Methods of Calculation the Increased Reinforced Concrete Elements by Carrying Capacity of Slope Sections

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Abstract. Reinforcement bending reinforced concrete structures by increasing the cross section and assessing the load-bearing capacity of the inclined section such elements is an urgent problem, as not yet accumulated adequate research data on the stress-strain state such structures in the span, which works on shear and shear bending moment and transverse force. Analyzing the development theories calculation reinforced concrete elements inclined to the longitudinal axis, we can identify many areas, the main approach of which was based on the calculation using the bases of material resistance, and the use of empirical dependencies. Theoretical approaches calculation the European construction magazine RILEM TC, SNiP 2.03.01.-84* are considered, DBN B.2.6-98 2009 (Eurocode 2), US ACI 318-19. Experimental studies reinforced concrete elements to determine the load-bearing capacity inclined sections were performed on the basis of 5 samples reinforced concrete beams, 14 reinforced samples of reinforced concrete and shotcrete a total of 19 pieces in four series. Beams were made of concrete in each series $f_{ck} = 19.08$ MPa; $f_{ck} = 27.74$ MPa; $f_{ck} = 20.48$ MPa, respectively, reinforced samples with concrete $f_{ck} = 17.95$ MPa; $f_{ck} = 19.5$ MPa (shotcrete $f_{ck} = 31.00$ MPa); shotcrete $f_{ck} = 19.9$ MPa; $f_{ck} = 19.9$ MPa. Also for the manufacture and reinforcement beams used flat and U-shaped frames with working longitudinal reinforcement Ø22, Ø16, Ø12, Ø10, Ø6 A400C, and transverse reinforcement Ø6 A240C (step 120 mm). Reinforcement inclined sections of the experimental beams was performed on one, two or three sides, depending on the variant of the sample and the type of frame flat or U-shaped. Investigations of beams were performed according to the static scheme - a beam on two supports, span L=2100 mm. Deformations of concrete and reinforcement in the samples when determining the bearing capacity of inclined sections were measured using microindicators of the clock type, strain gauges. According to the results theoretical and experimental studies the bearing capacity inclined sections to the longitudinal axis, we can see a significant reassessment between the theoretical values inclined sections according to the new DBN B.2.6.-98: 2009 (Eurocode 2) over the actual results obtained during testing samples 53-67% for conventional beams, and 27-50% for reinforced beams. The results US regulations ACI 318-19 showed convergence of results in the range of 2-9% for samples without reinforcement and 1-7% for samples with reinforcement, but the values show the excess of experimental data over theoretical, indicating the impossibility of accurately determining the actual final bearing capacity. The results the calculation obtained by the method of SNiP 2.03.01-84*, both unreinforced and reinforced beams has a satisfactory agreement with the experimental values in the range of 6-10%.
The results according to the method construction log RILEM TC 162 show a discrepancy in the results between the theoretical and experimental values of 1-11%. Also in the following theoretical and experimental researches of strengthened reinforced concrete elements on bearing capacity of inclined sections it is expedient to consider the level of residual deformations at a certain level of strengthening.

1. Introduction
Reinforcement bending reinforced concrete structures by increasing their cross sections is performed using materials such as concrete, polymer concrete, fiber concrete, as well as the use of reinforcement with carbon fiber tapes and webs. Effective and reliable in operation is the reinforcement of bending reinforced concrete structures with shotcrete, with the possibility of placement in thin layers of structural reinforcement.

Estimation the load-bearing capacity inclined cross-section reinforced concrete elements for the combined action bending moment and transverse force has been considered many times by many researchers, with a large number of calculation proposals, which differed in individual design provisions and fundamentally different approaches. reinforcement, and others - to the insufficient reliability of the structure.

The method calculating structures consisting of several layers (such structures are formed during reinforcement) is approximate, because not yet accumulated a sufficient amount of experimental data on the stress-strain state of such structures in the area span, working on the cut, provided the combined bending moment and transverse force. The contact area of such structures is subjected to the simultaneous action of compressive, tensile, or shear forces. To date, there is not enough experimental justification to estimate the shift beyond the contact zone. Therefore, it is important to choose the method of amplification and, accordingly, the method of calculation taking into account the above factors [1-5].

