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INFLUENCE OF REINFORCEMENT PARAMETERS ON THE WIDTH OF CRACK OPENING IN REINFORCED CONCRETE STRUCTURES

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INTRODUCTION

The determination of the stress-deformation state of any discontinuous body with a crack (where the integrity of the body is violated) aims to establish relationships between stresses and displacements that occur in dangerous and responsible cross-sections of building structures of industrial, agricultural, public and civil buildings and engineering structures. Existing available analytical methods developed in the theory of elasticity, plasticity and resistance of materials cannot be applied in such a case.

Nevertheless, the use of the basic method of sections on material with existing cracks brings its positive results[1]. This also applies to the approximate method of determining the stress intensity factor. It can also be used when selecting a special two-cantilever element[2], which is widely used in fracture mechanics.

There were developed two-cantilever elements (TCE) under various force influences in the scientific works[3]: bending; eccentric compression; central tension; in the area of inclined cracks; according to the presence of multi-tier reinforcement; with free orientation of reinforcing rods; universal TCE, for complex resistance – torsion with bending.

The working conditions and dependencies necessary for the construction of deformation models of the resistance of tensioned concrete between cracks and the distance between them in reinforced concrete

[1] Верюжский Ю.В., Колчунов В. И. Методы механики железобетона. Киев: НАУ, 2005. 653 с.

[2] Iakovenko I., Kolchunov Vl. The development of fracture mechanics hypotheses applicable to the calculation of reinforced concrete structures for the second group of limit states. *Journal of Applied Engineering Science*. 2017. Vol. 15(3), article 455. P. 366–375. URL: http://scindeks.ceon.rs/Article.aspx?artid=1451-41171703367I

[3] Iakovenko I. The Development of Transformation Elements between the Fracture Mechanics Dependences and the Equations of the Reinforced Concrete Theory. *International Journal of Engineering & Technology*. 2018. Vol. 7(4.8), 58–64. URL: http://dx.doi.org/10.14419/ijet.v7i4.8.27214

structures (including composite ones) are obtained, taking into account the compliance of the joint between different concretes in the form of conditional concentrated shear[4], the effect of discontinuity[5], and relative conditional concentrated mutual displacements between different concretes, concrete and reinforcement.

The proposed prerequisites are based on the traditional provisions of the theory of reinforced concrete and fracture mechanics[6], which allows us to significantly approximate these most important calculation parameters to the actual ones[7] observed in many experimental studies[8].

Taking into account the effect of discontinuity of reinforced concrete structures[9] and relative conditional concentrated mutual displacements between reinforcement and concrete and different concretes, in the form of conditional concentrated shear, allows to significantly clarify the value of constant integration when solving the problem of the resistance of tensioned concrete between cracks and the distance between them in reinforced concrete structures.

The hypothesis of the deformation effect between the reinforcement and concrete in combination with the Thomas–Holyshev hypothesis allows to determine the relative mutual displacements on the surface of the bond between the concrete that is around the working reinforcement

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[4] Баширов Х.З., Колчунов Вл.И., Федоров В.С., Яковенко И.А. Железобетонные составные конструкции зданий и сооружений : монография. М.: АСВ, 2017. 248 с.

[5] Голышев А.Б., Колчунов Вл.И. Сопротивление железобетона. Киев: Основа, 2009. 432 с.

[6] Яковенко І.А. Напрямки розвитку механіки руйнування залізобетону стосовно до розрахунку залізобетонних конструкцій за граничними станами другої групи. *Сучасні проблеми та перспективи розвитку машинобудування України*: зб. тез доп. міжн. наук.-практ. конф., присвяченої 20-й річниці з дня створення факультету конструювання та дизайну НУБіП України (Київ, 23-24 вересня 2021 р.). К.: НУБіП України, 2021. С. 55–57. URL: http://dglib.nubip.edu.ua/bitstream/123456789/8171/1/55_Iakovenko.pdf

[7] Колчунов В.И., Демьянов А.И., Яковенко И.А., Гарба М.О. Приведение в соответствие опытных данных трещиностойкости железобетонных конструкций их теоретическим значениям. *Наука та будівництво*. 2018. № 1 (15). С. 42–49. URL: http://journal-niisk.com/index.php/scienceandconstruction/article/view/7

[8] Колчунов В.И., Яковенко И.А., Усенко Н.В., Приймак А.О. Основные результаты экспериментальных исследований трещиностойкости наклонных сечений в составных железобетонных конструкциях при деформационном воздействии. *Ресурсоекономні матеріали, конструкції, будівлі та споруди*. 2014. Вип. 28. С. 212–220. URL: http://nbuv.gov.ua/UJRN/rmkbs_2014_28_33

[9] Верюжский Ю.В., Колчунов В. И. Методы механики железобетона. Киев: НАУ, 2005. 653 с.

and the reinforcement[10] with an accuracy quite acceptable for practical engineering calculations of reinforced concrete structures. The essence of this hypothesis: the width of the opening of cracks in reinforced concrete structures means the accumulation of relative mutual displacements of deformations of reinforcement and concrete[11] in the area between adjacent cracks.

1. Model of cracks formation in reinforced concrete structures of different types and levels

Scientific work is devoted to the numerical analysis of the reinforcement influence on the model of crack openings calculation of reinforced concrete constructions.

The aim of the work. On the basis of analysis and generalization of experiments, construction of working hypotheses that most fully reflect the actual stress-strain state of reinforced concrete structures, analyze the influence of the parameters of working reinforcement on the proposed Yakovenko's[12] crack-resistance model (formation and width of crack opening).

Research tasks:

– on the basis of the performed survey of research, synthesis and analysis of the collected results of experimental and theoretical studies to determine the impact of working reinforcement on the crack resistance of reinforced concrete structures;

– to conduct numerical studies of the parameters of the stress-strain state for the evaluation of the strength of reinforced concrete structures at the variation of the diameter of the working reinforcement, the reinforcement area, the perimeter of the reinforcement, etc.

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[10] Kolchunov V.I., Yakovenko I.A., Dmitrenko E.A. The analytical core model formation of the nonlinear problem bond armature with concrete. *Збірник наукових праць. Серія галузеве машинобудування, будівництво*. Полтава : ПолтНТУ, 2016. Вып. 2(47). С. 125–132. URL: http://journals.nupp.edu.ua/znp/article/view/76

[11] Колчунов В.И., Яковенко И.А. Разработка методики расчета ширины раскрытия трещин составных внецентренно сжатых железобетонных конструкций. Збірник наукових праць Українського науково-дослідного та проектного інституту сталевих конструкцій імені В. М. Шимановського. Київ: Сталь, 2009. Вип. 3. С.245–259. URL: https://urdisc.com.ua/rl/info/3'2009.pdf

[12] Яковенко І.А. Моделі деформування залізобетону на засадах механіки руйнування: дис. … докт. техн. наук: 05.23.01. Київ, 2017. 409 с. URL: https://nupp.edu.ua/uploads/files/0/main/page/specializovani-vcheni-radi/4405202/disertacii/2018-YakovenkoIA.pdf

Object of research: reinforced concrete constructions of industrial, agricultural, public, civil buildings and engineering structures.

Subject of research: the influence of reinforcing parameters on the width of the cracking of reinforced concrete structures buildings and facilities.

Methods of research: It is used the experimental-theoretical method. In the theoretical and numerical studies that were performed in the work, general methods of deformable solid state mechanics are used in the theory of reinforced concrete.

