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EXPERIMENTAL AND THEORETICAL RESEARCH OF STRENGTH OF COMPRESSED REINFORCED CONCRETE ELEMENTS WITH TRANSVERSE REINFORCEMENT OF WELDED MESHES

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Summary. Transverse reinforcement with welded meshes is used in areas of significant compressive forces, usually in local places, where it is necessary to increase the strength of concrete in axial compression. In a calculated way, such an increase in the strength of concrete is usually taken into account by introducing coefficients that were obtained on the basis of experimental researches. Calculation of the strength of such elements on the basis of empirical dependencies is a significant drawback that can lead either to overspending on materials or to insufficient reliability of structures. Improving the calculation method with transverse reinforcement is a rather promising direction.

The presented work presents a method for determining the ultimate compressive stresses of concrete in compression in places of transverse reinforcement with welded meshes, based on the theory of plasticity of reinforced concrete, within which the mesh reinforcement is considered as an internal bond that limits the transverse deformations of concrete in compression and causes the emergence of reactive compressive stresses in concrete acting in the plane of the meshes. As a result, concrete within the location of the reinforcing meshes passes from a stressed state of axial to triaxial compression, which causes an increase in its strength, and at the same time the strength of the entire element in the area of the compressive force.

Based on the above-mentioned premises, theoretical calculations were obtained to determine the ultimate stresses in concrete in places of reinforcement with welded meshes, which take into account the intensity of transverse reinforcement (diameter, mesh reinforcement pitch and their location along the height of the element), the strength characteristics of concrete and the corresponding reinforcement.

To verify the developed calculation tool, we conducted local experimental researches of the strength of reinforced concrete elements with transverse reinforcement with welded meshes.

The analysis of the results of the experimental and theoretical studies made it possible to establish the general regularities of the stress-strain state and the strength of centrally compressed elements with transverse reinforcement.

As a result of comparing experimental and theoretical data, it was established that the developed calculation method for determining the strength of compressed reinforced concrete elements in zones of transverse reinforcement with welded meshes has a sufficiently high accuracy, since the ratio between the calculated and experimental load at failure was 0.87…1.06, and after further experimental testing it can be used for calculating structures.

Keywords: transverse reinforcement; central compression; strength of reinforced concrete elements; welded meshes; "compression" effect; limit state.

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INTRODUCTION

The use of transverse reinforcement of reinforced concrete structures, especially in the areas of joints, concentrated loads or in the areas of anchoring of prestressed reinforcement, which is usually located perpendicular to the direction of external loading, has become common construction practice. The increase in strength and deformation characteristics of such elements is due to the influence of the "compression " effect.

The reinforcement of compressed reinforced concrete elements with transverse reinforcement contributes to the increase in the strength of the concrete core (the result of which is the increase in the load-bearing capacity of the entire structure), and also creates favorable conditions for the effective use of high-strength reinforcement.

Among the large number of different types of transverse reinforcement (rings, spirals, frequently located clamps, transverse sheet reinforcement, solid metal clamps, clamps made of angles and connecting strips, etc.), the most widely used in engineering practice is transverse reinforcement in the form of welded meshes.

According to existing methods, the calculation of reinforced concrete elements with transverse reinforcement by welded meshes is based on the introduction of reduced prismatic strength σ_{C} instead of prismatic strength $\sigma_{\mathrm{C},red}$, the determination of which is based on empirical dependencies.

The disadvantages of the empirical approach are well-known - the lack of a clear physical meaning, the reliability of the obtained solutions only for the processed array of experimental data, etc., which does not allow the application of this calculation method in all cases that occur in practice and leads in some cases to the overspending of material, and in others to insufficient reliability of the design.

At the same time, one of the most promising areas for improving the methodology for calculating the strength of elements with transverse reinforcement is the construction of a calculation model based on the theory of the limit state of reinforced concrete.

PROBLEM STATEMENT AND ANALYSIS OF PREVIOUS RESEARCH

Most of the researches conducted to date on the influence of reinforcement on the stress-strain state of concrete in compressed reinforced concrete elements are experimental researches of the strength of elements reinforced with flat welded meshes and protective reinforcement, as well as pipe-concrete elements. The experimental researches conducted included, among other things, tests for axial compression of reinforced concrete elements reinforced with welded meshes, in which the intensity of volumetric reinforcement, the diameter of the rods, the pitch of the reinforcement in the meshes and their position along the height were varied [1, 2, 3, 4, 5, 6, 7, 8, 9, 10].