2. Analysis research and publications
The bearing capacity reinforced concrete sections inclined to the longitudinal axis is one of the urgent problems of the theory of reinforced concrete. Studies of this problem conducted in the second half of the XX century, revealed new factors influencing the load-bearing capacity of inclined sections of reinforced concrete bending elements. Based on the results of numerous experimental studies, a certain picture of the stress-strain state of reinforced concrete structures.

Reinforcement reinforced concrete elements by the bearing capacity inclined sections has become relevant today, in connection with the introduction of regulations on [6-8], so this problem is actively studied by a number of scientists [1-3, 9-11].

Theoretical studies the load-bearing capacity sections inclined to the longitudinal axis reinforced concrete elements were conducted according to various methods: the methodology of current regulations, the development of international construction journals, as well as the proposal of domestic scientists.

Evaluation of the load-bearing capacity of reinforced concrete sections inclined to the longitudinal axis was carried out on the basis of experimental beam samples according to the recommendations of the international European construction magazine RILEM TC. The bearing capacity of the inclined section of the reinforced concrete beam is defined as the sum of the components of concrete \( V_c \), transverse reinforce \( V_w \) and stretched fibers \( V_f \). The terms \( V_c, V_f \) and \( V_w \) have the same forms as in Eurocode 2.

\[
V_R = V_c + V_f + V_w
\]

The contribution fibers consists of the integration shear strength, shear due to the fibers at the critical shear of the crack, which is defined as follows:

\[
V_f = k_f \cdot k \cdot \cos \theta \cdot \tau_{fd} \cdot b_w \cdot d \cdot \cot \theta
\]
where $\theta$ - is the inclination the compression stand, $k_f$ - is the factor, taking into account the compressed element.

Components of concrete $V_c$, where the shear strength is determined as follows:

$$V_{Rd,c} = \left[\frac{0.18}{\gamma_c} \cdot k \cdot (100 \cdot \rho_l \cdot f_{ck})^\frac{2}{3} + 0.15 \cdot \sigma_{cp}\right] \cdot b_w \cdot d$$  \hspace{1cm} (3)

where $\gamma_c$ - is the coefficient reliability of concrete, usually $\gamma_c = 1.5$. This dependence is completely empirical.

The contribution of the transverse reinforcement $V_w$ is determined by:

$$V_w = \frac{A_{sw} \cdot z \cdot f_{ywd}}{s_w} \cdot \cot \theta;$$  \hspace{1cm} (4)

where $z$ -is the arm of the working section ($z = 0.9d$), $A_{sw}$ - is the area of $S_w$ the transverse reinforcement, $S_w$ - is the distance between the transverse reinforcing bars, $f_{ywd}$ is the yield strength of steel; $\alpha$ - inclination of transverse reinforcing bars [12, 13].

The basis of the calculation model proposed by Babich E.M., Korniychuk O.I., were the normative documents of SNiP 2.03.01.-84* [9, 14].

Practically the load-bearing capacity inclined section the reinforced concrete element was determined by the transverse force in the normal section of the reinforced concrete structure depending on the arm of application of force placed above the crack and the force acting in the reinforcement within the length of the inclined section:

$$V = V_b + V_{sw} + F_{crc} \cdot \sin \theta + V_s;$$  \hspace{1cm} (5)

$V_b$ - ultimate force perceived by concrete over the critical inclined crack; $V_{sw}$ - force perceived by the transverse reinforcement and bent rods; $F_{crc}$ - adhesion forces in an inclined crack; $V_s$ - force perceived by the longitudinal reinforcement (nail force).

The force perceived by the concrete over the critical inclined crack:

$$V_b = 1.5 \cdot f_{ck} \cdot b \cdot x_c \cdot \omega_l$$  \hspace{1cm} (6)

where $\omega_l$ - coefficient of the relative span of the cut $c/h_0=0.5; x_c$ is the height of the compressed zone concrete over the inclined crack; $f_{ck}$ - characteristic value of axial tensile strength of concrete.

