of the stressed-deformed state of concrete in the envelope shell surrounding the reinforcement beyond the contact layer, as result the destruction of the anchoring occurs only by shearing. Recognizing this deficiency, the authors of the theory of coupling allowed the possibility of removing it by special (constructive) methods. They believed that "accidental nature of the development of longitudinal cracks, their danger and the difficulty of their calculated make it necessary to widely apply transverse reinforcement" [5].

In Russian and European design standards has been adopted a model of destruction of the shear. The transition from the probabilistic model of Russian standard (SNIP 2.03.01-84*) to the physical model of Eurocode 2 [6] and SNIP 52-101-2003 made it possible to more accurately reflect the mechanism of interaction of reinforcement with concrete at the anchoring length, but at the same time it wasn't provide demands of the Russian design standards to need to consider the influence of the stressed state of concrete, the protective layer, group reinforcement, formation and development of cracks, and so on the anchoring length.

Destruction from cracking is considered unacceptable as very dangerous, and for its prevention provides structural events (transverse reinforcement, compression of concrete, etc.).

Destruction from cracking is usually associated with the formation and development of cracks along the reinforcement. In old Russian standard (SNIP 2.03.01-84*), constructive measures were provided to prevent the formation of cracks from stretching the concrete along the anchored rods. But the conditions of formation such cracks in the anchoring zone by design standards aren't described. In the current design standards the possibility of splitting concrete in the anchoring zone of non-tensioning reinforcement isn't mentioned at all.

It's known that the transition from calculated methods of ensuring reliability to constructive methods indicates about non-availability of development of the theory. For this reason and with the appearance of new types of reinforcement, the question of the reliability of anchoring in different conditions arises again.

In the United States and some other countries the concept of design model of the destruction anchorage failure of anchoring as a result of splitting the concrete shell around the reinforcement from ring stresses is common [7, 8]. The idea of this model (the analogy of hydrostatic pressure) was first time presented by R. Telfers in 1973 [9, 10]. On figure 1 shows the distribution of circular (splitting) stresses σ_t in a concrete shell with reinforcing bar located at the distance c from the surface of the shell or structural element. On figure 1 shows the distribution of circular stresses σ_t in a concrete shell with reinforcing bar located at the distance from the surface of the shell or structural element. R. Telfers considered the stressed-deformed state of the concrete shell in the elastic stage and took the stress distribution angle σ_t along the anchoring length α = 45º. Later the model was made more accurate by taking into account the plastic deformations and angle was decreased to α = 30 °[11, 12].

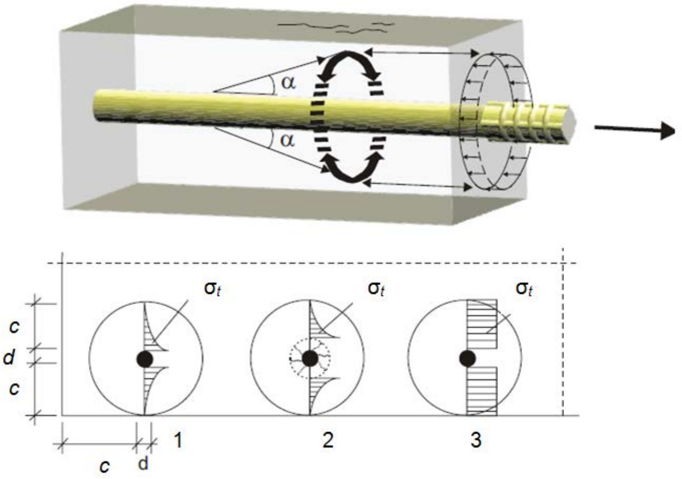

Figure 1. Tensile stresses in a concrete shell in the elastic stage – 1; stresses in the concrete shell in the elastic stage with cracks – 2; stresses in the concrete shell in the plastic stage – 3

The priority factor for breaking by splitting is the thickness of the protective layer of concrete but is not profile of armature [13, 14]. Cracks in the protective layer of concrete sharply reduce the adhesion strength, so their formation isn't allowed.