As a result of the conducted researches, experimental data were obtained on the type of the destruction of the strength of elements, changes in longitudinal and transverse deformations of concrete, and stresses in the reinforcement during loading, including cyclic loading [9, 11]. It was found that the presence of reinforcement in the form of meshes, due to the limitation of transverse deformations, leads to the occurrence of a triaxial stress state in concrete and an increase in the strength of samples under axial compression by 1.10-1.45 times, which corresponds to the results of concrete tests under triaxial compression at corresponding values of transverse compressive stresses within 0.1 ... 0.5 of the ultimate under axial compression [12, 13, 14, 15, 16, 17]. At the same time, with an increase in transverse reinforcement with meshes or protective reinforcement, the strength and ductility of the elements increase.

The calculated assessment of the influence of transverse reinforcement on the strength of elements under central compression is reduced to the introduction of empirical coefficients that take into account the intensity, type, configuration and construction of transverse reinforcement [18, 19, 20, 21, 22, 23].

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At the same time, there are real prerequisites for building a theoretical approach to determining the strength of concrete of reinforced concrete elements in the zone of transverse reinforcement with welded meshes based on taking into account the real stress-strain state of concrete.

The object of research is centrally compressed reinforced concrete elements with transverse reinforcement with transverse welded meshes.

The purpose of the work is to improve the methodology for calculating the strength of centrally compressed elements with transverse reinforcement with welded meshes and to build a calculation model based on the limit state of reinforced concrete.

Research objectives:

- develop a method for calculating the strength of centrally compressed reinforced concrete elements with transverse reinforcement;
- obtain experimental data on the strength of centrally compressed reinforced concrete elements with transverse reinforcement;
- perform a comparison of the strength results of the test samples with the theoretical values obtained by the presented calculation method.

Subject of research.

To construct a theoretical approach to determining the concrete strength of reinforced concrete elements in the zone of transverse reinforcement with welded meshes based on taking into account the real stress-strain state of concrete. To verify the developed calculation model, to conduct local experimental researches of the strength of reinforced concrete elements with transverse reinforcement with welded meshes. To compare the results of theoretical and experimental researches (local and others) to obtain general patterns of the stress-strain state and strength of centrally compressed elements with transverse reinforcement.

MAIN MATERIAL AND RESULTS OF RESEARCH

The method of calculating the strength of centrally compressed reinforced concrete elements with transverse mesh reinforcement presented in this article is based on the following initial assumptions, which were obtained from the analysis of numerous experimental data:

- the destruction of the element occurs when the limit state is reached in the concrete core; if certain design requirements are met, the destruction of the element occurs when the limit state is simultaneously reached in the concrete core and transverse reinforcement;
- at the stage of limit equilibrium, compatibility of deformations of transverse reinforcement and concrete in the transverse direction is ensured;
- transverse reinforcement located in a concrete mass is an internal connection that ensures the constraint of transverse deformation and, as a consequence, a change in the stress state of concrete under given loading conditions;
- the core concrete is in a volumetric stress state, for the assessment of which the strength condition of Lukshi L.K. is used (1) [24]:

$$\begin{gathered}\sigma_{b1}^2+\sigma_{b2}^2+\sigma_{b3}^2-2(\sigma_{b1}\sigma_{b2}+\sigma_{b2}\sigma_{b3}+\sigma_{b3}\sigma_{b1})-\\-(\sigma_c-\sigma_{ct})(\sigma_{b1}+\sigma_{b2}+\sigma_{b3})-\sigma_c\sigma_{ct}=0\end{gathered} \tag{1}$$

The calculation model of the element at the limit equilibrium stage is shown in Fig. 1.

The ultimate load on an element is determined from the equation of external and internal forces on the vertical axis:

$$N_u=\sigma_{b1}A_{ef}+f_yA_s \tag{2}$$

where σ_{b1} - axial stresses in the concrete core, determined from the condition of concrete strength (1), in which the main stresses σ_{b2}, σ_{b3}

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are determined based on the following considerations.

