РАЗДЕЛ VI. МАТЕРИАЛОВЕДЕНИЕ

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Diversity and completeness of the results of targeted experimental research are the main factors in the development of a reliable theory of calculating of bending reinforced concrete elements along inclined sections

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doi: 10.18411/scienceconf-03-2021-23

idsp: scienceconf-03-2021-23

Abstract

The results of calculating the strength of bending reinforced concrete elements along inclined sections obtained according to regulatory documents, or according to the calculation method developed by individual researchers, often differ significantly from the experimental results. One of the reasons for this may be the narrow focus of many experimental researches used in the development of the theory of calculations. Sometimes the proposed theory of calculations is not at all substantiated by experimental research. Analysis of numerous experimental and theoretical studies, both Russian and foreign, as well as testing by the author of the article independently made curved reinforced concrete elements without prestressing longitudinal steel reinforcement along inclined sections and a large number of prestressed elements, including beams with one, two and three axial prestressing of steel reinforcement (for spans of bridge structures), allowed, ultimately, to obtain a detailed picture of the stress-strain state in concrete and steel reinforcement in the zone of joint action of bending moments and maximum shear forces. At the same time, the values of the influence on the load-bearing capacity of the bending reinforced concrete elements of a number of main factors are established. Based on the results of experimental researches, partially described in this article, I consider it advisable to improve the methodology for calculating the strength of bending reinforced concrete elements along inclined sections, laid down in the current regulatory documents, as well as in private researches on this issue.

Keywords: bending elements, bearing capacity, experimental researches, inclined sections, stress-strain state.

Introduction

In the regulatory documents of Russia - SP 63.13330.2012 «Concrete and won concrete construction», in SP 35.13330.2011 «Bridges and culverts», as well as in the regulatory documents of a number of other countries, a number of physical and geometric factors are not taken into account in the calculation formulas when determining the bearing capacity along inclined sections of bending reinforced concrete prestressed elements and elements without prestressing, or some of them are not fully taken into account by introducing a number of empirical and semi-empirical dependencies and coefficients into the calculation model, which sometimes leads to significant discrepancies between theoretical and experimental results.

For a more complete establishment of the influence of many factors on the stress-strain state of elements under the action of a load and on their bearing capacity, especially in the area of joint action of bending moments and maximum shear forces, starting 1973, first at NIIZhB (Moscow), then at the Vologda State Technical University, extensive experimental

research has been carried out, in which more than 500 bending and eccentrically compressed reinforced concrete elements have been tested.

The purpose of the research is - on the basis of the obtained results of experimental data, to improve the existing method of calculating of bending reinforced concrete elements along inclined sections. This article outlines only a part of the experimental research conducted by its author.

Main part

For conducting the above researches at NIIZhB, prestressed beams were made, as well as beams without prestressing with a section of 15x30 cm., cube strength of the concrete - 45-55 MPa. Strained, and in some beams non-stressed, longitudinal steel reinforcement: bottom 2ø18A_{T-V}, top 2ø10A_{T-VI}, transverse steel reinforcement 2ø6 A-I with a pitch of closed transverse bars (clamps) in half-spans: strong transverse steel reinforcement - 5 cm on one side of the beam and 10 cm on the other; average transverse steel reinforcement - 15 cm on one side of the beam and 20 cm on the other; weak transverse steel reinforcement - 20 cm on one side of the beam, and there was no steel reinforcement on the other side of the beam.

The tension of the longitudinal steel reinforcement was carried out on a long stand, consisting of three lines. Each series of test samples, consisting of 6 beams, was manufactured on a separate line of the stand, which made it possible in all samples to have the same value of prestressing of steel reinforcement, concrete strength, conditions of its hardening and other characteristics. The connection of individual rods of longitudinal steel reinforcement along the length of the stand was carried out using couplings and threaded heads pressed at the ends of the steel reinforcement, since welding of steel of classes A_{T-V} и A_{T-VI} according to technical conditions is not recommended. The beams were tested on a jack installation by two forces symmetrically located relative to the middle of the span. After the destruction of the beams on one side, a bandage was put on the destroyed part and its second half was brought to destruction.

Based on experimental research by the author of the article (1973 - 1976 and continuing until 1984), in Russia SNIP 2.03.01-84 for the first time, they began to take into account the effect of prestressing of longitudinal steel reinforcement located in the tensile zone of concrete under load on the strength along inclined sections. In T-profile beams, in the presence of transverse steel reinforcement, for the first time, they also began to take into account the effect of overhangs of compressed flanges on their bearing capacity in the zone of action of transverse forces.

However, the disadvantage of this calculation methodology laid down in SNIP 2.03.01-84 is that its authors do not take into account the degree of influence of prestressing of longitudinal steel reinforcement on the strength along inclined sections, depending on the amount of transverse steel reinforcement, and the value of the specified influence of the prestressing of the longitudinal steel reinforcement ϕ_n , depending on the thickness of the ribs of the beams in the cross section of the elements b , determined by the formula (79) of the above SNIP, contradicts the results of experimental researches, which showed that with an increase in the width of the cross-section of the elements, the effect of prestressing on the strength along inclined sections increases.