According to P. Telfers's model, the splitting occurs under the following condition: $\sigma_t = R_{bt}$, in which the stress σ_t for stage 3 (Figure 1) is determined by the following formula:

$$\sigma_t = Tdtg\alpha / 2c. \quad (1)$$

Research of the effect of puncturing cracks on the anchoring of reinforcing bars of periodic profiles was carried out in Russia [15, 16].

To obtain experimental data on the adhesion of reinforcement to the concrete of the protective layer, by standard EN 10080:2005 provides for the testing of special samples in the form of beams (Figure 2). Beam models were used, for example, when was researched models of the adhesion of rusted reinforcement to concrete [17].

Recently, attempts have been made to improve the theory of adhesion [13, 18, 20, 21], including using finite element models [19, 22, 23, 31]. But now the calculation models of anchoring used in design standards have an empirical basis. Different coefficients are used which characterize the adhesion of the reinforcement to the concrete. It should be noted that experimental researches of the interaction of reinforcement with concrete are mainly performed in order to clarify the strength of adhesion but this does not always match to the unfavorable conditions of the real work of the design. In the "pull-out" tests of the reinforcement bar from made of prisms supported by the butt, the researchers can't observe the development of cracks and deformation of the outside surface of the samples. This disadvantage defect is easily eliminated by computer simulation [30].

It should be noted that the theoretical basis of the existing design models is the stress state of reinforcement and concrete in the anchoring zone, without taking into account their joint deformations. Therefore, consideration of the joint operation of reinforcement and concrete in the anchoring zone is an actual task.

The purpose of this research is to improve the design model of anchoring taking into account the joint elastic deformations of reinforcement with concrete.

The objectives of this research are:

1. Using of FEM to observe the development of cracks and deformation of the face surface of the samples;
2. Determinate the dependence of the splitting stresses on the reinforcement anchoring length;
3. Evaluate the value of the splitting stresses on the anchoring when tested according to the recommendations of the RS-6 RILEM / CEB / FIP;
4. Make recommendations for estimating the value of splitting stresses;
5. Compare the results of calculating the length of the anchoring.

2. Methods

In [24], the equations of the theory of elasticity were used to theoretically substantiate an anchoring model, which was destroyed by the splitting of concrete. The dependencies of the theory elastic are applied, taking account that the tests are of a short time. The correctness of the calculation formulas was verified by experiments and Finite elemental modeling. The premise of quasi-elastic deformations of materials was used to justify the design models. This greatly simplifies the calculation and doesn't exclude the appearance of inelastic deformations.

In the research was used method of the computer's simulation and results of experiments given in the monograph [25].

In Figure 2 shows the scheme according to the standard EN 10080: 2005 [4], which was used in the test.

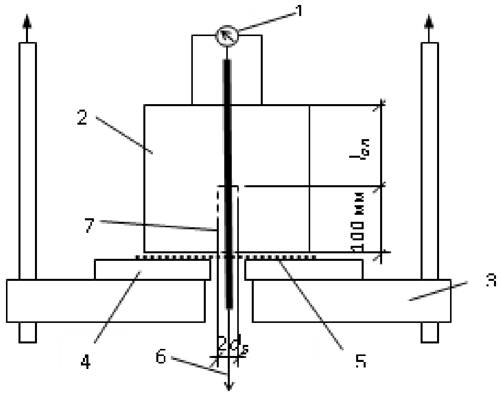

Figure 2. Scheme test of pull according to the recommendations of RS-6 RILEM / CEB / FIP, which was used in [23]: 1 – a strain gauge; 2 – test sample of concrete; 3 – base plate; 4 – steel plate; 5 – rubber lining; 6 – shows the direction of the pulling force; 7 – area with broken adhesion

The tests were conduct in the different organizations and had aim to determine the strength and deformation of the adhesion of the reinforcement of the periodic profile with concrete. A total of 335 samples with dimensions of 200 × 200 × 200 mm by l_{an} = 100 mm, and 250 × 250 × 250 mm and 300 × 300 × 300 mm with l_{an} > 100 mm were tested. The length of the anchoring l_{an} was changed from $5d_s$ to $15d_s$. In the same, a zone with a length of 100 mm with broken adhesion in the tested samples was provided. The pulling of reinforcing bars when concrete was revealed during the cutting of concrete by profile ribs or from a concrete sample was split. The pulling was observed at low values of l_{an} or relatively low strength of concrete. At l_{an} > $8d_s$ and the design compressive resistance of concrete to compression R_b > 17 MPa, destruction, as a rule, occurred during the splitting of concrete.