The force that can be perceived by the transverse rods (clamps):

$$V_{sw} = \frac{f_{ywd} \cdot A_{sw}}{s_w} \cdot c_0;$$  \hspace{1cm} (7)

where $A_{sw}$ - is the cross-sectional area of the transverse reinforcement; $c_0$ - projection of a dangerous inclined crack; $f_{ywd}$ - the value of the strength of the transverse reinforcement.

The magnitude of the adhesion force in an inclined crack

$$F_{crc} = 0.0464 \cdot yf_{crc} \cdot k_3 \cdot f_{ck} \cdot b_w \cdot l_{crc};$$  \hspace{1cm} (8)

where $yf_{crc}$ - coefficient of working conditions; $k_3$ is the coefficient of adhesion in an inclined crack; $f_{ck}$ - value of concrete tensile strength taking into account the coefficient of working conditions.
The force perceived by the longitudinal reinforcement (nail effect):

\[ V_S = 0.8 \cdot n_s \cdot \frac{d \cdot c_0}{c} \cdot d^2 \cdot f_{c k} \cdot f_{yd} \cdot \frac{1}{10}; \]  

where \( n_s, d_s \) - the number and diameter of the longitudinal rods.

Building Code Requirements for Structural Concrete (ACI 318-19) [15]. Except for members designed in accordance with norms, design of cross sections subject to shear shall be based on: \( \phi V_n \geq V_u \) where \( V_u \) is the factored shear force at the section considered and \( V_n \) is nominal shear strength computed by:

\[ V_n = V_c + V_s \]  

where \( V_c \) - is nominal shear strength provided by concrete calculated in accordance and \( V_s \) is nominal shear strength provided by shear reinforcement calculated in accordance.

Shear strength provided by concrete for nonprestressed members. \( V_c \) shall be computed by provisions through, unless a more detailed calculation is made in accordance

\[ V_c = 2 \sqrt{f'_c b_w d} \]  

where \( f'_c \) - the cylindrical strength of concrete; \( b_w, d \) - geometric dimensions

For members subject to axial compression

\[ V_c = 2 \left(1 + \frac{N_u}{2000 A_g}\right) \sqrt{f'_c b_w d} \]  

Shear strength provided by shear reinforcement. Where shear reinforcement perpendicular to axis of member is used

\[ V_s = \frac{A_{vfy2d}}{s} \]  

where \( A_v \) is the area of shear reinforcement within spacing \( s \).

3. Methods experimental research

Experimental studies of reinforced concrete elements to determine the load-bearing capacity of inclined sections were carried out on the basis of 4 series of reinforced concrete beams in the amount of 19 pieces.

At the first stage of research, non-reinforced beams were tested for the perception of concentrated loads by inclined sections, at a loading step equal to 0.1F from the destructive, the opening width of inclined cracks was limited to \( w_k = 0.4 \) mm. The process of research of beams was performed according to the static scheme - a beam on two supports, span \( L = 2100 \) mm. After reaching the state of fluidity, the samples were unloaded, their maximum operating loads were taken as control for all beam samples that were reinforced according to the series. The values of the value of the bearing capacity of the experimental reinforced concrete beams were obtained on the supporting sections with the arm of application of force (a = 350 mm).

The next stage of the work was to strengthen the inclined sections of the experimental beams. The main method of reinforcement was the application of a reinforcing layer of concrete or shotcrete, which was applied to the side surface of the main beams (from one, two or three sides), depending on the variant of the sample, which are shown in Figure 1, and an additional flat or U-shaped reinforcing frame [1, 10].
Figure 1. Amplification schemes of prototypes:
   a) option 1: B-1-3PBA, B-1-4PBA; B-2-4PTA, D, B-2-5PTA, D, B-2-6PTA, D, B-2-7PTA, D;
   b) option 2: B-3-2PTA, G, B-3-3PTA, G, B-3-4PTA, G, B-3-5PTA, G; c) option 3: B-4-2PTA, G, B-4-3PTA, G

Based on previous in-house studies [11], it is proposed to ensure proper connection of reinforced layers with glued metal anchors.

After amplification, the test specimens were subjected to a concentrated load with the same arm, force scheme, and span. The proposed method of research and placement of measuring instruments allowed to obtain the necessary data to assess the load-bearing capacity of inclined sections of reinforced concrete beams (Figure 2).

