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BEHAVIOR TO SHEAR FORCE OF A REINFORCED BAR IN THE CONCRETE

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In the existing design practice, there are quite a lot of cases when it is necessary to take into account the behavior of the reinforcing bar located in the concrete to the shear force. Such behavior is interpreted as a dowel action in the reinforcement. The dowel action occurs and requires consideration when calculating the shear force at the intersection of longitudinal reinforcement with a critical inclined crack, calculations of joints of prefabricated and monolithic structures of columns with beams, joints of slabs, roadway pavements, structural connections for precast concrete buildings, column anchors and other cases. Numerous experimental and theoretical studies have been devoted to the study of the dowel action in the reinforcement. However, the existing methods of calculation, primarily practical, still remain far from perfect. This work presents the results of theoretical research of the dowel action in longitudinal reinforcement, based on the systematization and analysis of experimental researches and practical design methods developed on their basis. A reinforcing bar located in the concrete was considered as a beam on an elastic base, for which the effective bending length, Foundation modulus is determined, then the forces in the bar are determined and the cases of reaching the ultimate limit state, both in the bar itself and in the surrounding concrete (crushing of concrete under the bar). At the same time, corresponding design dependencies were obtained and comparison with experimental data was performed, which revealed a fairly high accuracy of the developed calculation method.

Keywords: reinforcing bar, concrete, dowel action, Winkler spring, concrete crushing, ultimate limit state.

1. Introduction

The dowel action in the reinforcement of reinforced concrete structures occurs at the intersection of the longitudinal reinforcement with a critical inclined crack in the zone of action of shear forces (Fig. 1, a), at the joints of precast (Fig. 1, b) and monolithic (Fig. 1, c) columns with beams and slabs, slab joints (Fig. 1, d), joints of precast monolithic constructions (Fig. 1, f), column anchors embedded in a concrete base. (Fig. 1, e).

The behavior of a reinforcing bar placed in concrete to the action of a shear force is accompanied by its characteristic bending (Fig. 1) followed by reaching the ultimate limit state in the bar itself or the surrounding concrete. In this case, in the general case, the reinforcing bar is in a state of longitudinal bending, and the concrete experiences crushing or, when the bar shear in the direction of a concrete cover, for example, in the support part of the element behind a critical inclined crack (Fig. 1, a) - splitting.

In the theoretical researches conducted to date, each of the considered cases (Fig.1) and other cases was considered separately with the construction of a corresponding design model. At the same time, as the systematization and analysis of the conducted experimental researches of the dowel action in reinforcement shows, all possible design cases can be constructed on the basis of a single theoretical approach to the behavior of a reinforcing bar located in a concrete to the action of a shear force. The present work is devoted to the construction of such theoretical foundations.

2. An overview of literary sources

The study of the resistance of a reinforcing bar located in concrete to the action of a shear force (dowel action) has been the subject of many years of numerous experimental and theoretical researches, which indicates the importance and complexity of this problem.

The experimental researches included shear tests of individual bars in concrete, special samples of various shapes, reinforced concrete beams that failure along a critical inclined crack, and bars in embedded parts [1-10]. The tests were conducted under both static and cyclic loading [2, 4], simulating seismic impact. The experimental researches yielded empirical data on the nature of bar deformation