An analysis of a two–console element used in fracture mechanics can make its positive results in calculating the distance between cracks s_r and width of crack opening w_k in reinforced concrete structures (including composite, bending, central or non eccentrically compression, central tension, in the presence of tiered reinforcement, with free orientation of reinforcing rods, etc.).

For compound reinforced concrete structures working on bending, central compression or non eccentrically compression, central tension, it is characteristic that in the second stage (for serviceability limit state for constructions) of the crack almost immediately (due to the fact that in the tensile stress zone – the development of cracks is unstable) develop to a neutral axis, and then (hit to the zone of braking compressive stresses) slowly grow only a few millimeters.

In this case, the length of the crack h_r can be considered as a constant – only cracking is changed. Then in the selected two–console element[13;14;15] parameter h_r is unchanged and the possibility of a simplified determination of the shear forces in zones adjacent to the crack appears – without the use of the functional of the fracture mechanics

[13] Iakovenko I., Kolchunov Vl. The development of fracture mechanics hypotheses applicable to the calculation of reinforced concrete structures for the second group of limit states. *Journal of Applied Engineering Science*. 2017. Vol. 15(3), article 455. P. 366–375. URL: http://scindeks.ceon.rs/Article.aspx?artid=1451-411717033671

[14] Iakovenko I. The Development of Transformation Elements between the Fracture Mechanics Dependences and the Equations of the Reinforced Concrete Theory. *International Journal of Engineering & Technology*. 2018. Vol. 7(4.8), 58–64. URL: http://dx.doi.org/10.14419/ijet.v7i4.8.27214

[15] Колчунов В.И., Яковенко И.А. Разработка методики расчета ширины раскрытия трещин составных внецентренно сжатых железобетонных конструкций. Збірник наукових праць Українського науково-дослідного та проектного інституту сталевих конструкцій імені В. М. Шимановського. Київ: Сталь, 2009. Вип. 3. С.245–259. URL: https://urdisc.com.ua/rl/info/3'2009.pdf

considered in relation to the reinforced concrete[16]. Here you can do using the usual methods of construction mechanics.

The basis for calculating the width of the opening of cracks w_k the following ***basic preconditions*** are laid out[17]:

- for average deformations of concrete and reinforcement in cross section between adjacent cracks, the fair hypothesis of plane cross sections within each core is considered to form a composite reinforced concrete rod[18];
- concrete and reinforcement stresses are determined using bilinear bond diagrams $\sigma - \varepsilon$ (fig. 1.1);

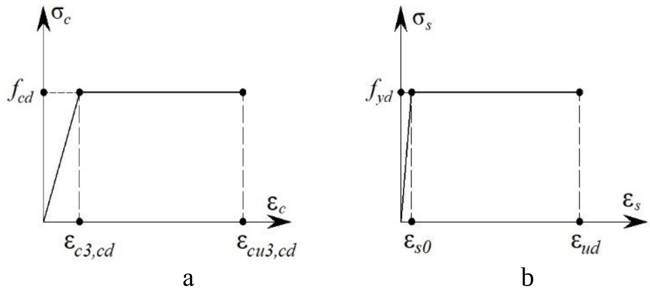

Fig. 1.1. Bilinear diagrams of the stress-strain state of materials " $\sigma - \varepsilon$ " are accepted at modeling:
***a*) – for concrete; *b*) – for reinforcement**

- the formation of cracks occurs after reaching the tensioned concrete fibers along the axis of transverse (longitudinal) reinforcement of the limiting strains;
- in the process of loading, there are **several levels of cracking**;
- the connection between the stresses of adhesion τ and relative conditional lumped mutual displacements of transverse (longitudinal) reinforcement and concrete $\varepsilon_g\left(y\right)$ (fig. 1.2) accepted as: $\tau(y) = G\varepsilon_g(y)$,

[16] Колчунов Вл.И., Яковенко И.А. Об учете эффекта нарушения сплошности в железобетоне при проектировании реконструкции предприятий текстильной промышленности. *Известия ВУЗов. Технология текстильной промышленности*. 2016. № 3 (363). С. 258–263. URL: https://www.researchgate.net/publication/316687268

[17] Голышев А.Б., Колчунов Вл.И. Сопротивление железобетона. Киев: Основа, 2009. 432 с.

[18] Баширов Х.З., Колчунов Вл.И., Федоров В.С., Яковенко И.А. Железобетонные составные конструкции зданий и сооружений : монография. М.: АСВ, 2017. 248 с.

where G – conditional modulus of strain grip of reinforcement with concrete:

$$\varepsilon_g\left(y\right)=\varepsilon_{sw}\left(y\right)-\varepsilon_{ctk}\left(y\right), \tag{1.1}$$

where based on work

$$\varepsilon_{sw}(y)=\varepsilon_{sw}+\frac{\Delta T}{E_{sw}A_{sw}}-\frac{S_{sw}}{E_{sw}A_{sw}}\int_0^y\tau(y)dy\,. \tag{1.2}$$

Dependence (1.2) is indicated by:

S_{sw} – the perimeter of the cross–section of the reinforcement rod (is defined as the sum of all perimeters of reinforcing rods);

ε_s – deformation of the reinforcement rod in a crack;

ΔT – the resulting conditional tangential stress in the local zone adjacent to the crack[19;20;21] – was first identified by prof. Vl.I. Kolchunov;

$\tau(x)$ – conditional tangential stresses in RCC.

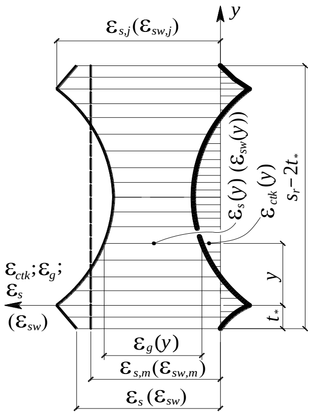

Fig. 1.2. Sections of concrete deformation $\varepsilon_{ctk}\left(y\right)$, rods of transverse reinforcement and their relative reciprocal displacement $\varepsilon_g\left(y\right)$ on the section between inclined cracks in reinforced concrete constructions

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[19] Верюжский Ю.В., Колчунов В. И. Методы механики железобетона. Киев: НАУ, 2005. 653 с.

[20] Голышев А.Б., Колчунов Вл.И. Сопротивление железобетона. Киев: Основа, 2009. 432 с.

[21] Колчунов В.И., Яковенко И.А. Разработка методики расчета ширины раскрытия трещин составных внецентренно сжатых железобетонных конструкций. Збірник наукових праць Українського науково-дослідного та проектного інституту сталевих конструкцій імені В. М. Шимановського. Київ: Сталь, 2009. Вип. 3. С.245–259. URL: https://urdisc.com.ua/rl/info/3'2009.pdf

The character of the essay $\varepsilon_{sw}(y)$, performed with the involvement of studies of other representatives of the scientific school[22] regarding the calculation and design of reinforced concrete structures by prof. O.B. Golyshev[23;24] shows that at a certain value of strain load in areas adjacent to cracks, begin to decrease and even change the sign, the deformation of the same in the middle of the area between the cracks continue to increase as long as there is no new crack in this place. An analysis of the nature of the diagram $\varepsilon_{ctk}(y)$ shows the necessity (fig. 1.2) to take into account the deformation effect in the crack[25;26;27].