During modeling samples for concrete were used the universal solid eight-nodes isoperimetric finite elements (KE -36) with dimensions 10 × 10 × 10 mm (E_b = 30000 MPa). The steel armature was modeled by the bar's elements (KE-10) with length 10 mm. During the simulation, all dimensions of the prototypes experience samples were taken as real (except for the borehole location on the broken's adhesion, which in all case dimensions was taken as 20 × 20 mm). The forces of pulling the reinforcement from the concrete were simulated by the node load *N* at the point with the coordinates $X = Y = Z = 0$.

For obtain a general idea of the computer model on the Figure 3 are shown characteristic isopolls of the splitting stresses σ_y in the planes *X0Z* (section Y = 0) and *Y0Z* (section X = 0).

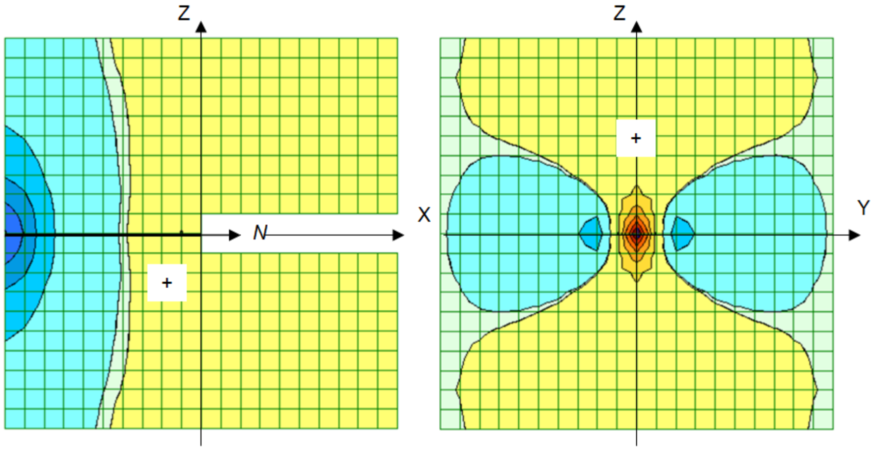

Figure 3. The isopoles of stress σy in computer models of experience samples from Pulling the reinforcing bar by force N (+ tension)

The main attention is drawn to the maximum stress σ_y in the concrete mass. When processing numerical results, the resistance of concrete to stretching at splitting is accepted $R_{tt} = 0.1R_b$ [26] into analyzing the results of the finite element method. It is known that under the condition $\sigma_y > R_{tt}$, crack's split are formed and most likely that samples are fracture from the split. Otherwise, the samples are destroyed as a result of cutting concrete with reinforcement. If $\sigma_y = R_{tt}$, the destruction by different schemes is equally probable.

3. Results and Discussion

The main conclusions from the analysis of stressed state of concrete prototypes:

- The area with the broken coupling of the reinforcement enters in the zone of probable splitting. If there are no antifriction pads this, the section is reduced by 2 to 3 cm and is approximately equal to 1/3 of the anchoring length;
- When the point of application of force *N* is shifted deep into the anchoring the qualitative picture of the distribution of splitting stresses does not change;
- The distance from the reinforcement, the splitting zone increases and extends over the entire width of the sample;
- The maximum values of the splitting stresses σ_y are obtained in the finite elements near to the point of application of the force N, and in all cases considerably exceed the resistance of the concrete to the stretching at splitting R_{tt};
- Elements are found we call them critical (in figure 3, in all cases their coordinates are X = -1.5 cm, Y = ± 1.5 cm and Z = ± 0.5 cm., in which the values of the splitting stresses may exceed the value of R_{tt};
- The value of the plitting stresses in the remaining elements are less than R_{tt};
- Stress values in the critical elements decrease with increasing diameter of the reinforcement, anchoring length and transverse dimensions of the specimens, and also when the force *N* is displaced deep into the anchoring zone.

