

Current state and prospects of development of diagrammatic methods for the calculation of reinforced concrete structures

O V Radaikin², L S Sabitov^{1,3}, N F Kashapov¹, I R Gilmanshin^{1,4}

¹Kazan Federal University, 18 Kremlyovskaya street, Kazan, 420066, Russian Federation

²Kazan State University of Architecture and Civil Engineering, Kazan, 420043 Russia

³Kazan State Power Engineering University, Kazan, 420008, Russian Federation

⁴Kazan national research technical university named after A N Tupolev, K. Marx St. 10, Kazan, 420111 Tatarstan, Russia

l.sabitov@bk.ru

Abstract. The article presents the current state and prospects of development of diagrammatic methods for the calculation of reinforced concrete construction. A brief review obtained by the authors results in this area, where great attention is paid to the improvement of curvilinear diagrams of concrete for different types of static loading of structures. Topical application of the considered methods for the analysis of structures in the zone of joint action of bending moments and shearing force that is not yet reflected in domestic and foreign regulations. In conclusion, the publication identifies ways for further research in the chosen area.

Due to the rapid development of computer technology and information technology, it has become possible in recent years to widely introduce into the engineering practice the design of reinforced concrete structures for nonlinear calculation methods. Among them, the most widely used are diagrammatic methods, using diagrams of deformation of materials in direct form. In 2003, the diagram method called "nonlinear deformation model" entered into the Russian norms - SNiP 52-01-2003 and further in SP 63.13330.2012. Thus, a significant step was taken to harmonize the domestic and European Norms, where the diagrams of the deformation of concrete and steel reinforcement as a calculated basis have been in existence since 1978 [1]. Nevertheless, in Russia in the modern form, the nonlinear deformation model and its physical relationships were first proposed in [2] in the 80s of the last century, and in [3] this model was developed with reference to the calculation of core structures in increments. The development and improvement of the diagram methods and the nonlinear deformation model in particular in our country were dealt with by Baikov V.N., Bondarenko V.M., Bondarenko S.V., Gvozdev A.A., Guscha Yu.P., Dodonov M.I., Dykhovich A.A., Il'in O.F., Karpenko N.I., Karpenko S.N., Lazovsky D.N., Lemys L.L., Mitasov V.M., Murashev V.I., Mukhamediev T.A., Rastorguev B.S., Sapozhnikov M.A. and others. Among foreign researchers, Leonhard F., L. Saenz, B. Sinha, P. Desayi, S. Krisnan, K. Gerstle, L. Tulin, Kabeila and many others were engaged in this issue. etc. As the literature analysis and own studies [4-14] show, the diagrammatic methods allow calculating strength, deformability and fracture toughness on the basis of a unified approach that makes it possible to

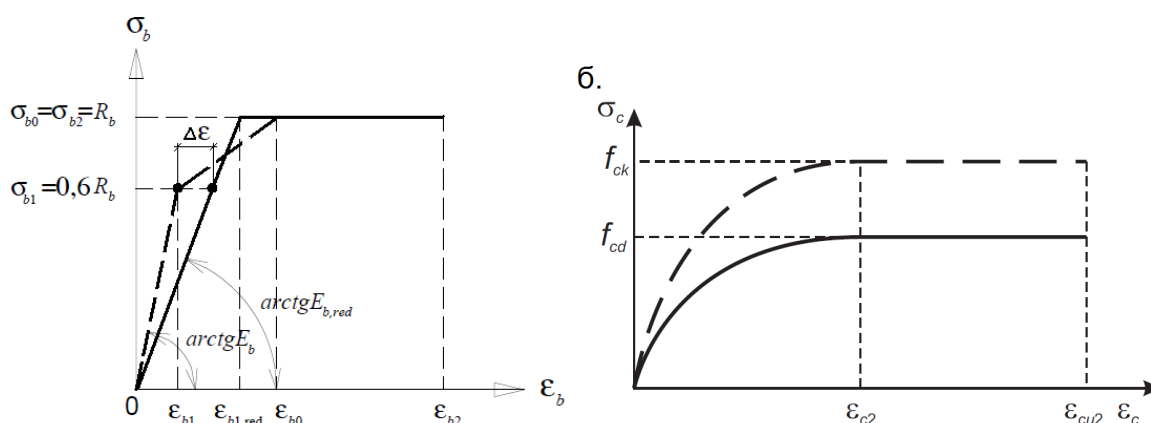


describe the stress-strain state of structures at all stages of loading - from the beginning of work up to destruction - taking into account the physical nonlinearity of materials and the development of cracks. Moreover, the authors obtained a material where, for the first time using the nonlinear deformation model, the calculation of the width of the opening of normal cracks in bent elements was brought to the final result and compared with the experimental data [15].