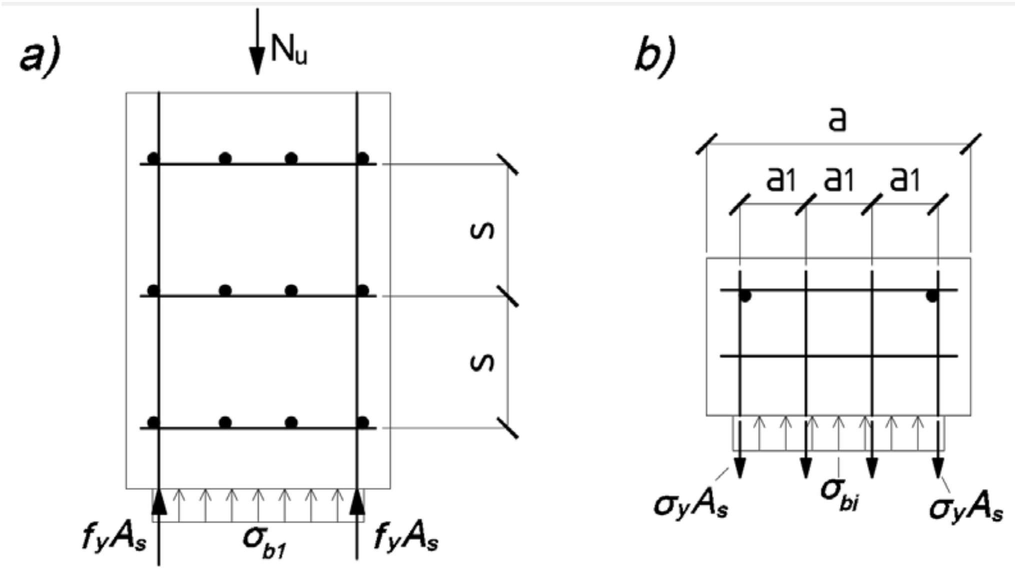

Fig. 1. Calculation model of a reinforced concrete element with transverse mesh reinforcement at the stage of ultimate equilibrium: a - external and internal forces in a flat horizontal section; b - external and internal forces in a flat vertical section

Рис. 1. Розрахункова модель залізобетонного елемента з непрямим сітчастим армуванням на стадії граничної рівноваги: а - зовнішні та внутрішні зусилля у плоскому горизонтальному перерізі; б - зовнішні та внутрішні зусилля у плоскому вертикальному перерізі

Loading an element with an axial compressive load causes its deformation: compression in the longitudinal and tension in the transverse directions. As a result, tensile stresses arise in the transverse reinforcement, and reactive compressive stresses that are mutually balanced with them are transferred to the concrete (Fig. 1, b). Thus, the stresses σ_{b2}, σ_{b3} are reactive stresses of concrete compression and are determined from the element equilibrium equations in flat vertical sections (Fig. 1, b):

$$\sigma_{b2} = \mu_{s,2}\sigma_{s2},$$
$$\sigma_{b3} = \mu_{s,3}\sigma_{s3}, \quad (3)$$

where

$\mu_{s,2}$ и $\mu_{s,3}$ - reinforcement coefficients in the corresponding direction;

σ_{s2} и σ_{s3} - stresses in transverse reinforcement of the corresponding direction in the ultimate state.

In construction practice, welded transverse meshes with the same reinforcement coefficients in orthogonal directions are predominantly used as transverse reinforcement, i.e. $\mu_{s,2} = \mu_{s,3} = \mu_{s,i}$.

Based on the above, we write down:

$\sigma_{s2} = \sigma_{s3} = \sigma_{si}$ и $\sigma_{b2} = \sigma_{b3} = \sigma_{bi}$.