The values of some parameters of the stress state of the testing samples are given in Table 1.

Table 1. Results of analysis stress of the testing samples

No.	d_s, **mm**	N, **kN**	R_{tt}, **MPa**	σ_y, **MPa**		**Character of destruction**		
				FEM	(2)	experience	FEM	(2)
1	2	3	4	5	6	7	8	9
1	12	16.25	1.7	0.9	1.0	section	cutting	cutting
2	12	34		1.9 (1.6)	2.1 (1.6)	cutting	cutting	split
3	14	32.4		1.6	1.7	cutting	cutting	cutting
4	16	68.3		2.7	3.2	split	split	split
5	18	35.5		1.3	1.5	split	cutting	cutting
6	18	66.5		2.3	2.7	split	split	split
7	25	82.5		2.1	2.6	split	split	split
8	12	26.8	3.5	1.5	1.6	cutting	cutting	cutting
9	12	48.3		2.7	3.0	cutting	cutting	cutting
10	14	49.1		2.4	2.6	cutting	cutting	cutting
11	16	90.3		3.6	4.2	split	split	split
12	18	65.5		2.4	2.7	cutting	cutting	cutting
13	18	97.2		3.4	4.0 (3.1)	cutting	cutting	split (cutting)
14	25	145		3.8	4.6	split	split	split
15	20	69.8	2.4	2.4 (2.2)	2.6 (2.4)	cutting	cutting	split (cutting)
16	20	84		2.6	3.2	split	split	split
17	20	83.5		2.9 (2.3)	3.2 (2.2)	split	split (cutting)	split (cutting)
18	20	87		2.7	3.3	split	split	split
19	25	101.6		2.7 (2.2)	3.2 (2.2)	split	split (cutting)	split (cutting)
20	25	111.3		2.8	3.5	split	split	split
21	25	145		3.9 (2.4)	4.6 (2.3)	cutting	split (cutting)	split (cutting)
22	25	116.9		2.9	3.7	split	split	split

Analysis of the stressed state of concrete showed that the nature of damage when using simulation in the elastic stage of deformation did not coincide with the experimental data in 5 cases out of 22. It is assumed that the results of the tests in these cases could be affected by inelastic deformation of the reinforcement and the formation of cracks in the concrete, especially when the samples are continuously loaded. The effect of inelastic deformations was taken into account in the calculation by replacing the concentrated force N by the force distributed along some part of the anchoring length (the corresponding values of σ_y are given in parentheses). Thus, with a force distribution of only 2 cm along the anchoring length, the cutoff condition $\sigma_y < R_{tt}$ in series 2 and 15 is satisfied, with a 3 cm distribution in series 17 and 19. In series 21, the maximum value of the test force is recorded, the effect of which was obviously the longest. The followability of reinforcement in this case should extend to a length of at least 7 cm at l_{an} = 12.5 cm. Thus, the nature of failure in the simulation of the tests as a whole did not coincide with the experimental character in only 1 case (series 5) of 22 (less than 5 %).

To evaluate the effect of reinforcement of different sections on the stress state of the test samples, the calculated values of the splitting stress σ_y in the samples of the same dimensions 200 × 200 × 200 mm and l_{an} = 100 mm were compared. In the column 3 of Table 2, these values are given at points with coordinates X = -1.5 cm and Y = ± 1.5 cm (in parentheses are the maximum stress values for reinforcement A 500). In line 7, the stresses σ_{0y} are given under the action of the force $N\backslash$ = 10 kN at the origin without taking into account the influence of the reinforcement excluding the effect of reinforcement.