The first series consisted of 2 unreinforced reinforced concrete samples (B-1-1, B-1-2) and 2 samples that were subjected to reinforcement (B-1-3PBA, B-1-4PBA) reinforced with ordinary concrete and metal joining anchors (A - anchors Ø5 mm). Reinforcement of the main beams was performed by flat reinforcing frames with working longitudinal reinforcement Ø22 A400C, upper reinforcement Ø10 A400C, and transverse reinforcement Ø6 A240C. Reinforcement of the samples of the first series was performed with a metal frame with longitudinal working reinforcement Ø12 A400C, upper reinforcement Ø6 A240C and transverse reinforcement Ø6 A240C. Transverse reinforcement Ø6 mm class A240C, in the main beams was installed with a step of 225 mm, and in the reinforcement elements was installed with a step of 120 mm. The concrete strength of the experimental beams was $f_{ck} = 19.08$ MPa, reinforced concrete $f_{ck} = 17.95$ MPa.
The second series consisted of 1 unreinforced reinforced concrete sample (B-2-1) and 6 samples that were reinforced. Of these, 2 samples (B-2-2PB_A, B-2-3PB_A) are reinforced with ordinary concrete and metal anchors (A - anchors Ø 5 mm), samples B-2-4PT_A, G, B-2-5PT_A, G, B-2-6PT_A, G, B-2-7PT_A, G) reinforced by shotcreting using adhesive primer (G - adhesive primer SB - Haftemulsion) and metal joining anchors. Reinforcement of the main beams was performed by flat reinforcing frames with working longitudinal reinforcement Ø16 A400C, upper reinforcement Ø10 A400C, and transverse reinforcement Ø6 A240C. Reinforcement of the samples of the second series was performed with a metal frame with longitudinal working reinforcement Ø12 A400C, upper reinforcement Ø6 A240C and transverse reinforcement Ø6 A240C. Transverse reinforcement Ø 6 mm class A240C, both in the main beams and reinforcement elements was installed with a step of 120 mm. The concrete strength of the experimental beams was $f_{ck} = 27.74$ MPa, reinforcement concrete $f_{ck} = 19.5$ MPa and shotcrete reinforcement $f_{ck} = 31.00$ MPa.

The third series of samples consisted of 1 unreinforced reinforced concrete sample (B-3-1) and 4 samples that were reinforced. Samples (B-3-2PT_A, G, B-3-3PT_A, G, B-3-4PTA, G, B-3-5PT_A, G) are reinforced with shotcrete on both sides of figure 1b. Koster SB-Haftemulsion adhesive primer and metal joint anchors were used in all reinforcement cases. Reinforcement of the main beams was performed similarly to the samples of the first series with flat reinforcing frames. Reinforcement of the samples of the third series was performed with a metal frame with longitudinal working reinforcement Ø12 A400C, upper reinforcement Ø6 A240C and transverse reinforcement Ø6 A240C, on both sides of the main beam. Transverse reinforcement Ø6 mm class A240C, both in the main beams and reinforcement elements was installed with a step of 120 mm. The strength of the concrete of the experimental beams was $f_{ck} = 20.48$ MPa, shotcrete reinforcement $f_{ck} = 19.9$ MPa.

The fourth series of samples consisted of 1 unreinforced reinforced concrete sample (B-4-1) and 2 samples that were subjected to reinforcement. These 2 samples (B-4-2PT_A, G, B-4-3PT_A, G) are reinforced with a "shirt" by shotcreting. Koster SB-Haftemulsion adhesive primer and metal joint anchors were used in all reinforcement cases. Reinforcement of the main beams was performed similarly to the samples of the previous series with flat reinforcing frames. Reinforcement of the samples was performed with a metal frame with longitudinal working reinforcement Ø12 A400C, upper reinforcement Ø6 A240C and transverse reinforcement Ø6 A240C frames made in a U-shape for reinforcement "shirt", the reinforcement scheme is shown in Figure 1c. Transverse reinforcement Ø 6 mm class A240C, both in the main beams and reinforcement elements was installed with a step of 120 mm. The concrete strength of the experimental beams was $f_{ck} = 20.48$ MPa, reinforcing concrete $f_{ck} = 19.9$ MPa.