Substituting $\varepsilon_{ctk}(y)$, which are determined in accordance with the method[28], in equation (1.1), we obtain:

Taking into account the dependence (1.2), the equation will have the form:

$$\varepsilon_{\mathrm{g}}(y)=\left(\varepsilon_{\mathrm{sw}}+\frac{\Delta T}{E_{sw}A_{sw}}-\frac{S_{sw}}{E_{sw}A_{sw}}\int_0^y \tau(y)dy\right)\cdot\left(1+\frac{E_{sw}\cdot A_{sw}}{P_{13,*}}\right)-$$
$$-\varepsilon_{\mathrm{sw}}\cdot E_{sw}\cdot A_{sw}\cdot\frac{1}{P_{13,*}}-\frac{P_{14,*}}{P_{13,*}}\cdot y-\frac{P_{15,*}}{P_{13,*}}. \qquad (1.3)$$

where $P_{1,*}\ldots P_{15,*}$ are the parameters from calculation schemes of the second level level of cracking[29;30] (on the basis of a detailed analysis of

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[22] Голышев А.Б., Колчунов В.И., Яковенко И.А. Сопротивление железобетонных конструкций, зданий и сооружений, возводимых в сложных инженерно-геологических условиях: монография. Киев: Талком, 2015. 371 с.

[23] Голышев А.Б., Колчунов Вл.И. Сопротивление железобетона. Киев: Основа, 2009. 432 с.

[24] Бамбура А.М., Павліков А.М., Колчунов В.І. та ін. Практичний посібник із розрахунку залізобетонних конструкцій за діючими нормами України (ДБН В.2.6–98:2009) та новими моделями деформування, що розроблені на їхню заміну. Київ: Толока, 2017. – 627 с. URL: http://reposit.nupp.edu.ua/handle/PoltNTU/5380

[25] Верюжский Ю.В., Колчунов В. И. Методы механики железобетона. Киев: НАУ, 2005. 653 с.

[26] Баширов Х.З., Колчунов Вл.И., Федоров В.С., Яковенко И.А. Железобетонные составные конструкции зданий и сооружений : монография. М.: АСВ, 2017. 248 с.

[27] Голышев А.Б., Колчунов В.И., Яковенко И.А. Сопротивление железобетонных конструкций, зданий и сооружений, возводимых в сложных инженерно-геологических условиях: монография. Киев: Талком, 2015. 371 с.

[28] Голышев А.Б., Колчунов В.И., Яковенко И.А. Сопротивление железобетонных конструкций, зданий и сооружений, возводимых в сложных инженерно-геологических условиях: монография. Киев: Талком, 2015. 371 с.

[29] Iakovenko I. The Development of Transformation Elements between the Fracture Mechanics Dependences and the Equations of the Reinforced Concrete Theory. *International Journal of Engineering & Technology*. 2018. Vol. 7(4.8), 58–64. URL: http://dx.doi.org/10.14419/ijet.v7i4.8.27214

[30] Баширов Х.З., Колчунов Вл.И., Федоров В.С., Яковенко И.А. Железобетонные составные конструкции зданий и сооружений : монография. М.: АСВ, 2017. 248 с.

the conducted experiments, reflected in scientific works, it was established that there can be several levels of cracking in reinforced concrete structures – up to three in the operational stage of the structure (loading of construction is about 60–80% of the ultimate load; when bringing the structure to complete destruction – up to five levels of cracks resistance) (for ex., Fig. 1.3). In more detail, schemes of the second level of crack formation[31] are presented in scientific monographs[32;33;34].

$$P_{1,*} = \frac{Q_{j+1,up}}{h_{j+1,up}} - \frac{Q_{j,up}}{h_{j,up}};$$

$$P_{2,*} = \left(\frac{Q_{j+1,up}}{h_{j+1,up}} - \frac{Q_{j,up}}{h_{j,up}}\right) \cdot t_* + \left(\frac{Q_{j+1,up}}{h_{j+1,up}} + \frac{Q_{j,up}}{h_{j,up}}\right) \cdot 0,5Stg\alpha_r;$$

$$I_{m,up} = \frac{b \cdot h_{m,up}^3}{12}; \qquad h_k = \frac{h - 2a_S}{2}; \qquad P_{3,*} = \frac{M_{j,up} + M_{j+1,up}}{2I_{m,up}};$$

$$P_{4,*} = \frac{M_{j,up} + M_{j+1,up}}{2I_{m,up}} \cdot \left(0,5h_{m,up} - t_*\right) + \frac{N_{j,up} + N_{j+1,up}}{2 \cdot b \cdot h_{m,up}};$$

$$P_{5,*} = \tau_{xy,m,up} = \frac{Q_{j,up} + Q_{j+1,up}}{2b \cdot h_{m,up}};$$

$$P_{6,*} = \frac{\mathrm{tg}^2\alpha_r - \mu_c}{\cos\alpha_r \cdot E_b \cdot \nu_c}; \qquad P_{7,*} = \frac{\left(\cos^2\alpha_r - \sin^2\alpha_r \cdot \mathrm{tg}^2\alpha_r\right)}{\nu_c \cdot E_c};$$

$$P_{8,*} = \frac{\left(\sin 2\alpha_r \mathrm{tg}^2\alpha_r + \sin 2\alpha_r\right)}{\nu_c \cdot E_c}; \qquad P_{9,*} = 1 - \left(\frac{\mu_c}{1 - \mu_c^2}\right) \cdot E_c \cdot \nu_c \cdot \cos\alpha_r \cdot P_{6,*};$$

$$P_{10,*} = \frac{E_c \cdot \nu_c}{1 - \mu_c^2} \cdot \frac{P_{6,*}}{P_{9,*}}; \qquad P_{11,*} = P_{3,*} \cdot P_{7,*} \cdot \frac{1}{P_{9,*}}; \qquad P_{12,*} = \frac{P_{4,*} \cdot P_{7,*} + P_{5,*} \cdot P_{8,*}}{P_{9,*}};$$

$$P_{13,*} = \frac{E_c \cdot \nu_c}{\left(1 - \mu_c^2\right)} \cdot \frac{S \cdot b}{\cos\alpha_r} - \frac{\mu_c}{\left(1 - \mu_c^2\right)} \cdot E_c \cdot \nu_c \cdot S \cdot b \cdot P_{10,*};$$

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[31] Яковенко І.А. Моделі деформування залізобетону на засадах механіки руйнування: дис. … докт. техн. наук: 05.23.01. Київ, 2017. 409 с. URL: https://nupp.edu.ua/uploads/files/0/main/page/specializovani-vcheni-radi/4405202/disertacii/2018-YakovenkoIA.pdf

[32] Баширов Х.З., Колчунов Вл.И., Федоров В.С., Яковенко И.А. Железобетонные составные конструкции зданий и сооружений : монография. М.: АСВ, 2017. 248 с.

[33] Голышев А.Б., Колчунов В.И., Яковенко И.А. Сопротивление железобетонных конструкций, зданий и сооружений, возводимых в сложных инженерно-геологических условиях: монография. Киев: Талком, 2015. 371 с.