Computer modeling let to allows to compare different various schemes of test and evaluate the errors of each of them. In the table 2 also shows the calculated values of the stresses σ_y in the absence of a region with broken coupling. When excluding such sections from the calculated models of samples, the maximum stress values σ_y are at points with coordinates X = 1.5 cm and Y = ± 0.5 cm. In the absence of reinforcement, critical stresses σ_{0y} = 0.38 MPa were obtained at X = 0.5 cm and Y = ± 1.5 cm.

Table 2. The values of the splitting stresses σy was calculated by the finite element method

No	d_s, мм	With areas with broken adhesion,		Without areas with broken adhesion,	
		σ_y, MPa	$k = \sigma_y/\sigma_{0y}$	σ_y, MPa	$k = \sigma_y/\sigma_{0y}$
1	12	0.57 (2.8)	1.64	0.50 (2.4)	1.32
2	14	0.48 (3.2)	1.40	0.46 (3.1)	1.22
3	16	0.43 (3.7)	1.23	0.43 (3.7)	1.14
4	18	0.38 (4.2)	1.10	0.41 (4.5)	1.08
5	20	0.35 (4.8)	1.01	0.39 (5.3)	1.03
6	25	0.29 (6.3)	0.85	0.35 (7.5)	0.94
7	0	σ_{0y} = 0.35	1.00	σ_{0y} = 0.38	1

On the Figure 4 was showed the characteristic stress lines σ_y in the concrete massif (the segment (area) with the broken coupling is absent). It should be noted that if you exclude the final elements of the reinforcement and the segment (area) with broken coupling (Figure 5-2), splitting is possible only outside the anticipated anchoring zone.

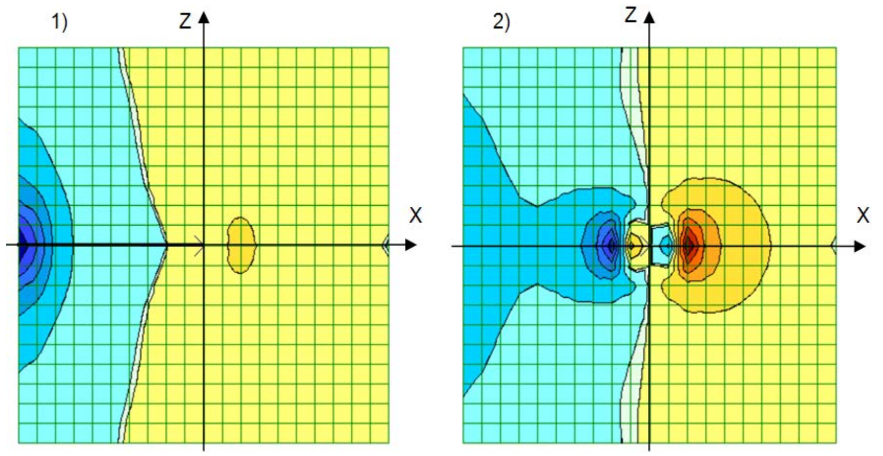

Figure 4. The stress line σ_y in a body of concrete. The concentrated force acts at the origin of coordinates: 1) with reinforcement; 2) without reinforcement

The results of the calculation with using the finite element models are approximate. The task of the action of the force applied at the point of an infinite body combined with the origin to evaluate the degree of approximation is considered.

The exact solution in cylindrical coordinates under the action of the force in the direction of the axis of symmetry x was obtained by Kelvin in the form of the equation of stresses in the circumferential direction [27]. Kelvin's equation is refined by introducing a coefficient k that takes into account the effect of the reinforcement and the segment with broken coupling (column 4 of Table 2).

$$\sigma_y = \frac{kN(1-2\nu)x}{8\pi(1-\nu)\cdot\left(x^2+y^2\right)\cdot\sqrt{x^2+y^2}}, \tag{2}$$

where ν = 0.2 is the Poisson's ratio for concrete.