Deformations of concrete in the samples when determining the inclined sections were measured using clockwise microindicators at a price of 0.001 mm, on metal clamps, which were glued with epoxy resin glue on the side surfaces of the beam with a base of 175-180 mm in the support areas. Microindicators were fixed in a vertical position and with an angle of 45°, which made it possible to obtain an extended picture of concrete deformations with the growth of an inclined crack at all levels of the cross-sectional face. Also on the support sections of the experimental beams from the boundary of the support to the application of a concentrated load on the side surfaces were glued with strain gauges [10] Similarly, the study of reinforcement deformation was performed using clock-type microindicators. They were installed on special holders attached to the outriggers, which were fixed to the longitudinal and transverse reinforcement during concreting. In the manufacture of beams, rubber pads were put on the outriggers, which were removed from the rods after the concrete set, thus ensuring free movement in the free space under load. In the supporting transverse rods, which were pre-milled with a chain, the testers were glued, protecting them with epoxy resin, and the deformations along the length of the rod were measured.
4. Research results

Graphs of dependence of deformations of concrete and reinforcement on loading, given in Figure 3-6, show the pattern of growth and are represented by beams B-1 -1, B-1-3PBA, similar patterns are observed in other samples. On the graphs of concrete deformations, the discrepancy between theoretical and experimental values is up to 8%. This result causes a satisfactory convergence of experimental and calculated values determined by current standards [6-8]. The analysis the results theoretical and experimental studies of reinforced concrete beams, the values which are given in table1

![Figure 3](image1.png)

**Figure 3.** Graph of the deformation of concrete deformations of the beam B-1 -1 at a distance of 180 mm from the upper face

![Figure 4](image2.png)

**Figure 4.** Graph of deformation of reinforcement Ø 6 mm beam B-1 -1

![Figure 5](image3.png)

**Figure 5.** Graph of the deformation on the face of the main part of the beam B-1-3PBA at a distance of 180 mm from the upper face
Figure 6. Graph of deformation of reinforcement Ø 6 mm beams B-1-3PBA

Table 1. Experimental and calculated values of bearing capacity of inclined sections of reinforced concrete elements

| Beam code | Experimental beam $V_{Rd,1}$ | Eurocode 2 $V_{Rd,2}$ | SNIP 2.03.01-84* $V_{Rd,3}$ | ACI 318-19 $V_{Rd,4}$ | RILEM TC 162 $V_{Rd,5}$ | The discrepancy between experimental and computation, % |
|-----------|-----------------------------|---------------------|---------------------------|-----------------|---------------------|---------------------------------------------|
| Б-1-1     | 47,0                        | 17.25               | 39,81                     | 55.2            | 46,3                | 61                                          |
| Б-1-2     | 52,5                        | 17.25               | 39,81                     | 55.2            | 46,3                | 67                                          |
| Б-1-3PB_A | 68,0                        | 49,6                | 64,3                      | 73.6            | 67,8                | 27                                          |
| Б-1-4PB_A | 68,5                        | 49,6                | 64,3                      | 73.6            | 67,8                | 28                                          |
| Б-2-1     | 62,5                        | 27,66               | 58,9                      | 64,7            | 60,13               | 56                                          |
| Б-2-2PB_A | 107,9                       | 55,32               | 98,2                      | 107,1           | 100,15              | 48                                          |
| Б-2-3PB_A | 107,4                       | 55,32               | 98,2                      | 107,1           | 100,15              | 48                                          |
| Б-2-4PT_A | 109,0                       | 55,32               | 102,4                     | 107,1           | 104,63              | 49                                          |
| Б-2-5PT_A | 109,9                       | 55,32               | 102,4                     | 107,1           | 104,63              | 49                                          |
| Б-2-6PT_A | 109,5                       | 55,32               | 102,4                     | 107,1           | 104,63              | 48                                          |
| Б-2-7PT_A | 111,1                       | 55,32               | 102,4                     | 107,1           | 104,63              | 50                                          |
| Б-3-1     | 58,7                        | 27,66               | 53,6                      | 60,8            | 56,47               | 53                                          |
| Б-3-2PT_A | 140,3                       | 82,98               | 132,0                     | 138,6           | 134,6               | 41                                          |
| Б-3-3PT_A | 141,9                       | 82,98               | 132,0                     | 138,6           | 134,6               | 42                                          |
| Б-3-4PT_A | 142,4                       | 82,9                | 132,0                     | 138,6           | 134,6               | 42                                          |
| Б-3-5PT_A | 143,1                       | 82,9                | 132,0                     | 138,6           | 134,6               | 42                                          |
| Б-4-1     | 58,6                        | 27,66               | 53,5                      | 60,7            | 55,1                | 53                                          |
| Б-4-2PT_A | 148,6                       | 83,74               | 134,2                     | 144,2           | 138,3               | 44                                          |
| Б-4-3PT_A | 149,8                       | 83,74               | 134,2                     | 144,2           | 138,3               | 44                                          |