[34] Бамбура А.М., Павліков А.М., Колчунов В.І. та ін. Практичний посібник із розрахунку залізобетонних конструкцій за діючими нормами України (ДБН В.2.6–98:2009) та новими моделями деформування, що розроблені на їхню заміну. Київ: Толока, 2017. – 627 с. URL: http://reposit.nupp.edu.ua/handle/PoltNTU/5380

$$P_{14,*} = P_{1,*} - \frac{\mu_c}{\left(1-\mu_c^2\right)} \cdot E_c \cdot \nu_c \cdot S \cdot b \cdot P_{11,*};$$

$$P_{15,*} = P_{2,*} + \frac{\mu_c}{\left(1-\mu_c^2\right)} \cdot E_c \cdot \nu_c \cdot S \cdot b \cdot P_{12,*}$$

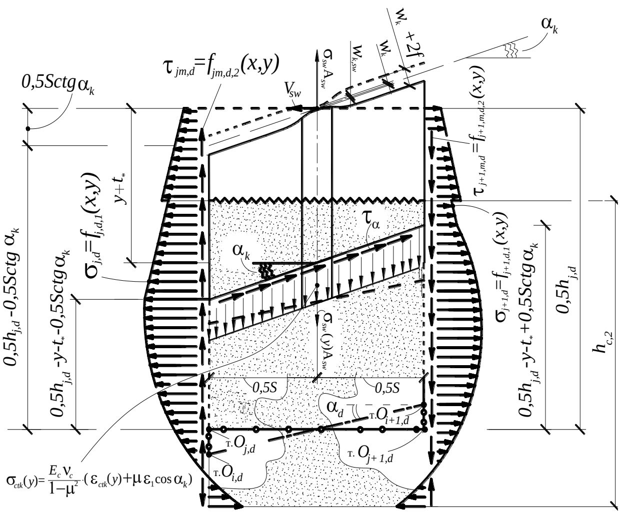

Fig. 1.3. A level model for determining the deformations of tensioned concrete $\varepsilon_{ctk}(y)$ along the axis of the transverse reinforcement of the *i*-th level of the formation of various types cracks[35] and the distance between them[36] in a reinforced concrete composite structures[37,38]

[35] Iakovenko I.A., Kolchunov V.I., Lymar I.V. Rigidity of reinforced concrete structures in the presence of different cracks. MATEC Web of Conferences. 6th International Scientific Conference «*Reliability and Durability of Railway Transport Engineering Structures and Buildings*». Transbud-2017. Kharkiv, Ukraine, April 19–21, 2017. Vol. 0216, 12 p. URL: https://doi.org/10.1051/matecconf/201711602016

[36] Колчунов В. И. Марьенков Н. Г., Яковенко И. А. Анализ схем трещин в железобетонных конструкциях сейсмостойких зданий и их учет по нормам Украины и еврокода 8. *Будівельні конструкції.* 2015. Вип. 82. С. 540-549. URL: http://nbuv.gov.ua/UJRN/buko_2015_82_61

[37] Усенко Н.В. Образование наклонных трещин первых двух типов в составных железобетонных конструкциях. *Промислове будівництво та інженерні споруди.* 2014. №1. С. 29–33. URL: http://nbuv.gov.ua/UJRN/Pbis_2014_1_7

[38] Усенко Н.В., Яковенко И.А., Колчунов В.И. Образование наклонных трещин третьего типа в железобетонных составных конструкциях. *Будівництво України*. 2013. Вип. 2. С. 24–28.

Denote,

$$\frac{1}{K} = 1 + \frac{E_{sw} \cdot A_{sw}}{P_{13,*}}. \quad (1.4)$$

Then, bond parameter of working reinforcement with tensioned concrete:

$$B_* = \frac{S_{sw} \cdot G}{A_{sw} E_{sw} K}. \quad (1.5)$$

After the differentiation (1.3) taking into account (1.5), we obtain:

$$\frac{d\varepsilon_g(y)}{dy} + B_*\varepsilon_g(y) = \frac{P_{14,*}}{P_{13,*}}. \quad (1.6)$$

The solution of the inhomogeneous differential equation of the first order (1.6) has the form:

$$\varepsilon_g(y) = \mathrm{C_{sw}} \cdot e^{-\mathrm{B}_* y} + \frac{P_{14,*}}{P_{13,*} \cdot B_{,*}}. \quad (1.7)$$

Continuous integration C_{sw} find from the boundary condition[39;40], according to which, with $y = 0$,

$$\varepsilon_g(y) = \varepsilon_{sw} + \frac{\Delta T}{E_{sw} A_{sw}} - \frac{\sigma_{ctk,c}}{\nu_c E_c}:$$

$$C_{sw} = \varepsilon_{sw} + \frac{\Delta T}{E_{sw} A_{sw}} - \frac{\sigma_{ctk,c}}{\nu_c E_c} - \frac{P_{14,*}}{P_{13,*} \cdot B_{,*}}. \quad (1.8)$$

In the equation (1.8) $\frac{\sigma_{ctk,c}}{\nu_c E_c}$ corresponds to deformations of concrete $\varepsilon_{ctk}(y)$ in a section located at a distance t_* from the section with a crack (Fig. 1.2). At the same time value $\sigma_{ctk,c}$ are accepted with the minus sign here and in all of the below formulas (Fig. 1.2).

Then,

$$\varepsilon_g(y) = \left(\varepsilon_{sw} + \frac{\Delta T}{E_{sw} A_{sw}} - \frac{\sigma_{ctk,c}}{\nu_c E_c} - \frac{D_{14,*}}{D_{13,*} \cdot B_*} \right) e^{-B_* y} - \frac{D_{14,*}}{D_{13,*} \cdot B_*}. \quad (1.9)$$

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39 Голышев А.Б., Колчунов Вл.И. Сопротивление железобетона. Киев: Основа, 2009. 432 с.

40 Колчунов Вл.И., Яковенко И.А. Об учете эффекта нарушения сплошности в железобетоне при проектировании реконструкции предприятий текстильной промышленности. *Известия ВУЗов. Технология текстильной промышленности*. 2016. №3 (363). С. 258–263. URL: https://www.researchgate.net/publication/316687268

From (1.1), taking into account (1.9) and (1.3), after algebraic transformations we obtain:

$$\varepsilon_{ctk}(y)=\frac{S_{sw}G}{E_{sw}A_{sw}}\left(\frac{1}{K}-1\right)\int_0^y \varepsilon_g(y)dy\,. \qquad (1.10)$$

The distance between the cracks s_r is determined on the basis of the second prerequisite from the condition that the elongation of the concrete on the surface of the design in the middle section (in the area between the cracks) is equal $\varepsilon_{ctk,u}$:

$$\varepsilon_{ctk}(y)\Big|_{y=0,5\,s_r-t_*}=\varepsilon_{ctk,u}\,. \qquad (1.11)$$

From the condition (1.11), taking into account $B_{2,*}\rightarrow 0$ we will get:

$$e^{-B_*(0,5s_r-t_*)}=1+\frac{\sigma_{ctk,c}}{\nu_c E_c B_{3,*}(K-1)}+\frac{\varepsilon_{ctk,u}}{B_{3,*}(K-1)}\,. \qquad (1.12)$$

Then, by analogy with the formulas given in the previous section, the parameter is determined $B_{4,*}$ with the corresponding constraints and calculates the functional distance between the cracks[41].

The distance between the cracks s_r is the most important parameter necessary for determining the width of the opening of cracks in reinforced concrete structures. Knowing the distance between cracks s_r, you can go to the definition of the width of the crack opening w_k.

Continuing the study of the width of the crack opening, the distance between the cracks in the reinforced concrete structures (including composites[42]) obtained by the author[43] below, the distribution of these dependencies in determining the width of the opening of cracks in reinforced concrete structures.

In this case, additional prerequisites are introduced to construct the calculation. The main ones are:

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[41] Голышев А.Б., Колчунов Вл.И. Сопротивление железобетона. Киев: Основа, 2009. 432 с.

[42] Баширов Х.З., Колчунов Вл.И., Федоров В.С., Яковенко И.А. Железобетонные составные конструкции зданий и сооружений : монография. М.: АСВ, 2017. 248 с.