The values of stress values determined by formula (2), at the individual points completely coincided with the calculated values obtained by the finite element method. For example, on points with coordinates X = 0.5 cm and Y = ± 1.5 cm, k = 1, σ_y = 0.38 MPa was obtained.

The results of calculating testing samples to formula (2) are given in Table 1. The overestimated values of the splitting stresses can be clarified by the distribution of the force N along the anchoring length. In this case, the calculation reduces to the solution of several equations (2) with an increase in unit coordinate x in each subsequent equation and using the average value of the force N.

For example, for series 2 (Table 1), the cut-off condition $\sigma_y < R_{tt}$ was obtained by a force distribution N of 5 cm with an anchoring length of 14.5 cm, for 13 series force N was distributed of 5 cm with an anchoring length of 12 cm, for 15 series – by 4 cm with an anchoring length of 10 cm, for 17 series – by 6 cm with an anchoring length of 10 cm, for 19 series – by 6 cm series with an anchoring length of 12.5 cm and 21 series – by 9 cm with an anchoring length of 12.5 cm.

The condition of joint operation of reinforcement and concrete is the equality of absolute deformations in the direction of pulling force, which is guaranteed by ideal connections of reinforcement and concrete.

$$w_s = w_b\,. \tag{3}$$

With the length of the l_{an} anchoring, the deformations of the reinforcement are determined by the formula

$$w_s = \sigma \cdot l_{an} / E_s\,. \tag{4}$$

The average stresses of the reinforcement at the anchoring length will be represented as a linear dependence on the resistance of the reinforcement to the stretching $\sigma = \alpha R_s$.

It is possible to use a theoretical model with a force at the boundary of an elastic half-space to determine the deformation of concrete during a short loading. The exact solution of this problem in cylindrical coordinates under the action of a force in the direction of the axis of symmetry x was obtained by Boussinesq [27]. The displacement of the point in which the concentrated force N is applied is determined by the formula:

$$w = N\left(1-\nu^2\right)/\,\pi \cdot E \cdot r\,, \tag{5}$$

where ν – is Poisson's ratio, E – is the modulus of elasticity, r – is the distance from the axis of symmetry.

According to equation 5, the displacement at the origin is infinite. This defect of equation 5 demand the replacement of the concentrated force by a statically equivalent load q distributed over a circular surface with radius r. Then the displacement at the boundary of the loaded circle of radius r can be determined by formula:

$$w_r = 4qr / \pi E\,. \tag{6}$$

The evenly distributed load acting on the armature pulled from the concrete is numerically equal to the stresses in the reinforcement.

From equation 6, it is possible to determine the absolute deformations of concrete on the boundary of a loaded circle with diameter *d*.

$$w_b = 2qd\left(1 - v_b^2\right) / \pi E_b \,. \tag{7}$$

Taking into account that the maximum value of the load corresponds to the identity $q_{max} = R_s$, the following expression is obtained from the joint solution of equations (3), (4) and (7):

$$l_{an} = \frac{2\left(1 - v_b^2\right)n}{\alpha \pi} d \,, \tag{8}$$

where $n = E_s / E_b$ is the coefficient of reduction.

Coefficient of average stresses α is determined by the distribution of stresses along the anchoring length. At the length of the anchoring of the stretched reinforcement, a gradual decrease of stresses occurs from the initial value $\sigma_s \le R_s$ in the calculated section to $\sigma_s = 0$ at the free end of the reinforcing element. Usually, a uniform reduction in stress is taken as the reinforcement cross-sections are removed from the loading point.

The stress distribution coefficient α is equal to 0.5 if the stresses in the reinforcement at the anchoring length vary linearly.

Computer simulation was performed with using elastic finite elements to refine the calculated coefficient value (Figure 5).