In deriving the calculated relations of diagrammatic methods, the equations of equilibrium of internal and external forces are used, the compatibility conditions for deformations in the form of a hypothesis of flat sections (in reinforced concrete elements with cracks in the interpretation of V.I. Murashev and improved by A.A. Gvozdev in relation to the average deformations of reinforcement and concrete in the area between the cracks) and the deformation diagram (in some sources - the state diagram) of the materials. The solution of the system of defining equations thus obtained in most cases is possible only numerically with the use of a computer, for example, by the method of stepwise iterations. For this purpose, the design sections of reinforced concrete elements are divided into elementary areas, and the stresses within each of them are averaged.

Most often, state diagrams relate the stresses and relative deformations arising in the material under simple uniaxial loading-stretching or compression (for example, « σ_{bt} - ε_{bt} » and « σ_b - ε_b » for concrete in Fig. 1).

a.



B.

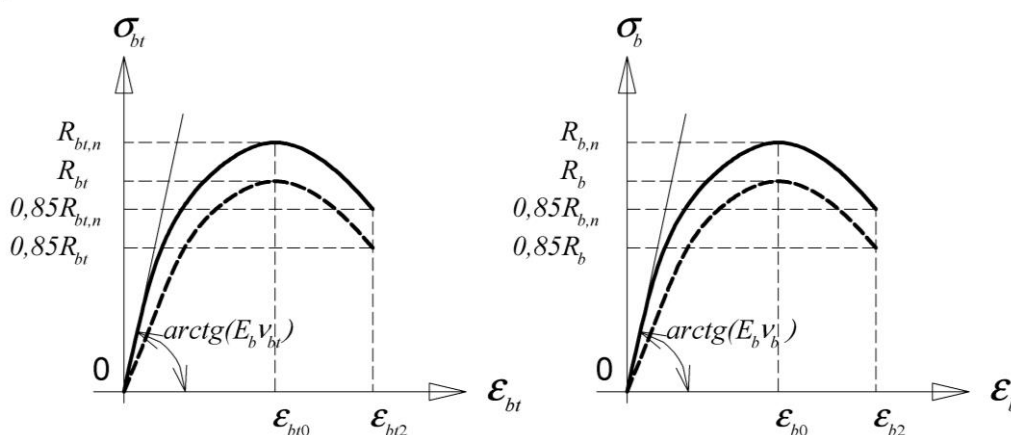


Fig. 1. Diagrams of deformation of concrete, constructed by methods:

a – CII 63.13330.2012; б – EuroCod-2; в – [4,7] (—normative diagrams, --- calculated)

More rarely, the diagrams obtained for two- and three-axis loads [16] are used. For example, in the norms of the Republic of Belarus - SNB 5.03.01-02 "Concrete and Reinforced Concrete Structures" - they are used in the calculation of a compressed-stretched concrete strip between inclined cracks.

In addition, load-balancing and deformation (moving) diagrams are used: for example, « $N-\Delta$ » for centrally compressed reinforced concrete columns, « $M-f$ » or « $M-1/r$ » for curved reinforced concrete beams. In this case, the work of the structure as a whole, and the material from which they are made to treat as a homogeneous composite with averaged in volume or cross-section properties, is estimated from them. In "Recommendations for calculating the skeletons of multi-storey buildings, taking into account the compliance of the node interfaces of prefabricated reinforced concrete structures" (TsNIIpromzdaniy, 2008), these diagrams are included.

Below are the data on the topic under consideration, obtained by the author together with prof. Sokolov BS and prof. Karpenko N.I.

At the first stage of the research, the question was solved which diagrams to give preference, since the results of the calculation depend on their type. In [4-6], the diagrams proposed by Academician N.I. Karpenko [16] and included in SP_63.13330.2012, as most fully responding to experiments. Taking into account the new theoretical and experimental data obtained in recent years, improvements have been made to them - in the expressions describing the diagrams, corrective coefficients have been chosen, which made it possible to approximate the calculated values of the cracking moment M_{crc} and the breaking moment M_{ult} in bent ferro-concrete elements, obtained by the diagram technique and by formulas SNIP 2.03.01.84 *. The choice of this SNiP as a "benchmark" for comparison is justified by the fact that this technique has passed more than 30 years of experimental testing and proved to be reliable in practice. After that, in [5], the results of the calculation of deformations of bent ferro-concrete elements are compared using the deformation model and various types of deformation diagrams of concrete and steel reinforcement, including those proposed by the authors. For comparison with the "standard" - with SNIP 2.03.01.84 * - three calculated approaches to the construction of material state diagrams are adopted: SP 52-01-2003; Eurocode-2; own theoretical developments. It is found that the discrepancy between the results in determining the stiffness of the cross-section, the moments M_{crc} and M_{ult} by the compared methods depends on the type of material state diagrams adopted, the concrete strength class, the reinforcement percentage and the loading level. The reasons for the discrepancy are analyzed, which consist in the difference between the analytical prerequisites for constructing diagrams and in the difference between the approaches of domestic and foreign Norms to determining the strength of concrete for tension and compression. When the rigidity of the bent ferro-concrete elements changed with increasing load, better convergence with SNiP 2.01.03-84 * showed the results obtained by the proposed method, which, as established in [6], also has satisfactory convergence with the experimental data of KA. Piradova, S.S. Vatagina and TA. Mukhamediyeva.