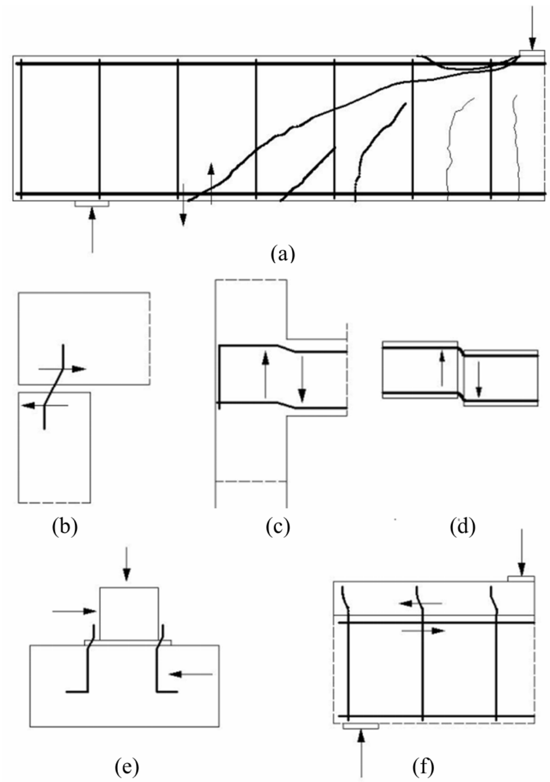

Fig. 1. Dowelactionin in reinforcement of reinforced concrete structures

along the embedment length, stress distribution along its length, the load - displacement relationship (V-Δ) of the bar end during loading, stresses in concrete in the embedment zone, and the types and nature of failure that occurred as a result of stresses in the rod reaching the yield point or crushing or splitting of concrete.

Based on the obtained experimental data, design dependencies of mainly empirical nature were obtained [1, 11-15], which were subsequently reflected in the corresponding dependence [16] for the ultimate shear force as a function of the bar area, the compressive strength of concrete and the empirical coefficient, which in turn also depended on the strength characteristics of concrete and reinforcement. Subsequent directions in theoretical studies of the dowel effect consisted in the development of calculation methods in relation to specific practical cases [18, 19] and the use of the finite element method in combination with the description of concrete in the form of Winkler spring to describe the behavior of a reinforcing bar in concrete [2, 4, 20, 21].

At the same time, despite the theoretical researches conducted, the existing methods for calculating the dowel action in reinforcement cannot be considered perfect, are fragmentary in nature, have limited practical application and, as a result, require further development in these areas.

The purpose of the work – to develop a theoretical basis for the behavior of a reinforcing bar located in concrete to the action of a shear force and a corresponding calculation model for assessing the ultimate limit state in the bar and concrete, followed by comparison with the results of experimental researches.

3. Presentation of the main material

The nature of the deformation and the distribution of forces in the reinforcing bar (curvature and bending moment at the point of intersection are close to zero, and the shear force reaches a maximum [3] allow us to consider the bar in the form of a beam clamped in an elastic foundation by Winkler spring, which is loaded with a shear force V (Fig. 2).

Vertical movements of the axis of such a beam are described by equation (1)

$$y = \frac{2\cdot V}{KL\Delta}[\mathrm{sh}\alpha\cdot\mathrm{ch}\xi\cdot\cos(\alpha-\xi)-\sin\alpha\cdot\cos\xi\cdot\mathrm{sh}(\alpha-\xi)], \qquad (1)$$

K – Foundation modulus;

$$L=\sqrt[4]{\frac{4E_sI_s}{Kd}};\quad \Delta=\mathrm{sh}^2\alpha-\sin^2\alpha;\quad \alpha=\frac{l_{an}}{L};\quad \xi=\frac{x}{L}.$$

At the same time, the principle diagrams of displacements, shear forces and bending moments along the length of the beam (see Fig. 2) fully correspond to the experimental data on the nature of the deformation and the distribution of forces along the length of the longitudinal reinforcement [1-10].

From the analysis of fig. 2 it follows that, with a sufficient degree of accuracy, the bending length l_x can be taken as the one at which the vertical movements and shear force in the beam (reinforcement bar) decrease to almost zero, and the bending moment increases to maximum values.

According to (1), the value of l_x is one of the real solutions of equation (2), which, according to the calculations at the real length of clamping for the longitudinal reinforcement (l_{an}·(10…20)d) and the ratio between E_s and K, corresponds to the area where the value of cos(α-ξ) tends to zero

$$y = [\mathrm{sh}\alpha \cdot \mathrm{ch}\xi \cdot \cos(\alpha - \xi) - \sin\alpha \cdot \cos\xi \cdot \mathrm{sh}(\alpha - \xi)], \quad (2)$$

Whereas, for the sake of simplification, $\cos(\alpha - \xi) = 0$, taking into account the notations in (1) and fig. 2, we get:

$$l_x = \frac{\pi}{2} L = \frac{\pi}{2} \sqrt[4]{\frac{4E_s I_s}{Kd}}. \quad (3)$$

At the same time, as the comparison showed, the discrepancy between (3) and the "exact" solution (2) does not exceed 3...4%.

