SECTION X. MATERIALS SCIENCE

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The technology of experimental researches of the strength of bent reinforced concrete elements in the zone of action of transverse forces

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Abstract

Extensive experimental researches of the author of the article showed that in T-profile beams, despite the fact that with an increase in the length of the shear span, the bearing capacity along inclined sections significantly decreases, the effect of overhangs of compressed flanges on the bearing capacity of these beams, on the contrary, increases, and when, with an increase in the length of the shear span, the beam becomes equal in strength in normal and inclined sections, the effect of overhangs, as a rule, becomes the same in both the strength of normal and the strength of inclined sections, which is not taken into account in the regulatory documents of Russia, the USA and a number of other countries. At the same time, experiments have shown that the smaller the rib width in the cross section of bent reinforced concrete T-profile beams (standard beams of bridge structures on the territory of Russia), the greater the effect of the overhangs of compressed flanges on their bearing capacity along inclined sections.

The values of the influences on the bearing capacity of bent reinforced concrete elements of such factors as: the forces of engagement of the rough surface of the banks when they are displaced in an inclined crack from the action of the load; the nagel effect in the longitudinal steel reinforcement at the intersection of it with an inclined crack; prestressing in longitudinal steel reinforcement, depending on the amount of transverse steel reinforcement and the width of the cross-section of the elements, etc.

The technology for conducting experimental researches will have a positive effect for the development of a reliable theory for calculating bent reinforced concrete elements along inclined sections only when it includes the whole complex of a variety of the influence of the main factors on the operation of the researched elements with its in-depth analysis.

Key words: bent elements, bearing capacity, experimental researches, inclined sections, stress-strain state, calculation method.

Introduction

In the 60s-70s of the last century, thanks to numerous experimental and theoretical research of Russian scientists such as: A. A. Gvozdev, S. A. Dmitriev and S. S. Davydov, V. V. Mikhailov, A. P. Vasiliev, V. I. Murashov, etc. the method for calculating reinforced concrete elements by limiting states, included in the regulatory documents, has received significant development.

The method for calculating bent reinforced concrete elements in the stage of failure along inclined sections using the theory of equilibrium of ultimate forces, proposed in 1946 by A.A. Gvozdev and M.S. Borishansky, was adopted instead of calculations using the truss analogy method developed by E. Merzh (Germany) which in those years was used as the main calculation method in the USSR. The proposed calculation method made it possible to move from the conditional stresses to the actual forces in the inclined section, which was subsequently included in the USSR regulatory documents. However, V.G. Karabash in his article «Chipping during bending of reinforced concrete beams» (1955) criticized the methods of calculating bending reinforced concrete elements along inclined sections existing at that

time, justifying the need to carry out such a calculation for the combined action of bending moments and shear forces at the action of the load, which is a very relevant factor for many researchers at the present time.

Among foreign researchers in the field of calculating the strength of inclined sections of bent reinforced concrete elements, referring to the results of experimental researches, one should especially note the works of F. Leonhardt and R. Walter (at the University of Stuttgart - Germany); as well as the works of J. G. McGregor and J. M. Henson, E. M. Zvoyer and S. P. Siesse (USA); works by N. Ryusch and J. Wiegerrust (Germany); R. Elstner's experiments (USA); G. N. I. Kani, R. Varner, A. Hall and others. It should also be noted the work of Professor of the Vienna University of Technology Rudolf Zaliger, who presented the results of research, including in the field of strength calculation of bent reinforced concrete elements along inclined sections, in 5 editions of his book «Reinforced Concrete Calculation and Design». The first edition of the book was published in 1905, the 5th edition, in September 1925. The book includes not only computational and graphic material with the presence of a large number of tables, but also many photographs based on the test results of reinforced concrete elements, where many processes of the formation and development of cracks as well as the destruction of reinforced concrete elements are clearly displayed. Some of the results of research by Rudolf Zaliger may be relevant to the present time.

However, in many theoretical researches on calculating the strength of bent reinforced concrete elements along inclined sections carried out both in Russia and in a number of other countries, there are significant drawbacks.