For the purpose of differentiated application in the calculation of reinforced concrete elements for the first and second groups of limiting states, the diagrams of concrete deformation are presented in [7] on the basis of unified mathematical expressions in the form of normative and calculated (working) ones. The transition between them was carried out by introducing the reliability coefficients for concrete: $\gamma_{bt}=R_{bt,n}/R_{bt}=1,5$ и $\gamma_b=R_{b,n}/R_b=1,3$.

In [8], the moment of crack formation in bent ferro-concrete elements was determined using a nonlinear deformation model with an inhomogeneous distribution of deformations along the height of the stretched zone of the element, which was achieved by introducing into the calculated expressions a coefficient that takes into account the gradient of deformations. This allowed obtaining the values of the sought-for moment close to the procedure of SNiP 2.03.01-84 *.

The second stage of scientific research was the consideration of eccentrically compressed concrete elements. In [9], the analysis of the strength, rigidity and fracture toughness of such elements was analyzed using a nonlinear deformation model using various diagrams of concrete deformation. On the basis of a unified approach, all stages of the work of elements are considered - from the beginning of loading up to destruction. To estimate the influence of the longitudinal force on the stress-strain state of eccentrically compressed elements, bending elements having analogous physicomachanical and geometric characteristics were also calculated. It is established that the type of diagrams considered does not practically affect the final result when determining the bending

moments of crack formation and fracture, but it affects the value of the calculated stiffness of the cross section. In addition, it was found that the influence of the longitudinal force on the rigidity, especially at the initial stages of loading, as well as on the breaking bending moment, is significant and depends on the percentage of reinforcement and the eccentricity of the longitudinal force. It is concluded that the concrete state diagrams obtained by the authors earlier for bent elements can be used for calculation of eccentrically compressed ones.

The third stage of the research is related to the consideration of the work of reinforced concrete bending elements in the zone of joint action of bending moments (M) and shearing forces (Q). It should be noted that, according to Russian standards, the strength of bent elements in the "shear span" for the action of M and Q is carried out separately, despite the experimentally established mutual influence of these power factors on the VAT of the structures. In addition, in most of the known calculation methods for bent structures, one assumes the assumption of flat sections as one of the prerequisites, which, as experiments show, do not occur with the appearance of inclined cracks in the "shear span". Preliminary work [10] in PC "Ansys" carried out computer simulation of the stress-strain state of bent concrete and reinforced concrete elements in the considered zone, taking into account cracks both normal and inclined to the longitudinal axis. These data served as the basis for the development of a technique for calculating oblique sections using the nonlinear deformation model [11, 12]. For this purpose, using the mathematical analysis software of MathCAD, an algorithm for calculation of concrete and reinforced concrete beams has been developed that takes into account the loading scheme, nonlinear properties of concrete and reinforcement, and the appearance and development of normal and inclined cracks. The algorithm allows us to use the diagrams of the state of concrete obtained by the authors earlier.

Generalizing the obtained data, an attempt was made in [13, 14] to develop, using a nonlinear deformation model, a unified methodology for calculating reinforced concrete bending elements for two groups of limiting states, both for normal and inclined sections. Comparison of the results of the numerical calculation with the experiment showed a satisfactory coincidence of the data - a difference of no more than 10%.

Further, the generalized technique was supplemented by the possibility to calculate the crack opening width a_{cr} from the value of the average deformations in the stretched reinforcement, which was done for the first time using the nonlinear deformation model [15]. Comparison of the calculation results with the experiment showed that the proposed procedure allows to reliably determine the value of a_{cr} .

At the moment, the research will continue. - An attempt is made to consider the influence of different loading schemes of structures, the shapes of their cross sections, the percentage of longitudinal reinforcement, the type of material deformation diagrams, the joint development of normal and inclined cracks, the presence of prestressed reinforcement, the redistribution of forces in statically indeterminate structures, the calculation of pipe-, steel-, fiber-reinforced concrete elements, as well as using diagram methods to study the work of reinforced concrete elements reinforced with composite reinforcement.

