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Approximation Models of the Method of Design Resistance of Reinforced Concrete for Bending Elements with Double and Multirow Reinforcement

Vasyl Rizak, Dmitro Kochkarev, Anna Azizova, and Tatiana Galinska

Abstract Approximation models of the method of design resistance of reinforced concrete were considered for the calculation of normal sections of reinforced concrete bending elements with double and multirow reinforcement. It is proposed to use approximation dependences of two types—polynomial and linear. Approximation models were developed based on the method of design resistance of the reinforced concrete, which is based on generally accepted theoretically proved assumptions and hypotheses. This method is based on the use of nonlinear diagrams of concrete deformation, acception of the Bernoulli hypothesis, and the usage of the extreme criterion for determining the bearing capacity based on the nonlinear deformation model of calculation. The proposed approximation formulas can greatly simplify the calculation of reinforced concrete bending elements with double and multi-row reinforcement. They eliminate the need for the usage of tables and the performance of complex calculations with iterative methods, as is the case with most existing deformation models. The results of calculations indicate sufficient accuracy for practical calculations of the proposed methods. The authors considered the examples of determining the bearing capacity and area of working reinforcement of normal cross-sections of bending elements from reinforced concrete in double and multi-row reinforcement. The proposed methods of calculation of bending elements, made of reinforced concrete, can be widely used in design practice.

Keywords Nonlinear strain model · Bending moment · Deformation · Reinforced concrete beam · Design resistance · Multi-row reinforcement

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1 Introduction

One of the most common reinforced concrete elements, used in construction practice, is bending elements. The most effective bending elements include elements with single reinforcement. At the same time, quite often architectural and planning requirements determine the low height of the bending elements, which leads to the need of performing double or multi-row reinforcement. In such elements, it is necessary to strengthen the compressive zone of the concrete or to arrange reinforcement on all height of an element. The calculation of such elements should be based on nonlinear diagrams of the deformation of materials, since the stresses in a certain amount of reinforcement on the height of the section, as a rule, do not reach their boundary values. The use of simplified models of calculation [1, 2] of elements with double and multi-row reinforcement is quite complicated. First, this is due to the fact that it is necessary to determine the stresses in the reinforcement using nonlinear or simplified diagrams of the deformation of materials. Such deformation diagrams are given in many deformation models [9–26] and normative documents [3, 4]. However, the calculation of elements with double and multi-row reinforcement should be performed by the method of iterations in the previously developed programs. It is also possible to calculate such elements by the method of design resistance of reinforced concrete [5, 6]. In this case, this method involves the use of tabular values of the design resistance of reinforced concrete. Let's consider an approximation model for the calculation of reinforced concrete elements with double and multi-row reinforcement based on this method.

2 Approximation Model of the Method of Design Resistance of Reinforced Concrete for Bending Elements with Double and Multi-row Reinforcement

The calculation of reinforced concrete bending elements, based on the modified method of design resistances [7, 8] of reinforced concrete is as follows:

1. It is necessary to determine the mechanical reinforcement ratio by the expression:

$$\omega = \frac{\rho_f \cdot f_{yd}}{f_{cd}}, \tag{1}$$

   where ρ_f—the reinforcement ratio of the cross-section with longitudinal reinforcement, f_{yd}—design resistance of the longitudinal reinforcement, f_{cd}—design resistance of compressive strength of concrete.
2. Then the parameter $k_z = f(\varpi)$ is determined according to the relevant graphs.
3. The design resistance of the reinforced concrete is established by the expression:

$$f_z = 6 \cdot k_z f_{cd}. \tag{2}$$

4. The bearing capacity of the element is set by the formula:

$$M = f_z W_c, \tag{3}$$

where f_z—the design resistance of reinforced concrete in bending, MPa, W_c—moment resistance of working cross section of concrete, b·h^2/6, m^3.

Also, the bearing capacity can be determined by substituting formula (2) in (3)

$$M = k_z f_{cd} \cdot b \cdot d^2. \tag{4}$$

The above formulas were derived using the Bernoulli hypothesis, generally accepted diagrams of deformation of concrete and reinforcement, as well as the failure criterion. Reaching the ultimate deformations of concrete and reinforcement is taken as the main failure criterion.

Let's present the functional dependences of the graphs $k_z = f(\varpi)$ for the bending elements with double and multi-row reinforcement (Figs. 1 and 2). These graphs show the data of the numerical experiment of dependence $k_z = f(\varpi)$ for all classes of concrete and reinforcing steel of classes A400C and A500C.