According to research data [22, 23, 24, 25, 26] the Foundation modulus of the concrete under the reinforcing bar is a function of the strength and deformation characteristics of concrete, the diameter of the bar and varies in a wide range of values K=(0,2…1,2) кН/мм^3. The analytical description of the Foundation modulus is based on the empirical dependences of the type $K=0,113E_c$ [23], $K=121f_C$ [25], $K=500f_c$, $K=1.2\ E_c f_c\ 10^{-3}$ [26], obtained during the processing of experiments, within which the diameter is not taken into account rod, and the discrepancy between the calculated values of K in some cases reaches more than 200...300%.

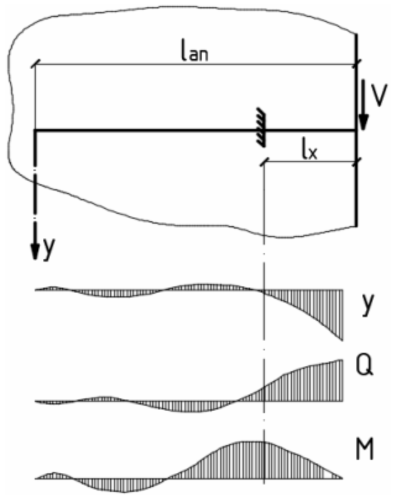

Fig. 2. Calculation scheme, diagrams of movements and forces in a reinforcing bar, as in a beam pinched in concrete

The theoretical way of calculating the Foundation modulus of the concrete under the reinforcing bar is described below, which is more justified, in our opinion.

The case of the effect of a round stamp on a concrete base is considered (Fig. 3). The Foundation modulus of the base in this case is found as the ratio of the evenly distributed load of intensity q applied to the stamp to the movement (settlement of the concrete base) of the stamp along the vertical axis:

$$K = \left(q/\Delta_c\right)L, \quad (4)$$

where

$$\Delta_c = \int_{0,5d}^{r} \varepsilon_c \mathrm{d}r = \int_{0,5d}^{r} \frac{q}{E_{c,\varepsilon}} \mathrm{d}r; \quad (5)$$

σ_r - radial compressive stresses at the base of the vertical axis of the stamp; $E_{c,\varepsilon}$ - modulus of elasticity of the concrete base, which is generally a function of deformations.

The change in stresses σ_r along the depth of the base is described by the well-known Boussinesq's equation, which for the considered case takes the form:

$$\sigma_r = 2q \frac{d}{\pi r}. \quad (6)$$

Since the analytical description of the dependence σ_c-ε_c in the conditions of a flat deformed state, in which the base concrete is under the stamp, encounters significant difficulties, the presence of inelastic deformations of concrete is taken into account by the coefficient υ, and in the value of $E_{c,\varepsilon} = \upsilon E_c$.

To determine the upper limit of integration for (5), the results of experimental research [9] on the distribution of compression deformations on concrete under a reinforcing bar were considered. At the same time, it was established that compression deformations practically disappear at a depth of 6d, and the regularity of their change in this zone is satisfactorily described by the accepted theoretical dependence (6) (see Fig. 3, b).