[43] Яковенко І.А. Моделі деформування залізобетону на засадах механіки руйнування: дис. … докт. техн. наук: 05.23.01. Київ, 2017. 409 с. URL: https://nupp.edu.ua/uploads/files/0/main/page/specializovani-vcheni-radi/4405202/disertacii/2018-YakovenkoIA.pdf

$$-R_{\sup} \cdot a \cdot 0,5\sigma_{b,1} \cdot \frac{(h_o - x_B)(h_o x - \frac{1}{3}x^2 - \frac{1}{3}x \cdot x_B - h_o x + \frac{2}{3}x_B^2)}{(h_o x_B - 0,5x_B^2)^2}$$ crack opening is the accumulation of relative conditioned, reciprocal displacements of reinforcement and concrete on sections located on both sides of the crack in the case of longitudinal reinforcement and Figure 1.2 in the case of transverse reinforcement), – the development of the Thomas-Golyshev hypothesis[44;45];

$$-R_{\sup} \cdot a \cdot 0,5\sigma_{b,1} \cdot \frac{(h_o - x_B)(h_o x - \frac{1}{3}x^2 - \frac{1}{3}x \cdot x_B - h_o x + \frac{2}{3}x_B^2)}{(h_o x_B - 0,5x_B^2)^2}$$

account is taken of the additional discontinuity effect in the crack associated with the violation of the solidity of the material – in our case – it is reinforced concrete.

Thus, according to the first additional prerequisite, the problem is by definition w_k, is reduced to the finding of relative reciprocal displacement of the valve $\varepsilon_g(y)$ and concrete in different sections between cracks.

Deformation of concrete $\varepsilon_{ctk}(y)$ are determined from the equilibrium condition of the block located between a section with a crack and a cross section passing at a distance $y + t_*$ from the crack[46;47].

After performing algebraic transformations, we obtain the differential equation of the first order (1.8) whose solution is sought in the form (1.9). In this case, constant integration is determined by the formula (1.10), taking into account the boundary condition, according to which, with $\lambda_1 = C_2^2 \cdot \lambda_3 \cdot k_2 - k_1;$,

$$\varepsilon_g(y) = \varepsilon_{sw} - \frac{\sigma_{ctk,c}}{\nu_c E_c} + \frac{\Delta T}{E_{sw} A_{sw}}.$$

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[44] Верюжский Ю.В., Колчунов В. И. Методы механики железобетона. Киев: НАУ, 2005. 653 с.

[45] Голышев А.Б., Колчунов Вл.И. Сопротивление железобетона. Киев: Основа, 2009. 432 с.

[46] Баширов Х.З., Колчунов Вл.И., Федоров В.С., Яковенко И.А. Железобетонные составные конструкции зданий и сооружений : монография. М.: АСВ, 2017. 248 с.

[47] Яковенко І.А. Моделі деформування залізобетону на засадах механіки руйнування: дис. … докт. техн. наук: 05.23.01. Київ, 2017. 409 с. URL: https://nupp.edu.ua/uploads/files/0/main/page/specializovani-vcheni-radi/4405202/disertacii/2018-YakovenkoIA.pdf

It should be noted that the boundary between sections I and II is determined approximately – the distribution of stresses in concrete is sought in the form of one elementary function (more precisely, it would be descriptive of this distribution in each section by a separate function).

Now, according to additional prerequisites, you can record:

$$w_k = 2\int_0^{t_*} \varepsilon_g\left(y_1\right)dy_1 + 2\int_0^{0,5s_r - t_*} \varepsilon_g\left(y\right)dy\,, \qquad (1.13)$$

After integrating those algebraic transformations, we obtain:

$$w_k = -\frac{2\cdot\Delta T}{G} + \frac{2\cdot B_{3,*}}{B}\left(1 - e^{-B_*\cdot\left(0,5S_r - t_*\right)}\right) + 2\cdot B_{2,*}\left(\frac{s_r}{2} - t_*\right), \qquad (1.14)$$

where parameters $B_{2,*}$ i $B_{3,*}$ are determined according to next formulas:

$$s_r = \frac{2\left(\ln B_{4,*} - B_* t_*\right)}{-B_*} = \frac{2\ln B_{4,*}}{-B_*} + 2t_*\,. \qquad (1.15)$$

$$B_{3,*} = \varepsilon_{sw} + \frac{\Delta T}{E_{sw}A_{sw}} - \frac{\sigma_{ctk,c}}{\nu_c E_c} - B_{2,*} = \frac{q_{sw}S}{E_{sw}A_{sw}} + B_{a,1}\,, \qquad (1.16)$$

$$B_{a,1} = \frac{\Delta T}{E_{sw}A_{sw}} - \frac{\sigma_{ctk,c}}{\nu_c E_c} - B_{2,*}\,. \qquad (1.17)$$

$$B_4 = 1 + \frac{\sigma_{ctk,c}}{\left(K-1\right)B_{3,*}\nu_c E_c} + \frac{\varepsilon_{ctk,u}}{B_{3,*}\left(K-1\right)} = 1 + \frac{1}{B_{3,*}}\cdot B_{a,2}\,, \qquad (1.18)$$

$$B_{a,2} = \frac{1}{K-1}\cdot\left(\frac{\sigma_{ctk,c}}{\nu_c E_c} + \varepsilon_{ctk,u}\right). \qquad (1.19)$$

Substituting expressions (1.15) – (1.19) into equation (1.14) we obtain:

$$w_k = -\frac{2\Delta T}{G} - \frac{2B_{a,2}}{B_*} - \frac{2B_{2,*}}{B_*}\ln\left(1 + \frac{B_{a,2}\cdot A_{sw}E_{sw}}{q_{sw}S_{sw} + B_{a,1}A_{sw}E_{sw}}\right). \qquad (1.20)$$

As a result, the formula (1.20) is obtained for determining the width of the crack opening at the level of the axis of the transverse (longitudinal) reinforcement rod of reinforced concrete structures. Regarding the use of the proposed method of determining the width of the opening of cracks at the level of the axis of the working longitudinal working armature under different types of force and deformation load, a detailed reflection is given in scientific works[48;49;50].

On the basis of the conducted experimental studies[51;52] and the construction of a chain of two-cantilever elements[53] that connect the main provisions of fracture mechanics with the theory of reinforced concrete there can be useful to take these values to future Building Codes and Requirements[54] for reinforced concrete constructions for any types of buildings and facilities.

The direction of further research can be considered the development of numerical modelling of the parameters of bond working reinforcement with concrete, the moment of crack formation[55], the distances between cracks in modern software complexes (Lira-CAD, Sapphire, etc.).

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[48] Яковенко І.А. Моделі деформування залізобетону на засадах механіки руйнування: дис. … докт. техн. наук: 05.23.01. Київ, 2017. 409 с. URL: https://nupp.edu.ua/uploads/files/0/main/page/specializovani-vcheni-radi/4405202/disertacii/2018-YakovenkoIA.pdf

[49] Колчунов Вл.И., Яковенко И.А. Об учете эффекта нарушения сплошности в железобетоне при проектировании реконструкции предприятий текстильной промышленности. *Известия ВУЗов. Технология текстильной промышленности*. 2016. № 3 (363). С. 258–263. URL: https://www.researchgate.net/publication/316687268

[50] Голышев А.Б., Колчунов В.И., Яковенко И.А. Сопротивление железобетонных конструкций, зданий и сооружений, возводимых в сложных инженерно-геологических условиях: монография. Киев: Талком, 2015. 371 с.