Solving (1) with respect to the main stresses σ_{bi} we obtain:

$$\sigma_{b1} = 2\sigma_{bi} + \frac{\sigma_c - \sigma_{ct}}{2} + \sqrt{4\sigma_{bi}^2 + 4(\sigma_c - \sigma_{ct})\sigma_{bi} + \frac{(\sigma_c - \sigma_{ct})^2}{4}} \quad (4)$$

where σ_{bi} - reactive stresses of lateral compression of concrete core:

$$\sigma_{bi} = \sigma_{si}\mu_{s,i}, \qquad (5)$$

According to experimental data, the magnitude of stresses in the reinforcement of meshes in the limit state (σ_{si}) is in a wide range - ${}^{\sigma_{si}}/_{\sigma_y} = 0{,}55 \ldots 1{,}0$ and depends on various design factors.

Let us represent the stresses σ_{si} in the following form:

$$\sigma_{si} = k_s\sigma_y, \qquad (6)$$

where $k_s \leq 1{,}0$ - coefficient of efficiency of using transverse reinforcement.

Based on the conducted generalization and analysis of a number of experimental and theoretical researches, it was established that the following design factors have the most significant influence on the value of the coefficient k_s: concrete compressive strength (σ_c), transverse reinforcement capacity ($\sigma_0 = \mu_{s,i}\ \sigma_y$,), mesh cell size ($a_1$) and mesh pitch (s).

According to the experimental data, it is advisable to present the above design factors in relative units, respectively, $\frac{\sigma_0}{\sigma_c}$, $\frac{a_1}{a}$ and $\frac{1}{\chi} = = \frac{a}{2s}$.

We determine the dependence of the coefficient k_s on the above factors by means of mathematical processing of the results of experimental researches by various authors, in which the efficiency coefficient is presented in the form:

$$k_s = \frac{\sigma_0}{\sigma_{bi}^{test}}, \qquad (7)$$

where σ_0- transverse reinforcement capacity; σ_{bi}^{test}- stresses of reactive compression of concrete, determined by substituting into dependence (1) the experimental values of σ_c, σ_{ct}и σ_{b1} and its solution relative to σ_{bi}.

As a result of the theoretical researches, it was established that, if the design requirements a_${}^{a_1}/_{a} \leq 0{,}33$ и ${}^{1}/_{\chi} \leq 1{,}00$ are met, the coefficient k_s is determined quite accurately by the following dependencies:

a) under ${}^{\sigma_0}/_{\sigma_c} \leq 0{,}10$,

$$k_s = 1{,}0 \qquad (8)$$

b) under ${}^{\sigma_0}/_{\sigma_c} > 0{,}10$,

$$k_s = 0{,}31\sqrt{\frac{\sigma_c}{\sigma_0}} \qquad (9)$$

If at least one of the above design requirements is not met, a significant spread of the values of k_s determined according to (7) and a general tendency towards a sharp decrease in the efficiency coefficient of transverse reinforcement are observed.

To verify the developed calculation model, local experimental researches of the strength of reinforced concrete elements with transverse reinforcement with welded meshes were conducted.

Concrete prisms with a cross-section of 150 x 150 mm and a length of 600 mm, reinforced with welded mesh, were adopted as test samples.

The variable factor was the step of the transverse meshes (s) and the coefficient of transverse reinforcement μ_s. In total, 3 series (P-I, P-II, P-III) of experimental samples were manufactured and tested, 3 twin samples in each series, as well as reference samples made of concrete.

Heavy concrete of class C20/25 was used for the production of the samples, and welded transverse meshes of wire reinforcement of class Bp-I with a diameter of 5 mm were used as transverse reinforcement. Longitudinal reinforcement was absent. The design parameters of the test samples are given in Table 1.

The designs of the experimental samples are shown in Fig.1.

The experimental samples were tested for short-term central compression on a PG-100 hydraulic press. The load was applied in steps of (1/10…1/20) of the expected destructive load, with each step of loading being maintained for 3…4 minutes. During the test, the ultimate load on the sample was determined, longitudinal and transverse deformations were measured, and a visual inspection of the samples was performed for cracks and peeling of the protective concrete layer. The ultimate load was defined as the maximum force that the test sample was capable of withstanding during loading. Longitudinal deformations were measured with dial gauges (0.001 mm division value) on a 200 mm base and strain gauges with a 50 mm base. Transverse deformations were measured with dial gauges (0.001 mm division value) on a 150 mm base and strain gauges with a 50 mm base.