In light of the above, after substituting (5) and (6) into (4), we get the equation for calculating the bed coefficient:

$$K = \frac{q}{\int_{0,5d}^{r} \frac{2q \cdot d}{\pi \cdot r \cdot E_c} \mathrm{d}r} = \frac{\pi \cdot E_c}{4d \cdot dl_{an}} = 0,315 \frac{E_c}{d}. \quad (7)$$

Thus, taking into account (7) and also $I_s = \dfrac{\pi \cdot d^2}{64}$; $\alpha = \dfrac{E_s}{E_c}$

$$l_x = \frac{\pi}{2}\sqrt[4]{\frac{4\pi d^4}{64 \cdot 0{,}315 E_c}} = 1{,}4 \cdot \sqrt[4]{\alpha} \cdot d. \tag{8}$$

Thus, in further design, a reinforcing bar wedged in concrete, loaded at the end by a shear force *V*, is considered as a beam on an elastic base with a Foundation modulus according to (7).

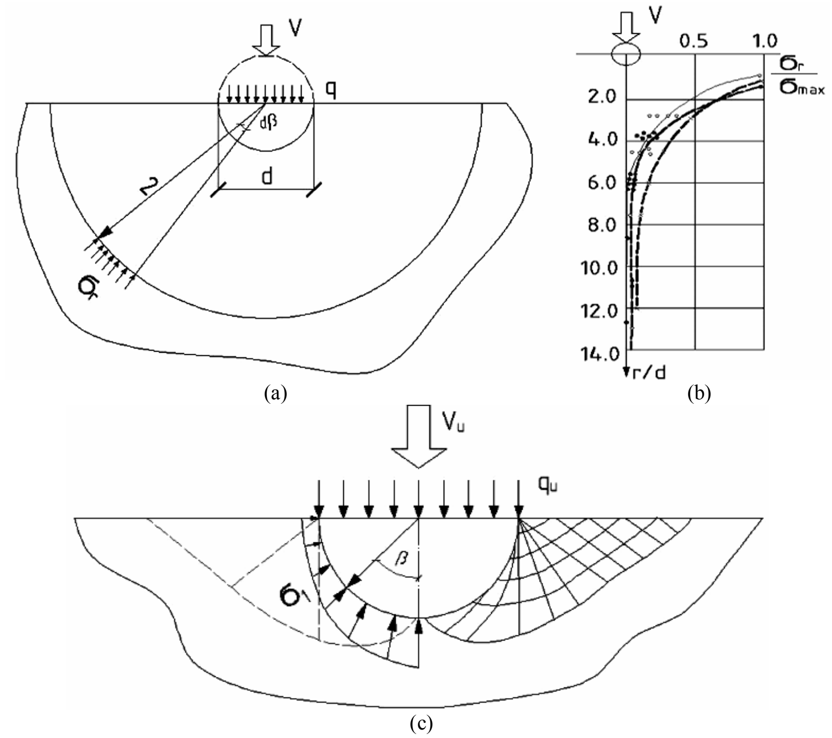

Fig. 3. Determination the Foundation modulus of the concrete under the reinforcing bar: (a) – calculation scheme; (b) – experimental and design dependences of the change relative to the stresses (deformations) of concrete along the depth of the base; (c) – calculation diagram of the ultimate limit state of concrete under the reinforcing bar

Perception of the shear force by the reinforcing bar and concrete occurs along the length, where the vertical displacements and shear force in the bar are reduced to almost zero, and the bending moment increases to the maximum value. The distance we are looking for is found from the solution of equation (2) and, other things being equal, depends on the nature of exhaustion of the bearing capacity of the concrete - reinforcing bar system.

Possible forms of exhaustion of the carrying capacity of the system are:

- reaching the ultimate limit state in concrete before reaching the ultimate limit state in the bar - crushing of concrete under the bar until the stresses in it reach the yield point;
- reaching the ultimate limit state in the bar before reaching the ultimate limit state in concrete - reaching the yield point of the stresses in the bar before crushing the concrete under it;
- simultaneous achievement of the ultimate limit state in the bar and concrete - achievement of stresses in the bar of the yield point, which is accompanied by crushing of the concrete under it.

The value of the bending moment was taken as the criteria of the ultimate limit state in the reinforcing bar:

$$M_u = \frac{f_y \cdot A_s}{4} \cdot d \tag{9}$$

and in concrete - the value of the limit linear load q_u on a round rigid stamp, in conditions of plane deformation.