For example: 1. The influence of prestressing on the strength of inclined sections of bent reinforced concrete elements in the regulatory documents of Russia and a number of other countries is accepted without taking into account the amount of transverse steel reinforcement and the width of the cross-section of rectangular and T-profile elements. The experiments of the author of the article have shown that the larger the cross-sectional width of bent reinforced concrete elements, the greater the effect of prestressing on the strength along inclined sections, and with a large cross-sectional width of the elements, transverse steel reinforcement can be abandoned without reducing the strength (for example, in prestressed hollow-core slabs of residential and civil buildings with a length of 6 meters or more);

2. The influence of transverse steel reinforcement on the strength of inclined sections in the design model is taken without taking into account the magnitude of the prestress in the longitudinal steel reinforcement, the shape of the cross section (in the experiments indicated below by the author of the article, it was also found that the smaller the rib thickness in the cross section of rectangular and T-profile beams, the greater the intensity of deformations in the transverse steel reinforcement after the formation of inclined cracks, under the action of a load), without taking into account the type of load (with the same load value - in beams loaded with uniformly distributed load, the stress in the clamps is much less compared to similar beams loaded with concentrated forces).

The lack of extensive targeted experimental researches in order to obtain data for orientation when drawing up a methodology for calculating the strength of bent reinforced concrete elements along inclined sections led to the fact that, as noted above, in the regulatory documents of Russia - SP 63.13330.2012 «Concrete and won concrete construction.», as well as in the regulatory documents of a number of other countries, a number of significant shortcomings have been identified, including a significant drawback that the effect of overhangs of compressed shelves is not taken into account at all in the strength calculations along inclined sections of T-profile beams. Apparently, such a theory was adopted on the basis of tests of beams with small shear spans, thick ribs in the cross section and a large width of thin compressed flanges, where the effect of overhangs of compressed flanges on their bearing capacity along inclined sections can indeed be neglected.

The variety and completeness of the obtained results of targeted experimental studies, some of which are given in this article, are the main factors in the development of a reliable

theory for calculating the strength of bent reinforced concrete elements along inclined sections.

Main part

To improve the methodology for calculating bent reinforced concrete elements along inclined sections, laid down in the regulatory documents of both Russia and a number of other countries, the author of the article tested over 500 beams of rectangular and T-profile.

The first tests were carried out at NIIZhB (Moscow) since 1974. In accordance with the assigned tasks, 24 experimental reinforced concrete prestressed beams and beams without prestressing were tested. Rectangular beams 15x30 cm in size, freely supported at the ends, which, during testing, were loaded with two concentrated forces symmetrically located relative to the middle of its length. The cubic strength of concrete for all test samples of the same is provided, which averaged 50 MPa. The lower longitudinal steel reinforcement consisted of 2&18 A_T-V, upper longitudinal steel reinforcement - 2&10 A_T-VI. The tension of the steel reinforcement was carried out on a stand consisting of three lines. Each series of test samples, consisting of six beams, was manufactured on a separate line of the stand (Fig. 1), which made it possible to have the same value of prestressing of longitudinal steel reinforcement in all samples of the series.

Fig.1. General view of prestressed beams located on the stand and beams without prestressing located outside the stand (see on the right).

The connection of individual rods of longitudinal steel reinforcement along the length of the stand was carried out using couplings and pressed heads (Fig. 2 - threaded connection), since welding of steel of classes A_T-V and A_T-V1 is not recommended according to technical conditions.

The steel reinforcement was tensioned by a hydraulic jack using a pumping station. Before tensioning the longitudinal steel reinforcement, strain gauges are glued with a chain on the upper and lower edges of each rod and they are carefully insulated from moisture and possible damage during the laying and compaction of concrete (fig. 1 and fig. 2 - wires from strain gauges). The tensile forces in the rods of the longitudinal steel reinforcement were controlled by strain gauges, strain gauges with a base of 100 mm, as well as by the pressure gauge of the pumping station.

Fig.2. The connection of the bars of the longitudinal prestressing steel reinforcement of the beams along the length of the stand.

In addition to the strain gauges glued to the longitudinal steel reinforcement, in order to control the deformations occurring during the descent of the prestressing of the reinforcement, as well as during the storage of the samples until the moment of their testing, on the lateral surface of the beams after removing the formwork, strain gauges with a base of 50 mm were also partially glued (Fig.3).

To control the loss of prestresses in longitudinal steel reinforcement from stress relaxation, a similar steel reinforcement was tensioned on a separate stand at a temperature of 208C. This control is carried out with the help of dynamometers during the entire time of concrete hardening up to the descent of the pre-tensioning of the steel reinforcement.

During the specified time period, the stress relaxation in the reinforcement proceeded most intensively and, after the tension was released, by the time the beams were tested, it sharply decreased depending on the value of the controlled preliminary stresses.

Fig. 3 General view of location of the strain gauges on concrete.