The tests also showed that in bending reinforced concrete beams, the trajectories of the main compressive stresses along which, as a rule, under the action of a load, oblique cracks develop change with an increase in the prestress of the longitudinal steel reinforcement. So, in the limiting state of the elements, the height of the compressed zone of concrete above the cracks inclined and normal to the longitudinal axis increases with an increase in prestressing, that is, in prestressed beams it turns out to be greater than in similar beams without prestressing (fig. 1).

Fig. 1. Destruction of experimental bending reinforced concrete beams: a) with prestressing of longitudinal steel reinforcement (beam B-I-2a); b) without prestressing longitudinal steel reinforcement (beam B-III- 2a);

In bending reinforced concrete beams without transverse steel reinforcement with a ratio of cross-sectional dimensions $b/h=0,5$ (thick ribs) prestressing of longitudinal steel reinforcement increased their bearing capacity along inclined sections very significantly - 2.7 times (fig. 2).

Fig. 2 Dependence of the experimental value of the destructive shear force on the compressive force of concrete by prestressing steel reinforcement in rectangular beams with a cross-sectional width $b = 0.5h$ and a shear span length $C = 2.3h_0$

With an increase in the number of transverse steel reinforcement ($\mu_{sw} = 0,19\%$ and $\mu_{sw} = 0,38\%$) the influence of prestressing of longitudinal steel reinforcement (concrete compression force N_0) on the bearing capacity of beams along inclined sections decreases (see fig. 2).

In SP 63.13330.2012 when determining the effect of prestressing of longitudinal steel reinforcement on the strength of bending reinforced concrete elements along an inclined strip between inclined cracks, as well as in calculating the strength along an inclined crack using the coefficient φ_n , only two characteristics are taken into account: the average compressive stress in concrete σ_{cp} and the prismatic compressive strength of concrete R_b (section.8.1.34).

These characteristics are clearly not enough to determine φ_n , since the effect of prestressing on the strength of bending reinforced concrete elements along inclined sections depends significantly on the number of transverse steel reinforcement μ_{sw} , the relative width of the rib in the cross section of rectangular and T-profile beams b/h , and to a lesser extent on some other factors. The limitation of the effect of prestressing on the strength of bending reinforced concrete elements along inclined sections to values $\varphi_n \leq \varphi_{1,25}$, adopted in SP 63.13330.2012 (section. 8.1.34), does not always correspond to the experimental results (see fig. 2).

At the same time, in experimental researches of the author of the article, it was first established that the effect of clamps on the bearing capacity along inclined sections in prestressed beams with the same ratio of cross-sectional dimensions ($b/h=0,5$) is much less than in similar beams without prestressing (fig. 3). So in beams with an average relative distance from the support to the line of action of the load ($c/h_0=2,3$) when the percentage of transverse reinforcement changed from 0 to 0,76%, in the absence of prestressing in the longitudinal steel reinforcement, the bearing capacity along inclined sections increased within up to 2.8 times (see fig. 3). With the same change in the percentage of transverse reinforcement in prestressed beams, the bearing capacity increased by only 12-15%. In these prestressed beams, an increase in the bearing capacity along inclined sections occurred mainly when the percentage of transverse reinforcement changed from 0 to 0,3%. With a further increase in the transverse reinforcement, the bearing capacity increased insignificantly - only by 1 – 2%. In beams without prestressing, the most intense increase in the bearing capacity along inclined sections occurred when the transverse reinforcement changed within 0,2 – 0,4%. With a further increase in the amount of transverse steel reinforcement, the bearing capacity increased slightly - by 8 – 12%.

Fig. 3. Influence of the intensity of transverse reinforcement on the magnitude of the destructive transverse force in rectangular beams with thick walls ($b/h=15cm/30cm=0,5$) and the relative distance from the support to the line of action of the load $c/h_0=2,3$.

Symbols: 1 – beams series I (with maximum prestressing in the lower longitudinal steel reinforcement); 2 – beams series II (with an average value of prestressing in longitudinal steel reinforcement); 3 – beams series III (without prestressing).

Thus, in bending reinforced concrete beams with relative cross-sectional dimensions $b/h=0,5$, the boundary (most cost-effective) value of the percentage of transverse reinforcement should be considered: 0,3% - for prestressed beams, 0,4% - for beams without prestressing (see fig. 3).

Figure 3 also shows that rectangular beams without prestressing with a cross-sectional ratio $b/h=0,5$, with the presence of transverse steel reinforcement in the range from 0 to 0,4% it is advisable to replace them with similar prestressed beams, since at the same time, their bearing capacity increases significantly. At the same time, with an increase in the specified amount of transverse steel reinforcement (from 0 to 0,4%) in prestressed beams, due to the effect of prestressing of longitudinal steel reinforcement, the bearing capacity along inclined sections, in comparison with beams without prestressing, increases in damping character - in ranging from 2,7 to 1,16 times.