Using the general approach [27], the value of q_u in the considered case was determined by (Fig. 3, c)

$$q_u = 2\int_0^{\pi/2} \sigma_1 \cdot \cos\beta \cdot r\,\mathrm{d}\beta, \tag{10}$$

where

$$\sigma_1 = \frac{t^2}{2T_0} + t - \frac{S_0^2}{6T_0};\; T_0 = \frac{f_c - f_{ct}}{2};\; S_0 = \frac{f_c + f_{ct}}{2}$$

and the value of t is found from equations

$$\tan\gamma - 2\gamma = \pi - 2\beta + (\tan 2\gamma_0 - 2\gamma_0) \tag{11}$$

with

$$\gamma = \arctan\sqrt{\frac{t - T_0}{t + T_0}};\; \gamma_0 = \frac{1}{2}\arccos\frac{T_0}{T_0 + \sqrt{T_0 + (s_0^2/2)}}.$$

When solving (10) by a numerical method, it was established that the value of the ultimate linear load for concrete of classes C15 and C55 varies in the range (6,41...6,53)f_c, which allows us to accept with a sufficient degree of accuracy:

$$q_u = 6{,}5 f_c. \tag{12}$$

Assuming that concrete crushing occurs at a length of l_x, which is equal to the length of the bending of the reinforcement in concrete according to (8), the value of the ultimate shear force, which corresponds to the exhaustion of the bearing capacity of the concrete before the onset of flow in the reinforcing bar, is (Fig. 4, a)

$$V_{c,an} = q_u l_x = 11{,}6 \cdot f_c \cdot A_s \cdot \sqrt[4]{d}. \tag{13}$$

To exhaust the bearing capacity of the bar before the onset of the ultimate limit state in concrete, the value of the ultimate shear force is found from the equation of the balance of the moments of external and internal forces, assuming a triangular plot of linear compressive stresses under the rod with maximum values $q \le q_u$, (Fig. 4, b)

$$V_{s,an} = 3 \cdot \frac{M_u}{l_x}. \tag{14}$$

The distance l_x to the section where the maximum bending moment acts in the basis determined by (3) from the general solution of equation (2)

$$l_x = \frac{\pi}{2} \cdot L = \frac{\pi}{2} \cdot \sqrt[4]{\frac{4E_s I_x}{K \cdot d}} = 1{,}4d \cdot \sqrt[4]{\alpha} \tag{15}$$

and the ultimate shear force (13) –

$$V_{s,an} = 0{,}54 f_y A_s \frac{1}{\sqrt[4]{\alpha}}. \tag{16}$$

When the ultimate limit state is simultaneously reached in the reinforcing bar and concrete, the value of the limit shear force is according to (Fig. 4, b)

$$V_{s,c,an} = 0{,}5 q_u\, d\, l_x (1+\omega) = 5{,}8 f_c\, A_s (1+\omega)\sqrt[4]{\alpha}, \tag{17}$$

where l_x - the distance to the section where the maximum bending moment in the bar acts, calculated by (15); ω - the relative length of the crumple section, which is determined from the joint solution of the equilibrium equations of shear forces and bending moments:

$$V_{s,c,an} = 0{,}5 q_u\, d\, l_x (1+\omega), \tag{18}$$

$$M_u = V_{s,c,an} l_x - q_u\, d\, l_x^2 \left[\omega(1 - 0{,}5\omega) + \frac{1}{3}(1-\omega^2)\right], \tag{19}$$

where

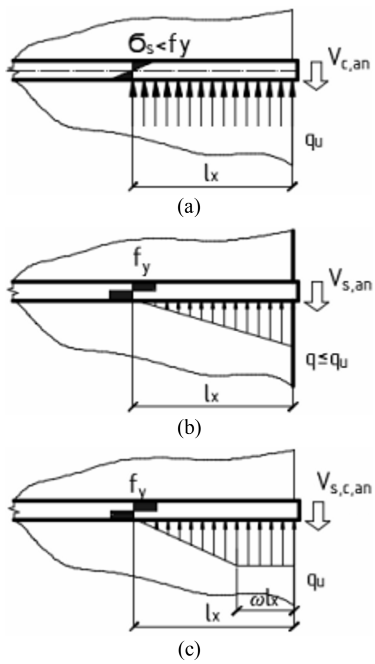

Fig. 4. Design diagram of the ultimate limit state for possible forms of exhaustion of the bearing capacity of concrete - reinforcing bar under the action of transverse force