[51] Колчунов В.И., Яковенко И.А., Дмитренко Е.А. Основные результаты экспериментальных исследований сцепления арматуры с бетоном при выдергивании и вдавливании деформационным воздействием с учетом ниспадающей ветви деформирования. *Вісник Кременчуцького національного університету імені Михайла Остроградського*. 2016. Вип. 5(100). С. 115–124. URL: http://www.kdu.edu.ua/PUBL/statti/2016_5_115_5-2016.pdf

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[53] Яковенко И.А. Трансформационный элемент, связывающий зависимости механики разрушения с теорией железобетона. *Наука та будівництво*. 2018. № 4 (18). С. 28–37. URL: http://journal-niisk.com/index.php/scienceandconstruction/article/view/54/52

[54] Голышев А.Б., Колчунов В.И., Яковенко И.А. Сопротивление железобетонных конструкций, зданий и сооружений, возводимых в сложных инженерно-геологических условиях: монография. Киев: Талком, 2015. 371 с.

[55] Дмитренко Є.А., Яковенко І.А. Чисельне моделювання моменту утворення тріщин у залізобетонних конструкціях із застосуванням ПК «САПФІР». *Ресурсоекономні матеріали, конструкції, будівлі та споруди* : зб. наук. праць. Рівне : НУВГП, 2021. Вип. 39. С. 74–83. URL: https://bud.nuwm.edu.ua/index.php/budres/issue/view/15

2. The influence of the main design parameters on the width of crack opening (w_k)

In accordance with the developed calculation algorithm[56], the necessary restrictions are introduced. Emphasis should be placed on the fact that when studying the influence of the main design parameters, it is necessary to take into account the limitations adopted in the construction of the calculation algorithm. These limitations will be reflected in each graph. At the same time, for convenience of description, we denote the introduced restrictions as follows:

– *limitation (1)* – corresponds to the inequality $s_r \geq 6t_*$, those the last physically possible level of cracking;

– *limitation* (2) – $\begin{cases} s_r \geq -2 \cdot \dfrac{\ln\left(1 - \dfrac{\Delta T \cdot B}{B_3 \cdot G}\right)}{B} + 2t_* \\ w_k \geq 0 \end{cases}$, condition resulting from physical limitation (when there are no cracks);

– *limitation* (3) – $s_r \geq 2 \cdot \dfrac{0,527}{B} + 2t_*$ obtained from the analysis of graphs, where his analytical conclusion is displayed;

– *limitation* (4) – $0 < B_4 \leq \dfrac{B}{0,3}$;

Study of the influence of the main design parameters on the width of crack opening (w_k)

On the basis of the conducted numerical studies of the crack opening width of reinforced concrete structures, let us analyze the plots of the crack opening widths w_k from various factors influencing the indicators of given values using the example of a full–scale sample of reinforced concrete structure, shown in Fig. 2.1 – the number of experiment construction is ЗБК – 18–18.

[56] Яковенко І.А. Моделі деформування залізобетону на засадах механіки руйнування: дис. … докт. техн. наук: 05.23.01. Київ, 2017. 409 с. URL: https://nupp.edu.ua/uploads/files/0/main/page/specializovani-vcheni-radi/4405202/disertacii/2018-YakovenkoIA.pdf

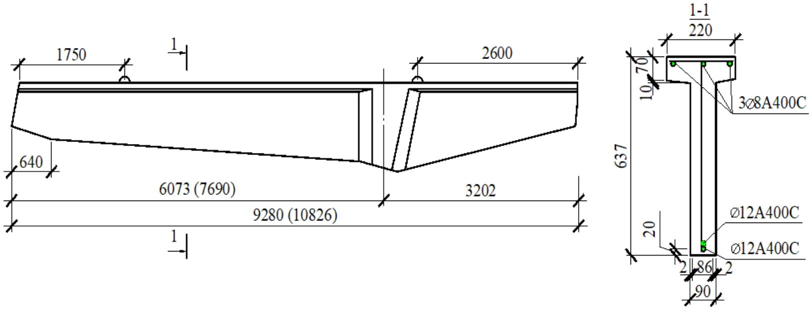

Fig. 2.1. Construction and reinforcement experiment "natural" construction ЗБК – 18–18 (geometric parameters of the structure, transverse and longitudinal reinforcement, detailed calculation of formation, width of crack opening and distances between cracks with a multi-level scheme of their formation as proposed by I.A. Yakovenko models of deformation of reinforced concrete taking into account the effect of breaking the integrity of concrete are given in the work[57], example No. 40)

Note: *the life-size experiment was carried out at the State Research Institute of Building Constructions, Kiyv by Kolchunov V.I. at the science school of prof. Golishev O.B.*

Variation of the diameter of the working reinforcement

When changing the diameter of the reinforcement Ø8, Ø10, Ø12, Ø14, Ø16, Ø18 *mm*, parameter dependency is determined B from the cross–sectional area of the reinforcement A_S, perimeter section of reinforcement S_S and, accordingly, the width of the crack opening changes w_k.

Coefficient K varies, as it depends on the percentage of reinforcement, i.e. on the diameter of the reinforcement. Voltage change σ_S reflected on the magnitude of the deformations ε_S rebar in a crack.

The following values are constant in this case $\sigma_{ctk,c}, \Delta T, E_S, E_{cm}, \varepsilon_{ctk,u} = const$.

Parameters B_3, B_4 change during the calculation.

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[57] Бамбура А.М., Павліков А.М., Колчунов В.І. та ін. Практичний посібник із розрахунку залізобетонних конструкцій за діючими нормами України (ДБН В.2.6–98:2009) та новими моделями деформування, що розроблені на їхню заміну. Київ: Толока, 2017. – 627 с. URL: http://reposit.nupp.edu.ua/handle/PoltNTU/5380

Analyze the dependence of the width of the crack opening, on the diameter of the reinforcement d, when it changes from Ø 8mm to Ø18 *mm* with step 1 *mm* (Fig. 2.2 *a, b*).

The analysis of the obtained dependence shows, with an increase in the diameter of the reinforcement, the width of the crack opening tolerates a change in direction: ascending (to Ø 10*mm*) on decreasing (to Ø 10*mm*) with a functional value s_r, without limitation (1) (Fig. 2.2, *a*, curve 2).

Virtually all of the studied area graphs of functional value s_r, without restrictions and with restriction (1), approach each other (Fig. 2.2 *a*, curves 1 and 2), and, restriction (1) changes the direction of the functional value s_r from increasing to decreasing.

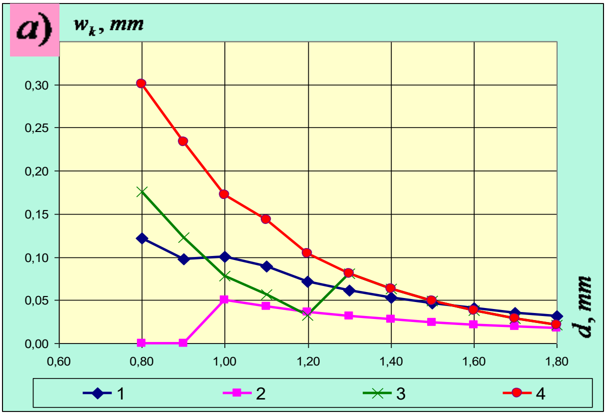
The same dependences are characteristic for level values s_r with restriction and without restriction (1) (Fig. 2.2 *a*, curves 3 and 4). Moreover, in almost the entire study area, there is a tendency for functional and level values to converge, which indicates a qualitative similarity of physical processes (Fig. 2.2, *a*, curves 1–4).