Table 1. Design parameters of experimental samples
Табл. 1. Розрахункові параметри дослідних зразків

Sample mark	Concrete		Transverse reinforcement					
	σ_c, МПа	σ_{ct}, МПа	σ_y, МПа	s, мм	μ_s,, %	$\mu_s\sigma_y/\sigma_{c0}$	s/a	a_1/a
P-I-1 P-I-2 P-I-3	23	2,08	539,9	30	2,03	0,48	0,20	0,30
P-II-1 P-II-2 P-II-3	23	2,08	539,9	50	1,22	0,29	0,33	0,30
P-III-1 P-III-2 P-III-3	23	2,08	539,9	100	0,61	0,14	0,67	0,30

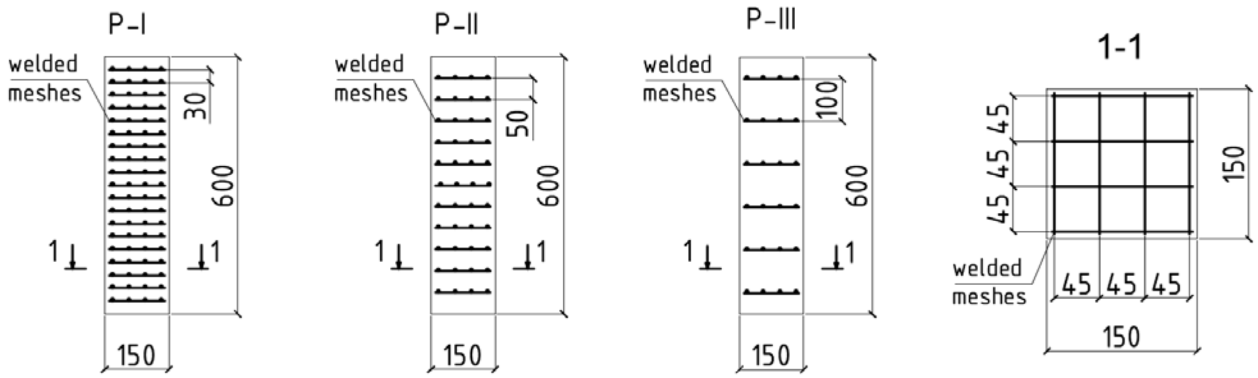

Fig. 2. The designs of the experimental samples
Рис. 2. Конструкції дослідних зразків

Comparison of the calculated (determined according to (6) taking into account (8, 9)) values of stresses in the transverse reinforcement in the ultimate state (σ_{si}^{calc}) with the experimental (measured directly during experimental researches) values of stresses (σ_{si}^{test}) shows a fairly high agreement between the results ($\sigma_{si}^{test}/\sigma_{si}^{calc} = 0{,}80 \ldots 1{,}15$),, which indicates a reliable display of the stress state of the mesh reinforcement by the above dependencies when the element reaches the ultimate state.

The values of σ_{bi} calculated according to (5) taking into account (6, 8, 9) are substituted into (4) and we find the axial stresses in the concrete core σ_{b1}. Substituting σ_{b1} into (2) we determine the value of the ultimate load on a reinforced concrete element with transverse mesh reinforcement without taking into account its flexibility.

The results of experimental researches and comparison of experimental and theoretical (determined by the developed method) values of ultimate stresses in concrete σ_{b1} are given in Table 2.

Dependence of concrete compressive strength on the percentage of transverse reinforcement is shown in Fig. 3.

The deformations of concrete, both in the longitudinal and transverse directions, until the load reaches the level $N/N_u = 0{,}50$ are practically independent of the percentage of transverse reinforcement of the samples μ_{xy} and coincide with the corresponding deformations of unreinforced concrete.

The ultimate deformations of concrete directly depend on the percentage of transverse reinforcement of the samples μ_{xy}, and their value for the samples of the P-II series is somewhat greater than for the samples of the P-I series.

The ultimate deformations of concrete for samples of the P-III series slightly exceed the corresponding deformations of unreinforced concrete, which can be explained by the large (greater than the limit according to design requirements) step of the transverse meshes, as a result of which the influence of transverse reinforcement (the influence of the compressive effect it creates) on the ultimate deformation of concrete is significantly reduced.