$$\omega = 0,5\left[\sqrt{0,372 \cdot \frac{f_y}{f_c} \cdot \frac{1}{\sqrt[4]{\alpha}} - 3} - 1\right] \tag{20}$$

the value of ω=0 corresponds to the minimum value of the shear force that causes the concrete crumpling:

$$V_{c,an}^{\min} = 5,8 f_y\ A_s \sqrt[4]{\alpha}. \tag{21}$$

The comparison of formulas (13), (16), (17) and (21) allows to change the limits of their application and the form of exhaustion of the bearing capacity of the concrete - bar system.

Equating the right-hand parts of (16) and (21), we obtain the condition:

$$f_y / f_c \le 10,7\sqrt[4]{\alpha} \tag{22}$$

during which the exhaustion of the bearing capacity occurs upon reaching the ultimate limit state in concrete, and the limit shear force is calculated (16)

$$f_y / f_c \ge 21,5\sqrt[4]{\alpha} \tag{23}$$

during which the exhaustion of the load-bearing capacity occurs upon reaching the ultimate limit state in concrete, and the limit shear force is calculated according to (13).

If conditions (22) and (23) are not fulfilled, what does the range correspond to:

$$10,7\sqrt[4]{\alpha} \le \frac{f_y}{f_c} \le 21,5\sqrt[4]{\alpha} \tag{24}$$

exhaustion of the load-bearing capacity occurs when the ultimate limit state is simultaneously reached in the rebar and concrete, and the limit shear force is calculated (17).

When transverse and longitudinal (tensile or compressive) forces act on the bar, its ultimate limit state is estimated according to the solution of the theory of plasticity for longitudinal-transverse bending

$$M/M_u + \left(N/N_u\right)^2 = 1 \tag{25}$$

formula (16) takes the form:

$$V_{s,an} = 0,54 f_y\ A_s \frac{1}{\sqrt[4]{\alpha}}\left[1 - \left(N/(f_y\ A_s)\right)^2\right] \tag{26}$$

and the coefficient ω when determining $V_{s,c,an}$ according to (17) is:

$$\omega = 0,5\left[\sqrt{0,372 \cdot \frac{f_y\left(N/(f_y\ A_s)\right)^2}{f_c \sqrt[4]{\alpha}} \cdot \frac{f_y}{f_c} \cdot \frac{1}{\sqrt[4]{\alpha}} - 3} - 1\right]. \tag{27}$$

Equations (22), (23) and (24) are thus transformed into:

$$\frac{f_y}{f_c} \le 10,7\sqrt[4]{\alpha} \frac{1}{1 - \left(N/(f_y\ A_s)\right)^2}, \tag{28}$$

$$\frac{f_y}{f_c} \ge 21,5\sqrt[4]{\alpha} \frac{1}{1 - \left(N/(f_y\ A_s)\right)^2}, \tag{29}$$

$$10,7\sqrt[4]{\alpha} \frac{1}{1 - \left(N/(f_y\ A_s)\right)^2} \le \frac{f_y}{f_c} \le 21,5\sqrt[4]{\alpha} \frac{1}{1 - \left(N/(f_y\ A_s)\right)^2}. \tag{30}$$

In order to verify the obtained calculation formulas, a mass comparison was made with the results of experiments [9, 26. 28, 29, 30, 31, 32], in which the following were tested: individual bar located in concrete, loaded with a shear force; reinforcing bars as part of embedded parts under the action of shear force and joint action of shear and longitudinal forces. In the processed experiments, all the main parameters were varied in a wide range - strength characteristics of concrete and reinforcement (f_c =14.4...61.8 MPa, f_y =327...467 MPa); bar diameter (8....22 mm); ratio between longitudinal and shear forces (*N/V*= 0...0.9). As a result of the comparison, it was established that the obtained formulas have the necessary accuracy (the average ratio of experimental and calculated loads for a sample of

141 samples was 1.08 with a root mean square deviation of 0.15) and correctly reflect the influence on the limit load of the main factors (Fig. 5).