If we take into account the restriction (1), then as the diameter of the reinforcement increases, the width of the crack opening gradually decreases, moreover, as for s_r leveled so for s_r functional (Fig. 2.2, *a*, curves 1, 3, 4).

It should be noted that the introduction of a restriction (4) concerning B_4, correctly reflects the qualitative nature of the processes. At the same time, the above–noted tendencies of convergence of the level and functional values l_{crc} with constraint (1), fig. 2.2, *b* curves 1–4.

Analyze the dependence of the width of the crack opening w_k from the cross–sectional area of the reinforcement, when changing the diameter from Ø 8mm to Ø18 mm with a step of 1 *mm* (Fig. 2.3, *a*, *b*). The analysis of the obtained dependence shows, with an increase in the cross–sectional area of the reinforcement, the width of the crack opening tolerates a change in direction: from increasing (to 1.5 cm^2) to decreasing (from 1.5 cm^2) with a functional value s_r, without limitting (1) (Fig. 2.3, *a, curve* 2).

Practically on all investigated graphs of functional value s_r, without restrictions and with restriction (1), approach each other (Fig. 2.3, *a*, curves 1 and 2), and, restriction (1) changes the direction of the functional value s_r from increasing to decreasing.



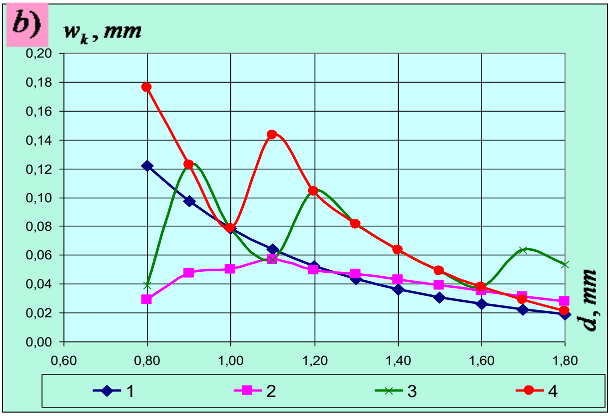
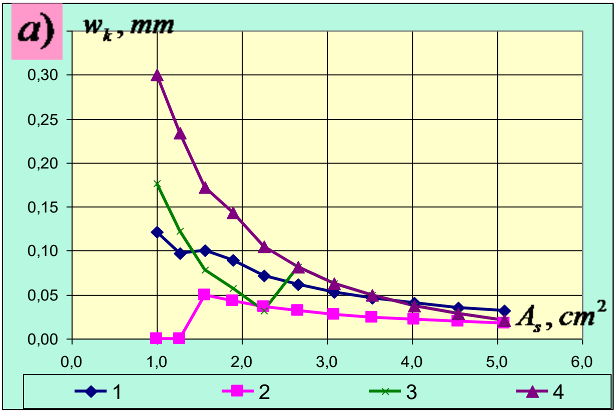


Fig. 2.2. Graphs of the width of the crack opening w_k on the diameter of the reinforcement: *a* – without taking into account the limitation on the parameter $B_4 \le B / 0,3$; *b* – subject to limitations $B_4 \le B / 0,3$; 1 – at s_r functional with constraint (1); 2 – at s_r functional without limitation (1); 3– at s_r level without restriction (1); 4 – at s_r level constrained (1)



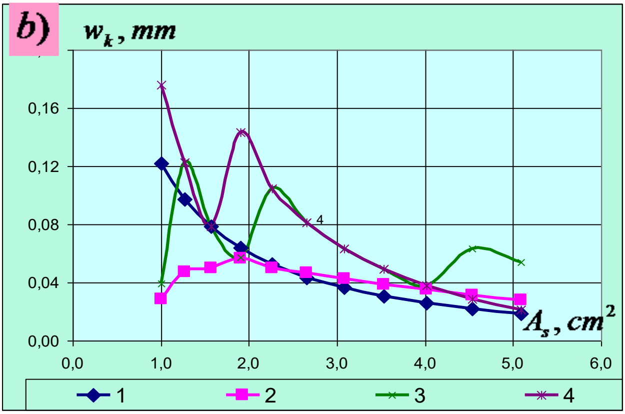


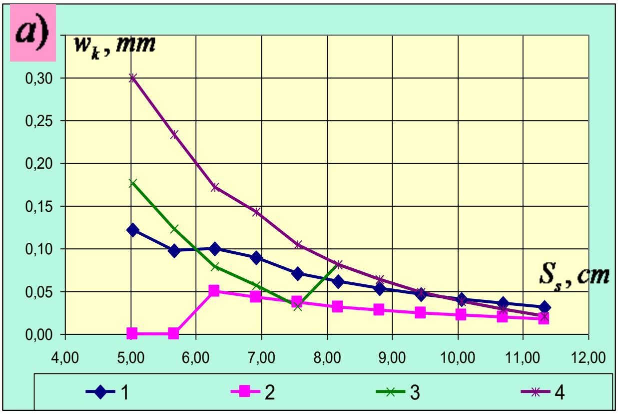
Fig. 2.3. The plots of the crack opening width versus the reinforcement cross–sectional area:
a **– without considering the parameter limitation** $B_4 \leq B/0,3$**;**
b **– subject to limitations** $B_4 \leq B/0,3$**;**

The same dependences are characteristic for level values. s_r with restriction and without restriction (1) (Fig. 2.3, *a*, curves 3 and 4).

Moreover, in almost the entire study area, there is a tendency towards the convergence of functional and level values, which indicates a qualitative similarity of physical processes (Fig. 2.3, *a*, curves 1–4).

If we take into account the restriction (1), then with increasing the cross–sectional area of the reinforcement, the crack opening width gradually decreases, moreover, as for s_r leveled so for s_r functional (Fig. 2.3, *a*, curves 1, 3, 4).

It should be noted that the introduction of the restriction (4) relating to correctly reflects the qualitative nature of the processes taking place (Fig. 2.3, *b*).



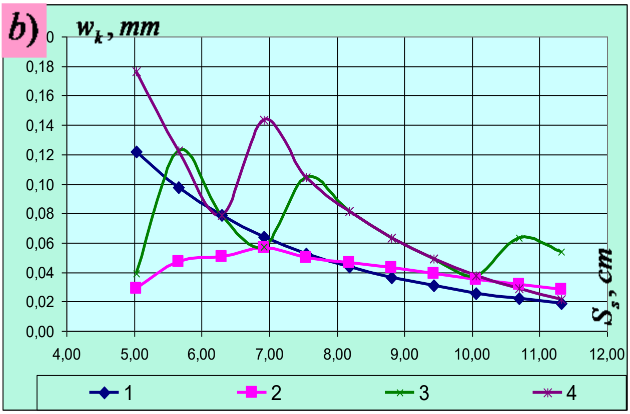


Fig. 2.4. Plots of crack opening width versus reinforcement perimeter: a – without taking into account the limitation on the parameter $B_4 \leq B / 0,3$; b – subject to limitations $B_4 \leq B / 0,3$;

1 – at s_r functional with limitation (1); 2 – at s_r functional without limitation (1); 3– at s_r level without restriction (1); 4 – at s_r level constraint (1)

At the same time, the above–noted tendencies of convergence of the level and functional values s_r with constraint (1), fig. 2.3, *b* curves 1–4.