Let's perform the approximation of the dependence $k_z = f(\omega)$. The dependence approximation for bending elements with multi-row reinforcement will be performed by linear functions and a polynomial of the 2nd degree (Figs. 1 and 2). We will perform a linear approximation in the following form:

$$k_z = 0{,}373 \cdot \omega. \tag{5}$$

The coefficient of variation, determined by the errors of dependence (5), is $\nu = 14.85\%$ in comparison with the true function.

The approximation expression in the form of a polynomial of the second degree has the following form:

$$k_z = 0{,}371 \cdot \omega - 0{,}021 \cdot \omega^2. \tag{6}$$

The coefficient of variation, determined by the errors of dependence (6) and the true function is $\nu = 7.05\%$.

For the elements with double reinforcement when performing a linear approximation, the expression for the definition $k_z = f(\omega)$ takes the following form:

$$k_z = 0{,}94 \cdot \omega. \tag{7}$$

The coefficient of variation, determined by the errors of dependence (7) and the exact function is $\nu = 3.81\%$.

The obtained expressions with the help of linear approximation lead to the following expressions of the bearing capacity:

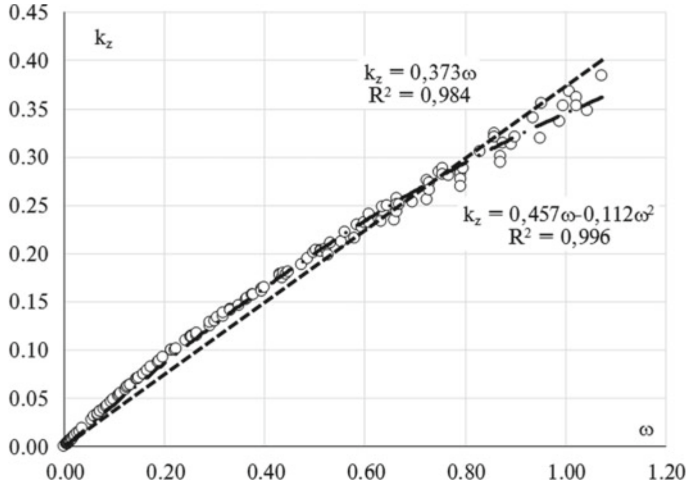

Fig. 1 Functional dependence $k_z = f(\omega)$ and its approximation for bending elements with multi-row reinforcement

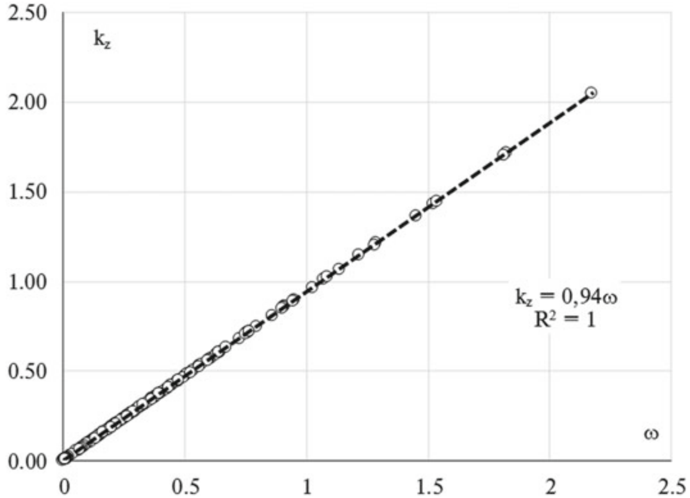

Fig. 2 Functional dependence $k_z = f(\omega)$ and its approximation for bending elements with double reinforcement

– for multi-row reinforcement

$$M_{Ed} = 0{,}373 \cdot A_s \cdot f_{yd} \cdot d; \tag{8}$$

– for double reinforcement

$$M_{Ed} = 0{,}94 \cdot A_s \cdot f_{yd} \cdot d. \quad (9)$$

Expressions (8) and (9) are obtained by substituting formulas (5) and (7) into formula (4) respectively.

It should be noted that expression (9) remains valid in determining the bearing capacity of reinforced concrete bending elements with single reinforcement, in which the failure occurs on the tensile reinforcement.

We shall confirm the validity of the obtained formulas on experimental samples.