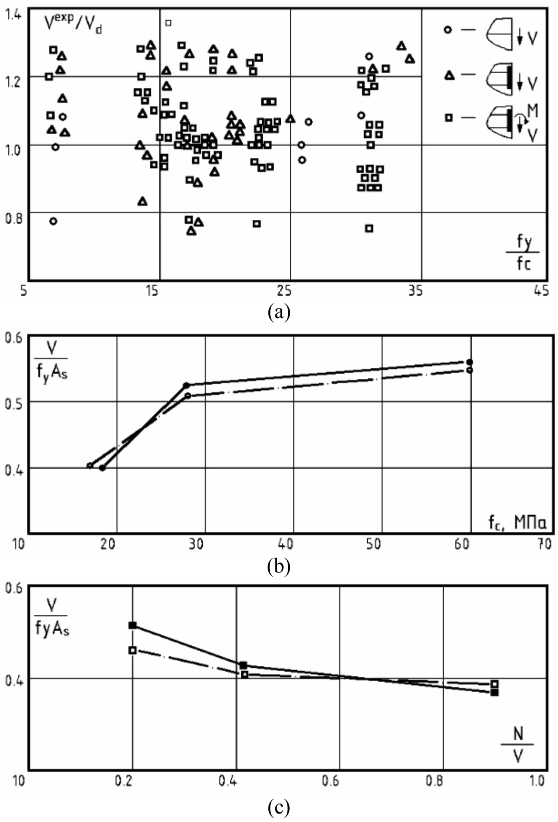

Fig. 5. Comparison of experimental (V_{exp}, ■——■) and calculated (V_d, □—·—□) shear force (a), experimental and design dependencies of the limit force on concrete strength and *N/V* ratio (b, c)

4. Conclusions

1. The problem of the behavior of a reinforcing bar placed in concrete under the action of a shear force, despite many years of numerous experimental and theoretical researches, still remains relevant. Existing design methods are fragmentary, have limited practical application and, as a result, require further development.

2. This paper presents a developed design model of a bar located in concrete under the action of a shear force, considering the bar in the form of a beam embedded in an elastic foundation by Winkler spring.

3. Theoretical design were used to obtain the calculation dependencies for calculating the Foundation modulus (7), the bar bending length (8), and the strength of concrete under the reinforcing bar during failure due to concrete crushing (12).

4. A method has been developed for determining the ultimate shear force based on possible forms of failure as a result of: reaching the ultimate limit state in the bar, including when acting jointly with a longitudinal force; reaching the ultimate limit state of concrete under the bar as a result of crushing; simultaneous reaching of the ultimate limit state in the bar and concrete under it.

5. The calculations obtained using the developed method were compared with the experimental data in a wide range of concrete strength (f_c = 14.4... 61.8 MPa), diameters (8….22 mm) and reinforcement strength (f_y = 327...467 MPa) for different samples and the acting external load - individual bars in concrete under the action of a shear force, reinforcement shears as part of embedded parts under the action of a shear force and the combined action of shear and longitudinal forces (Fig. 5). It was found that the obtained calculated dependencies have the required accuracy (the average ratio of the experimental and calculated values of the destructive load for a sample of 141 samples was 1.08 with a standard deviation of 0.15) and correctly reflect the influence of the main factors on the magnitude of the failure shear loads (Fig. 5, b, c).