Analyze the dependence of the width of the crack opening w_k from the perimeter of the reinforcement, when the diameter changes from Ø 8 *mm* to Ø18 *mm* with a step of 1 *mm* (Fig. 2.4, *a*, *b*).

The analysis of the obtained dependence shows, with increasing the perimeter of the reinforcement, the width of the crack opening tolerates a change in direction: from increasing (to 6.2 *cm*) to decreasing (from 6.2 *cm*) with a functional value s_r, without limitation (1) (Fig. 2.4, *a*, curve 2).

Virtually the entire study area, the graphs of functional value s_r, without restrictions and with restriction (1), approach each other (Fig. 2.4, *a*, curves 1 and 2), and, restriction (1) changes the direction of the functional value s_r from increasing to decreasing.

The same dependences are characteristic for level values s_r with restriction and without restriction (1) (Fig. 2.4 *a*, curves 3 and 4).

Moreover, in almost the entire study area, there is a tendency towards the convergence of functional and level values, which indicates the qualitative similarity of physical processes (Fig. 2.4, *a*, curves 1–4).

If we take into account the restriction (1), then as the reinforcement perimeter increases, the width of crack opening gradually decreases, moreover, as for s_r leveled so for s_r functional (Fig. 2.4, *a*, curves 1, 3, 4).

It should be noted that the introduction of a restriction (4) concerning B_4, correctly reflects the qualitative nature of the processes. At the same time, the above–noted tendencies of convergence of the level and functional values s_r with constraint (1), fig. 2.4, *b* curves 1–4.

Let us analyze the dependence of the width of crack opening w_k from the ratio of the perimeter to the area of the reinforcement, when the diameter changes from Ø 8 *mm* to Ø18 *mm* with a step of 1 *mm* (Fig. 2.5, *a*, *b*).

The analysis of the obtained dependence shows, with an increase in the ratio of the perimeter to the area of the reinforcement, the width of the crack opening tolerates a change in direction: from increasing (to 4) to decreasing (from 4) with a functional value s_r, without limitation (1) (Fig. 2.5, *a*, curve 2).

Virtually the entire study area, the graphs of functional value s_r, without limitations and with constraint (1), approach each other (Fig. 2.5, *a*, curves 1 and 2), and, constraint (1) changes the direction of the functional value from decreasing to increasing.

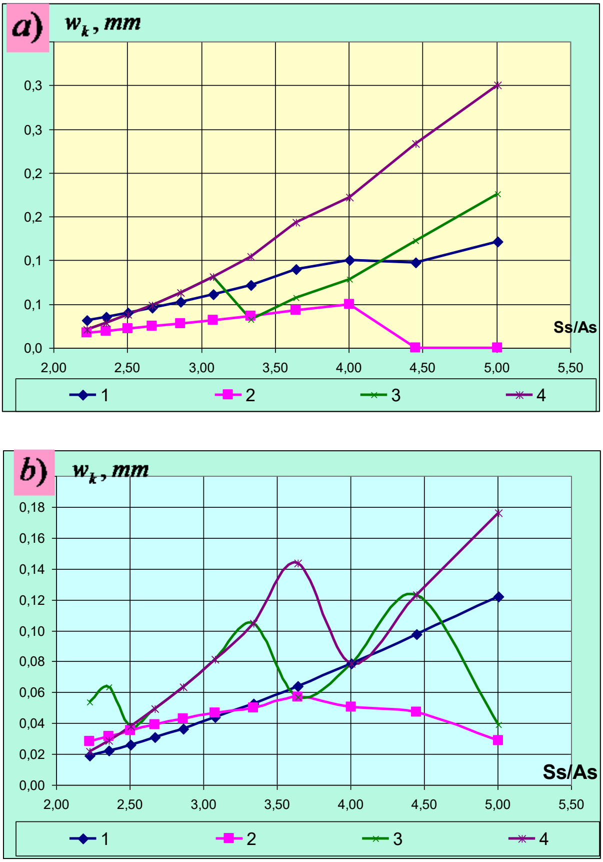


Fig. 2.5. Graphs of the width of the crack opening on the ratio of the perimeter to the area of the reinforcement: *a* – without taking into account restrictions on the parameter $B_4 \le B/0,3$; *b* – subject to limitations $B_4 \le B/0,3$;

1 – at s_r functional with limitation (1); 2 – at s_r functional without limitation (1); 3– at s_r level without restriction (1); 4 – at s_r level with constraint (1)

The same dependences are characteristic of the level values with the restriction and without the restriction (1) (Fig. 2.5, *a*, curves 3 and 4). Moreover, in almost the entire study area, there is a tendency towards the convergence of functional and level values, which indicates a qualitative similarity of physical processes (Fig. 2.5, *a*, curves 1–4).

If we take into account the restriction (1), then as the ratio of the perimeter to the area of the reinforcement increases, the width of the crack opening increases smoothly, moreover, as for s_r leveled so for s_r functional (Fig. 2.5, *a*, curves 1, 3, 4).

It should be noted that the introduction of a restriction (4) concerning B_4, correctly reflects the qualitative nature of the processes. At the same time, the tendencies of approaching the level and functional values noted above with the constraint (1) are also observed in Fig. 2.5, *b*, curves 1–4.

CONCLUSIONS

There were developed two-cantilever elements in the presence of different cracks in reinforced concrete structures for different types of resistance, which act as transformational elements between adapted, in relation to reinforced concrete, dependencies of fracture mechanics and dependencies of the theory of reinforced concrete by prof. Yakovenko I.A.

Developed new calculation schemes of the second level are proposed for determining the formation of cracks, the width of their opening and multi-level distances between them at the scientific school of prof. Golyshev O.B.

These calculation schemes of the second level cracks formation proposed new calculation models of reinforced concrete structures for determining the formation of cracks, the resistance of tensioned concrete between cracks in reinforced concrete structures, the distance between cracks and the width of the opening of cracks, which are based on the basic principles of fracture mechanics.

On the basis of the conducted numerical studies of the influence of reinforcement parameters on the developed model of the crack opening width of reinforced concrete structures, analytical dependences of the change in the crack opening width were constructed.

The obtained dependences on how the diameter of the working longitudinal reinforcement, the area of the working reinforcement, the perimeter of the entire working reinforcement and their ratio affect the width of the opening of cracks in reinforced concrete structures.

These dependencies are confirmed by detailed analysis of experimental data and physical content – taking into account the effect of discontinuity that occurs in reinforced concrete structures.

The theoretical and practical value of the scientific work is to analyze the influence of reinforcing parameters, the crack strength of reinforced concrete structures that on the basis of the proposed model of crack strength of reinforced concrete structures. This allows us to identify the reserves for efficient use of materials in the rational design of reinforced concrete constructions.

SUMMARY

The presented scientific work is devoted to the numerical analysis of the influence of reinforcement (diameter, area and perimeter) on the proposed I.A. Yakovenko's. model for calculating crack resistance (formation and width of crack opening) of reinforced concrete structures for industrial, agrocultural, public, civil buildings and engineering structures.

The study of the parameters of the stress-strain state for the assessment of crack resistance was performed on the experiment full-scale structure 3BK–18–18, which was chosen by the authors as a reference sample. It was established how the crack opening width depends on the percentage of reinforcement, diameter and perimeter of the working reinforcement. The numerical study was carried out taking into account the multi-level scheme of the formation and propagation of cracks, the parameters of the connection of reinforcement with concrete, the effect of breaking the continuity.

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