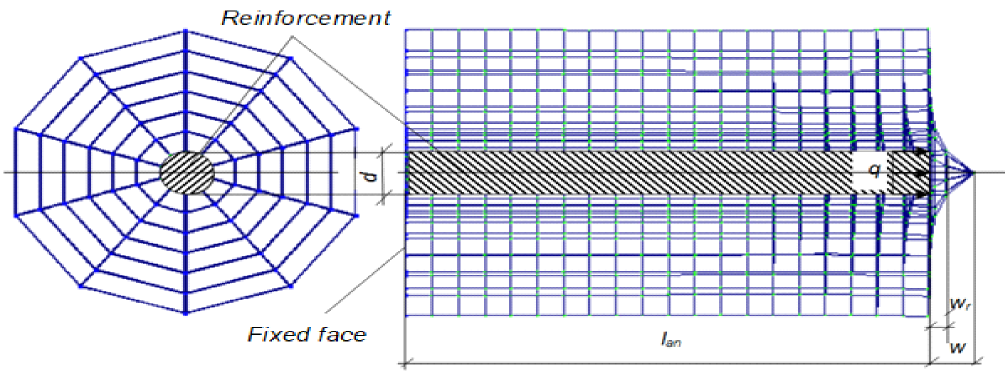

Figure 5. Axisymmetric finite element model and deformed fragment of scheme in the interaction of reinforcement with concrete

The result of the simulation were obtained data of changing stress in the reinforcing bar along the anchoring length l_{an} = 10 cm (Fig. 6) [28]. In this case, α = 0.3.

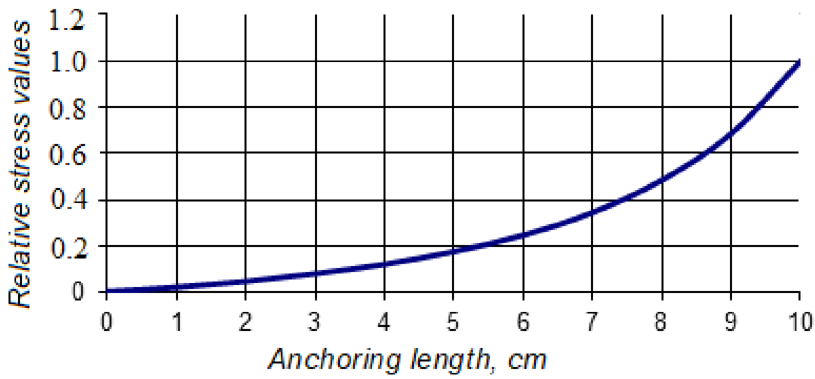

Figure 6. Relative stresses σ_s / R_s in the reinforcement along the anchoring length

Selected results of comparing the estimated_anchoring lengths for a combination of concrete B 25 and reinforcement A 500 are shown in Table 3. Values l_{an} were calculated with using the formula 8

$E_b = R_{bt} / \varepsilon_{bt0}$ (tensile strength of the concrete = 1.05 MPa, ultimate tensile strength = 0.0001) and α = 0.3. The normative data are taken from [29].

Table 3. Selected results of comparison of the calculated anchoring lengths

SNIP 2.03.01-84 (old Russian standards, 1984)	**SP 52-101-2003 (Russian standards)**	**EN 1992-1-1 (6)**	**(7)**
32 d	41.4 d	46 d	38.8 d

4. Conclusions

1. The method of computer modeling can be an effective means of predicting the destruction of direct anchoring.

2. There was no direct correlation between the splitting stresses and the anchoring length. On the value of splitting stresses is affected by the length of the anchoring section on which the pulling force is distributed, or the depth of displacement of the concentrated force in the anchoring zone. The formation of splitting cracks and breakage by a split depends mainly on the tensile strength of the concrete during the splitting of R_{tt} and the degree of distribution of the pulling force.

3. When testing the anchoring by scheme 1, the nature of the destruction of the samples is random and depends on the duration of the pulling force. Then longer the load application time, the greater the probability facture by shear.

4. The value of the splitting stresses on the anchoring is expedient to be estimated according to the scheme of the elastic half-space, taking into account the influence of the protective layer. The use of constructive methods of eliminating the split (transverse reinforcement) promotes a favorable distribution of pulling force.

5. The results of calculating the anchoring length according to the deformation model are bit (slightly) different from the data obtained by design standards.

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