Conclusions:

1. The present state of the development of diagrammatic methods for calculating reinforced concrete structures is highlighted. A brief review of the results obtained by the author in this area is given, where great attention is paid to improving curvilinear diagrams of concrete state in relation to various types of static loading of reinforced concrete structures: pure bending, eccentric compression, joint action of bending moments and shear forces. It is shown that the diagrammatic methods make it possible to calculate the strength, deformability and fracture toughness on the basis of a single approach, which makes it possible to describe the stress-strain state of structures at all stages of loading - from the beginning of work up to destruction - taking into account the physical nonlinearity of materials and the development of cracks.
2. The ways of further research on the chosen direction are outlined. The data obtained will serve as the basis for the development of a software package for the automated calculation of reinforced

concrete structures with various reinforcement schemes and loading applications using the diagram method.

References

- [1] Code-sample of ECB-FMP / For the norms on SCR. - T.11. - Euro-International Committee for Concrete. - Moscow: 1984. - 263 p
- [2] Karpenko N I, Mukhamediev T A, Sapozhnikov M A 1987 *To the construction of a technique for calculating the rod elements on the basis of material deformation diagrams* Perfection of methods for calculating statically indeterminate reinforced concrete structures pp 4-24
- [3] Karpenko S N 2010 *On the construction of connections between the increments of stresses and deformations on the basis of various diagrams* Bulletin of Civil Engineers No 1 (22) pp 60-63
- [4] Karpenko N I, Radaykin O V 2012 *To improve the diagrams of concrete deformation for determining the cracking and fracturing moment in bent ferro-concrete elements* // Construction and Reconstruction No 3 (41) pp 10-17
- [5] Karpenko N I, Sokolov B S, Radaykin O V 2012 *To definition of deformations of bent ferro-concrete elements with use of diagrams of deformation of concrete and armature* // Construction and Reconstruction No 2 pp 11-20
- [6] Radaykin O V 2012 *To the diagram method of calculation of bent ferro-concrete elements* // Proceedings of the 1st International (VII All-Russian) Conference "New in Architecture, Design of Building Structures and Reconstruction" (NASSCR) pp 87-91
- [7] Karpenko N I, Sokolov B S, Radaykin O V 2013 *Analysis and improvement of curvilinear diagrams of concrete deformation for the calculation of reinforced concrete structures by the deformation model* Industrial and civil construction No 1 pp 25-27
- [8] Karpenko N I, Sokolov B S, Radaykin O V 2013 *Perfection of the calculation procedure for bent ferro-concrete elements without preliminary stress by the formation of normal cracks* // Journal of Building Materials No 6 pp 54-55
- [9] Karpenko N I, Sokolov B S, Radaykin O V 2013 *To calculate the strength, rigidity and crack resistance of eccentrically compressed reinforced concrete elements using a nonlinear deformation model* Izvestiya KazGASU No 4 (26) pp 113-120
- [10] Sokolov B S, Radaykin O V 2014 *Investigation of the stress-strain state of concrete and reinforced concrete bending elements in the zone of joint action of bending moments and shear forces* Proceedings of the VIII Academic Readings of RAASN - International STC "Mechanics of Destruction of Building Materials and Structures" pp 312-17
- [11] Sokolov B S, Radaykin O V 2014 *To calculate the deflections of bent reinforced concrete elements, taking into account the joint action of bending moments and break forces using the nonlinear deformation model* Izvestiya KGASU No 4 p 37
- [12] Sokolov B S, Radaykin O V 2014 *To the calculation of the stiffness of normal sections of reinforced concrete bending elements under the joint action of bending moments and shear forces* Proceedings of the II International Scientific Conference NASKR-2014 pp 201-205.
- [13] Sokolov B S, Radaykin O V 2015 *To the construction of a unified methodology for calculating the strength, rigidity and crack resistance of bent ferro-concrete elements, taking into account the joint action of bending moments and shearing forces with the application of a nonlinear deformation model* Fundamental studies of the RAASN on the scientific support of the development of architecture, urban planning and the construction industry of the Russian Federation in 2014 pp 589-99
- [14] Sokolov B S, Radaykin O V 2015 *To the definition of the curvature of concrete and reinforced concrete elements along the span, taking into account the joint action of bending moments and shear forces* Construction and Reconstruction No 2 (58) pp 38-41

- [15] *To the evaluation of strength, rigidity, the moment of crack formation and their opening in the zone of pure bending of reinforced concrete beams with the use of a nonlinear deformation model* 2016 Izvestiya Vuzov. Building No 3 (687) pp 5-10
- [16] Karpenko N I 1996 *General models of mechanics of reinforced concrete* (Moscow: Stroiizdat) p 416