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ОПІР ПОПЕРЕЧНІЙ СИЛІ АРМАТУРНОГО СТЕРЖНЯ В БЕТОННОМУ МАСИВІ

У існуючій проектній практиці досить широко трапляються випадки, коли необхідно враховувати опір арматурного стержня, розташованого в бетоні при дії зсувної поперечної сили. Такий опір сприймається як нагельний ефект в арматурі. Нагельний ефект виникає і вимагає обліку в розрахунку на поперечну силу в місці перетину поздовжньої арматури критичною похилою тріщиною, розрахунках стиків збірних і монолітних конструкцій колон з ригелями (балками), стиків плит, насамперед дорожніх, стиків збірно-монолітних конструкцій, анкерів колон і інших випадках. Дослідженням нагельного ефекту в арматурі присвячено численні експериментально-теоретичні дослідження. Разом з тим, існуючі методи розрахунку, насамперед практичні, все ще залишаються далекими від досконалості. У цій роботі наведено результати теоретичних досліджень нагельного ефекту в поздовжній арматурі, що базуються на систематизації та аналізі проведених експериментальних досліджень та розроблених на їх основі практичних методів розрахунку. Арматурний стержень, розташований у бетонному масиві, розглядається як балка на пружній підставі, для якої визначається ефективна довжина згину, коефіцієнт постелі, далі визначаються зусилля в такому стрижні та розглядаються випадки досягнення граничного стану в самому стержні та навколишньому бетонному масиві (зминання бетону під стержнем). При цьому отримано відповідні розрахункові залежності та виконано співставлення з експериментальними даними, що виявило досить високу точність розробленого розрахункового апарату.

Ключові слова: арматурний стержень, бетонний масив, нагельний ефект, коефіцієнт постелі, зминання бетону, граничний стан.

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BEHAVIOR TO SHEAR FORCE OF A REINFORCED BAR IN THE CONCRETE

In the existing design practice, there are quite a lot of cases when it is necessary to take into account the behavior of the reinforcing bar located in the concrete to the shear force. Such behavior is interpreted as a dowel action in the reinforcement. The dowel action occurs and requires consideration when calculating the shear force at the intersection of longitudinal reinforcement with a critical inclined crack, calculations of joints of prefabricated and monolithic structures of columns with beams, joints of slabs, roadway pavements, structural connections for precast concrete buildings, column anchors and other cases. Numerous experimental and theoretical studies have been devoted to the study of the dowel action in the reinforcement. However, the existing methods of calculation, primarily practical, still remain far from perfect. This work presents the results of theoretical research of the dowel action in longitudinal reinforcement, based on the systematization and analysis of experimental researches and practical design methods developed on their basis. A reinforcing bar located in the concrete was considered as a beam on an elastic base, for which the effective bending length, Foundation modulus is determined, then the forces in the bar are determined and the cases of reaching the ultimate limit state, both in the bar itself and in the surrounding concrete (crushing of concrete under the bar). At the same time, corresponding design dependencies were obtained and comparison with experimental data was performed, which revealed a fairly high accuracy of the developed calculation method.

Keywords: reinforcing bar, concrete, dowel action, Winkler spring, concrete crushing, ultimate limit state.

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Розроблено розрахункову модель арматурного стержня, розташованого в бетоні, при дії поперечної сили, що розглядає стержень у вигляді балки, защемленою в пружну основу. Теоретичним шляхом одержано розрахункові залежності для обчислення коефіцієнта постелі основи, довжини згину стрижня та міцності бетону під арматурним стрижнем при руйнуванні в результаті зминання. Розроблено методику визначення граничної поперечної сили виходячи з можливих форм руйнування. Виконано зіставлення розрахунків за розробленою методикою з експериментальними даними.

Іл. 5. Бібліогр. 32 назв.

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This paper presents a developed design model of a bar located in concrete under the action of a shear force, considering the bar in the form of a beam embedded in an elastic foundation by Winkler spring. Calculation dependencies were obtained theoretically for calculating the Foundation modulus, the bar bending length, and the strength of concrete under the reinforcing bar during failure due to concrete crushing. A method has been developed for determining the ultimate shear force based on possible forms of failure. The calculations obtained using the developed method were compared with the experimental data.

Fig. 5. Ref. 32

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