Table 2. Results of experimental and theoretical researches of centrally compressed reinforced concrete elements with transverse reinforcement by welded meshes

Табл. 2. Результати експериментальних та теоретичних досліджень центрально-стиснутих залізобетонних елементів з поперечним армуванням зварними сітками

Sample mark	$\sigma_{bi}{}^{calc}$, MPa	$\sigma_{b1}{}^{calc}$, MPa	$N_u{}^{test}$, kN	$\sigma_{b1}{}^{test}$, MPa	$\sigma_{b1}{}^{test}/\sigma_{b1}{}^{calc}$
P-I-1	4,92	46,1	753,0	45,2	0,98
P-I-2			777,3	46,7	1,01
P-I-3			813,8	48,9	1,06
P-II-1	3,81	41,2	728,9	43,8	1,06
P-II-2			655,8	39,4	0,96
P-II-3			680,3	40,9	0,99
P-III-1	2,70	36,2	558,7	33,6	0,93
P-III-2			522,2	31,4	0,87
P-III-3			505,9	30,4	0,84

To assess the accuracy of the developed calculation method, a comparison and corresponding statistical processing of theoretical and experimental data on the bearing capacity of centrally compressed reinforced concrete elements with longitudinal and transverse mesh reinforcement was performed.

The processed data array included test results of 120 prototypes from other authors. The main factors that have the greatest influence on the load-bearing capacity of reinforced concrete elements varied in the following ranges: the ratio between the length and transverse size of the specimens - $l/a = 3 \ldots 6{,}7$;

the relative capacity of transverse reinforcement - $\sigma_0/\sigma_c = 0{,}04 \ldots 0{,}92$;

the relative cell size - $a_1/a = 0{,}07 \ldots 0{,}31$;

the relative step of the grids – $1/\chi =$
$= 1{,}00 \ldots 5{,}3$;

the resistance of longitudinal reinforcement to compression - $f_y = 235 \dots 447$ MPa. The elements were made of heavy concrete with the strength $f_y = 16{,}5 \dots 48{,}00$ MPa.

As a result of statistical processing of experimental data, the following results were obtained: the average ratio of experimental destructive loads to calculated ones according to the developed method is 0.991; the standard deviation is 0.097; the variation coefficient is 0.098.

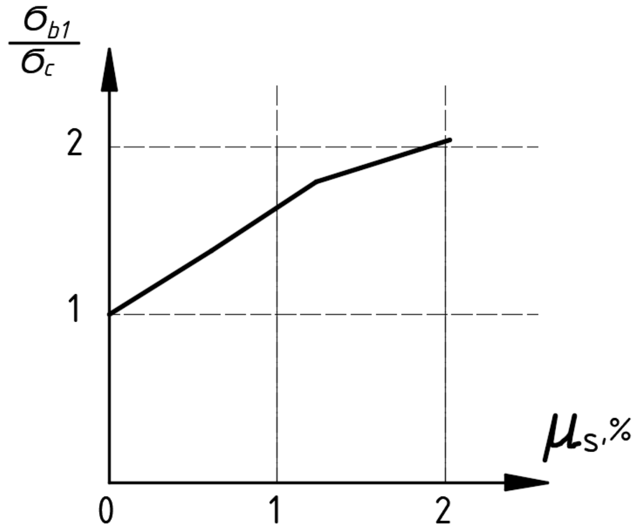

Fig. 3. Dependence of concrete compressive strength on the percentage of transverse reinforcement
Рис. 3. Залежність міцності бетону на стиск від відсотку непрямого армування

CONCLUSIONS

Generalization, systematization and analysis of the results of the conducted experimental and theoretical researches allowed us to establish the following general patterns of the stress-strain state and strength of centrally compressed elements with transverse reinforcement:

- the experimental values of the concrete core strength (σ_{bi}) of the samples of the P-I and P-II series are largely consistent (deviation up to 5.9%) with the theoretical values determined using the developed method;
- a significant deviation (underestimate) of the experimental values of the strength of the concrete core $\sigma_{bi}$of the P-III series samples from the theoretical ones determined by the developed calculation method (deviation up to 19.1%) is obviously connected with the non-fulfillment, in this case, of the design requirements for the arrangement of the transverse reinforcement grids in height (required $^{s}/_{a} \leq 0{,}5$);
- deformation of concrete, both in the longitudinal and in the transverse directions, before reaching the load level $^{N}/_{N_u} = 0{,}50$, practically do not depend on the percentage of transverse reinforcement of samples μ_{xy} and coincide with the corresponding deformations of unreinforced concrete;
- the ultimate deformations of concrete directly depend on the percentage of transverse reinforcement of the samples μ_{xy}, and for the samples of the P-II series their value is slightly greater than for the samples of the P-I series;
- the ultimate deformations of concrete for samples of the BIII series slightly exceed the corresponding deformations of unreinforced concrete, which can be explained by the large (greater than the limit according to design requirements) pitch of the transverse meshes, as a result of which the influence of transverse

reinforcement (the influence of the compressive effect it creates) on the ultimate deformation of concrete is significantly reduced.

As a result of comparing experimental and theoretical data, it was established that the developed calculation method for determining the strength of compressed reinforced concrete elements in zones of transverse reinforcement with welded meshes has a sufficiently high accuracy, since the ratio between the calculated and experimental load at failure was 0.87…1.06, and after further experimental testing it can be used for calculating structures.

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ЕКСПЕРИМЕНТАЛЬНО-ТЕОРЕТИЧНІ ДОСЛІДЖЕННЯ МІЦНОСТІ СТИСНУТИХ ЗАЛІЗОБЕТОННИХ ЕЛЕМЕНТІВ З НЕПРЯМИМ АРМУВАННЯМ ЗВАРНИМИ СІТКАМИ

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Анотація. Непряме армування зварними сітками застосовується у зонах дії значних зусиль стиску, як правило місцевого характеру, де необхідно підвищення міцності бетону на осьових стиск. Розрахунковим шляхом таке підвищення міцності бетону, зазвичай, враховується введенням коефіцієнтів, які були отримані на основі експериментальних досліджень [1]. Розрахунок міцності таких елементів на підставі емпіричних залежностей є суттєвим недоліком, який може привести або до перевитрат матеріалів або до недостатньої надійності конструкцій. Удосконалення методики розрахунків з непрямим армуванням є досить перспективним напрямком

У представленій роботі наведений метод визначення граничних напружень стиску бетону при стиску в місцях непрямого армування зварними сітками, оснований на теорії пластичності залізобетону [1], у рамках якої арматура сіток розглядається як внутрішня в'язь, що обмежує поперечні деформації бетону при стиску і викликає виникнення реактивних стискаючих напружень у бетоні, що діють в площині сіток. Як наслідок, бетон у межах розташування арматурних сіток переходить від напруженого стану осьового до трьохосьового стиску, що і обумовлює підвищення його міцності, а разом з тим і міцності всього елементу у зоні дії стискаючого зусилля.

Виходячи з зазначених передумов, теоретичним шляхом отримані розрахункові залежності для визначення граничних напружень в бетоні в місцях армування зварними сітками, які враховують інтенсивність непрямого армування (діаметр, крок арматури сіток і їх розташування по висоті елементу), характеристики міцності бетону і відповідної арматури.

Для перевірки розробленого розрахункового методу були проведені локальні експериментальні дослідження міцності залізобетонних елементів з непрямим армуванням зварними сітками.

Аналіз результатів проведених експериментально-теоретичних досліджень дозволив встановити загальні закономірності напружено-деформованого стану і міцності центрально стиснутих елементів з непрямим армуванням.

В результаті порівняння експериментальних і теоретичних даних встановлено, що розроблений розрахунковий метод визначення міцності стиснутих залізобетонних елементів в зонах непрямого армування зварними сітками має достатньо високу точність, так співвідношення між розрахунковим і дослідним навантаження при руйнуванні складало 0,84…1,06, і після подальшої експериментальної апробації може бути застосований для розрахунку конструкцій.

Ключові слова: непряме армування; центральний стиск; міцність залізобетонних елементів; зварні сітки, ефект «обійми»; граничний стан.

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