Note: Table values are in kN, $V_{Rd}$.
In the results of studies of reinforced concrete samples of all series, in which ordinary concrete was chosen for reinforcement and ensuring the joint work of old and new concrete was carried out with metal anchors, it was possible to observe partial stratification between concrete layers in the form of longitudinal cracks at 0.75-0.85 destructive value on the supporting areas of the samples. In all other samples that were reinforced with shotcrete using metal anchors and adhesive priming, the stratification between the layers of the main and reinforced concrete did not pass.

Despite the asymmetry of the reinforcement in the samples of the first and second series, the measured deformations in different cross sections showed high convergence, including with the theoretical values.

Having conducted theoretical and experimental studies of the bearing capacity of the elements inclined to the longitudinal axis by different methods adopted in different regulations, we can see that the current standards theoretical values in comparison with experimental create a large margin of safety in the range of 53-67% for conventional beams, and 27-50% for reinforced beams. The truss calculation model of DSTU B 2.6-156: 2010 underestimates the bearing capacity, as it does not take into account the contribution to the bearing capacity of stretched concrete or engagement between the cracks. After analyzing the results of the calculation of experimental samples of other authors who study the bearing capacity of the elements inclined to the longitudinal axis, the values obtained by them also show an underestimation of the calculated bearing capacity of 45-60%.

The values obtained by the SNiP method showed greater convergence of results in the range of 6-9% for samples without reinforcement and 5-10% for samples with reinforcement. It should be noted that the obtained values show high statistical convergence, which at a high level describes the load-bearing capacity of structures.

The results of US regulations ACI 318-19 showed convergence of results in the range of 2-9% for samples without reinforcement and 1-7% for samples with reinforcement, but the values show the excess of experimental data over theoretical, indicating the impossibility of accurately determining the actual final bearing capacity.

The results according to the method of the construction log RILEM TC 162 show a discrepancy in the results between the theoretical and experimental values of 1-11%. The basis of the components that perceive the forces in the cross sections of reinforced beams inclined to the longitudinal axis is a component of concrete + reinforcement + compressed braces (similar to the engagement of the cracks), the sum of which qualitatively estimates the load-bearing capacity of the structure.

5. Conclusions
According to the results of theoretical and experimental studies of the bearing capacity of inclined sections to the longitudinal axis, we can see a significant reassessment between the theoretical values of inclined sections according to the new DBN B.2.6.-98: 2009 (Eurocode 2) over the actual results obtained during testing of samples in laboratory conditions, when using the calculation of DSTU B 2.6-156: 2010 it is advisable to take into account the contribution of concrete to the overall strength of the inclined sections.

The results of the calculation obtained by the method of SNiP 2.03.01-84*, both unreinforced and reinforced beams has a satisfactory agreement with the experimental values in the range of 6-10%. When using (Figure 1 and 2) US regulations ACI 318-19 convergence of results is 1-9%.

In our opinion, it is necessary to conduct experimental studies of reinforced concrete elements, and compare them with the calculation method, which will take into account all components of the stress state of the structure, as currently the methodology of existing regulations creates a significant
reassessment of load-bearing capacity. Reinforced concrete elements for the load-bearing capacity of inclined sections, it is advisable to take into account the level of residual deformation at the level of reinforcement.

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