3 Examples of Calculation of Reinforced Concrete Bending Elements by the Proposed Methods

Example № 1. Reinforced concrete element of rectangular cross section b × h = 110 × 30 cm is made of concrete class C16/20 and reinforced with steel class A400C, f_{cd} = 365 MPa, placed evenly in five layers along the height of the element. We are going to determine the cross-sectional area of the reinforcement, if the element perceives the calculated bending moment M_{Ed} = 850 kNm.

The solution. Let's accept the arrangement of the reinforcing rod in the section on Fig. 3. The height of the working section is d = 105 cm.

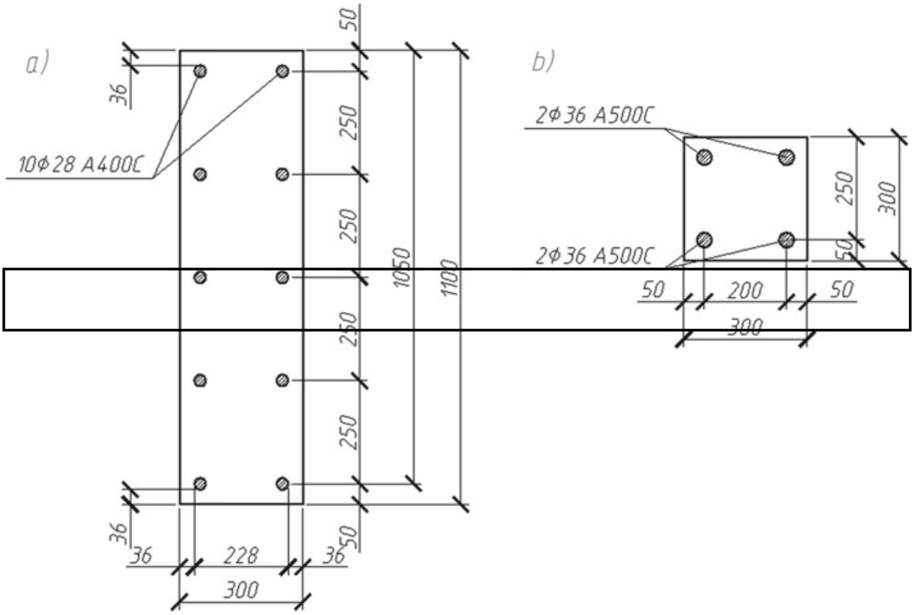

Fig. 3 Illustration of the examples **a** №1; **b**. №2

From the expression (8) we will determine the required cross-sectional area of the reinforcement

$$A_s = \frac{M_{Ed}}{0{,}373 \cdot f_{yd} \cdot d} = \frac{850 \cdot 10^3}{0{,}373 \cdot 365 \cdot 105} = 59,46\ \text{cm}^2.$$

The value of the surface area of the reinforcement area, determined by the nonlinear deformation model, is 55.73 cm^2.

The relative error is $\Delta = \frac{55{,}73 - 59{,}46}{55{,}73} \cdot 100\% = 6{,}7\%$.

Let's check the minimum reinforcement ratio:

$$\rho_f = \frac{A_s}{b \cdot d} = \frac{59{,}46}{30 \cdot 105} = 0.0189 > \rho_{\min} = 0.0013.$$

For the reinforcement we accept 10Ø28 A400C, $A_s = 61{,}58$ sm^2.

Example № 2 Reinforced concrete element of rectangular cross section b × h = 30 × 30 cm is made of concrete class C20/25 and reinforced stell of class 2Ø32 As = 16.09 cm^2 A500C in compressed and stretched zones, $f_{cd} = 415$ MPa, (see Fig. 2). The task is to determine the bearing capacity of the section.

The solution. The height of the working section is d = 25 cm.

The bearing capacity of the cross-section of the element is determined by the expression (9)

$$M_{Ed} = 0{,}94 \cdot A_s \cdot f_{yd} \cdot d. = 0{,}94 \cdot 16{,}09 \cdot 415 \cdot 25 \cdot 10^{-3} = 156{,}92\ \text{kNm}.$$

The value of bearing capacity, determined by the nonlinear deformation model, is 164.43 kNm.

The relative error is $\Delta = \frac{164{,}43 - 156{,}92}{164{,}43} \cdot 100\% = 4{,}57\%$.

4 Conclusions

The considered approximation models of the method of calculated resistances of reinforced concrete give the possibility to check the durability of normal sections of reinforced concrete bending elements at multirow and double reinforcement. The proposed calculation formulas provide an opportunity for rapid checking calculations and can be widely used by students, engineers, and engineering technicians in the practice of design and training.

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