Experimental researches continued at VSU, including testing 48 beams of rectangular and T-profile with a shelf in the compressed zone of concrete and with small relative dimensions of the rib cross-section $b/h=6\text{cm}/31\text{cm}=0,19$ (thin ribs - models of beams of bridge structures). In the lower zone of the beams, widening is provided to accommodate prestressed steel reinforcement and to ensure the stability of the beams during testing. The strength of concrete in most of the beams was 30-40 MPa. Longitudinal prestressing, and in some beams, non-prestressing steel reinforcement consisted of $3\phi 12\text{A-T-V}$. The transverse steel reinforcement consisted of $2\phi 5\text{Bp-I}$, as well as $2\phi 6\text{A-III}$ with a pitch $S=5\text{cm}$, 10cm and 15cm . Similar beams were also manufactured without transverse steel reinforcement. The test of the beams was carried out on a jack installation with two loads symmetrically located relative to the middle of their span. Distance between support and line of action of load $C=80\text{cm}$. The relative shear span length $C/h_0=3,0$ (beams are conditionally attributed to large shear spans). The distance between the lines of action of two loads is 60cm , the total length of the beams $l=2,6\text{m}$.

When testing these T-profile beams, it turned out that after the formation of inclined cracks in concrete, in transverse steel reinforcement, in the places where it intersects with inclined cracks, the intensity of deformation development under the action of a load is significantly higher than in similar rectangular beams.

In some T-section beams with large shear spans, with a prestress value in longitudinal steel reinforcement $N_0=128,8\text{kN}$ (beams B-29 and B-36), as well as in a beam without prestressing (B-33) the transverse steel reinforcement, crossed by an inclined crack, suddenly broke and their sharp (brittle) destruction occurred (fig. 4).

Experiments have shown that only in 3 of the above 36 beams, failure along inclined sections occurred with a simultaneous rupture of transverse steel reinforcement: in beam B-29 with an average shelves width located in the compressed zone of concrete ($b_f'=29\text{cm}$), with a pitch of transverse steel rods $S=15\text{cm}$ ($\mu_{sw}=0,43\%$), breaking load $P=240\text{kN}$; in beam B-36 with wide shelves ($b_f'=52\text{cm}$), with a pitch of transverse steel bars $S=10\text{cm}$ ($\mu_{sw}=0,65\%$), breaking load $P=246,15\text{kN}$, and in a beam (B-33) without prestressing with an average width of shelves ($b_f'=29\text{cm}$), with a pitch of transverse bars $S=10\text{cm}$, $P=210,8\text{kN}$.

Fig. 4. View of destruction of T-profile beams with a break of transverse steel reinforcement B-29 with an average shelf width located in the compressed zone of concrete and B-36 with a wide shelf.

In T-profile beams with thin ribs in the cross section ($b/h \leq 0,2$), both in the presence of prestressing of the longitudinal steel reinforcement, and in its absence, the transverse steel reinforcement significantly increases their bearing capacity along inclined sections with an increase in the percentage of transverse reinforcement in the range of up to 1,3%, which does not occur in rectangular beams with a ratio $b/h=0,5$ (see fig. 3). With a further increase in the amount of transverse steel reinforcement within the range of up to 1,9% in beams without prestressing with thin ribs, the bearing capacity along inclined sections increases insignificantly - within the range of up to 1,06 times.

In the researches of the author of the article, transverse steel reinforcement made of steel of class A-III was adopted for the purpose of using it in T-profile beams when creating two and three axial prestressing in steel reinforcement (see fig. 5) to compare the performance of such beams under load with beams reinforced with longitudinal prestressing reinforcement located only in the tensile zone of concrete (uniaxial prestressing). At the same time, brittle fracture did not occur in T-profile beams at 3-axis prestressing (in which stress is provided in the longitudinal steel reinforcement, in the transverse steel reinforcement located in the rib of the beams and in the transverse steel reinforcement located in the upper, compressed from the load, in shelf) despite high loads and deflections before their destruction.

Fig. 5. Anchoring of transverse steel reinforcement in compressed shelves and ribs of reinforced concrete T-beams.

Crack resistance and bearing capacity along inclined sections of such beams are significantly higher compared to similar beams with uniaxial prestressing only with longitudinal steel reinforcement. Inclined cracks in such beams are formed under higher loads, compared to uniaxial prestressing, and after their removal they close tightly. Such a springy work of beams is very valuable in bridge structures exposed to multiple repeated loads, in which the decrease in the bearing capacity along inclined sections with an increase in the shear span is less compared to beams with uniaxial prestressing, and even more so to compared with beams without prestressing.