On concrete, strain gauges were glued along the entire length of the upper edge of the beams, as well as on the lateral edge in the places where normal and inclined cracks were supposed to form (see Fig. 3).

Such a scheme for gluing strain gauges made it possible to evaluate the most stressed zones of concrete, to obtain its ultimate deformations during destruction, to reveal approximately the height of the compressed zone of concrete both above normal and above inclined cracks, and also to assess the nature of the development of deformations in normal and inclined sections throughout the entire zone of action of bending moments and shear forces taking into account the presence of cracks. Dial indicators are installed along the ends of the beams (see Fig. 3) to assess the possible slippage of the longitudinal steel reinforcement in the support areas after the formation of inclined cracks near the supports.

Thus, the use of a large number of experimental beams (24 test samples), the use of a perfect installation for their testing, the use of about 4 thousand strain gauges, as well as a large number of mechanical and electrical measuring instruments, ultimately made it possible to obtain a detailed picture of the stress-strain the state of concrete and steel reinforcement along inclined sections of bent reinforced concrete elements under the action of shear forces.

The beams were tested on a jack installation with two weights symmetrically located relative to the middle of the span. According to the readings of the strain gauges obtained during the testing of beams, graphs of the distribution of deformations in concrete (Fig. 4) and steel reinforcement (Figs. 5 and 6) were built, the analysis of which made it possible to reveal the following.

Fig. 4. Distribution of longitudinal deformations in concrete when testing a prestressed beam B-I-1a (a) and a beam without prestressing B-III-1 (b):

— — — after the formation of normal cracks; — • — during the development of a critical inclined crack; — before the destruction of the beam

After the formation of cracks normal to the longitudinal axis of the beam (before the formation of inclined cracks), along the length of the beam, the shortening deformations of the upper face were distributed linearly with a maximum under load and zero values at the support (see Fig. 4 — dashed lines). After the formation of inclined cracks and in the process of their development with an increase in the load, in the zone of action of transverse forces, a redistribution of the indicated deformations took place. At the places where the load was applied, the shortening deformations increased sharply, and in the areas located closer to the support, they decreased, turning into elongation deformations (see Fig. 4 - dash-dot lines). At the stage of development of inclined cracks, on the lateral faces of the beams, it can be seen that, with an increase in the load, the closer the normal sections are to the beam support, the lower the neutral axis went down. The maximum values of shortening deformations in normal sections along the length of the zone of action of transverse forces by the time of destruction of the beams moved from the upper face in the section under load to $1/3 \cdot 4 \cdot 1/4$ of the height of these beams from the lower face in the sections located closer to the supports (see Fig. 4 - solid lines). With the formation of inclined cracks in the zone of action of transverse forces in the test beams, under the action of a load, a temporary insignificant instantaneous closure of normal cracks in the zone of pure bending was observed. In this case, the height of the compressed zone of concrete above normal cracks did not decrease until the destruction of the beam along inclined sections.

In the process of testing beams, the research of deformations in longitudinal steel reinforcement in the section between the support and the line of load action, carried out using strain gauges glued on two diametrically opposite sides of this steel reinforcement (Fig. 5), makes it possible to obtain deformation diagrams of the upper and lower fibers of the bar, on the basis of which it was planned to establish the presence in the steel reinforcement of the nagel effect at the points of its intersection with an inclined crack.

In places where an inclined crack intersects, the longitudinal reinforcement undergoes local bending - the deformations on its upper and lower edges differ from each other. As you move away from this place, the difference between the values of deformations on opposite faces of the bar decreases and becomes equal to zero at some distance (see Fig. 5).

With an increase in the load, a new inclined crack appears, and at the point where it intersects the longitudinal steel reinforcement, the following jump is observed in the difference in the deformation values on the upper and lower edges of the bar. In this case, in the section of the length of the longitudinal steel reinforcement, limited by inclined cracks, the deformation diagrams of the lower and also the upper fibers change sign relative to the line of axial deformations (see Fig. 5). This nature of the deformation change indicates that under the influence of local bending at the intersection of the inclined crack, the longitudinal steel reinforcement perceives part of the shear force from the load, i.e. in the longitudinal steel reinforcement, the nagel effect is manifested.

In the experimental beams, according to the deformations of longitudinal steel reinforcement on diametrically opposite upper and lower fibers, the transition to stresses is carried out using the elastic modulus of the steel reinforcement. If the strains on the extreme fibers of the longitudinal steel reinforcement exceeded the values of the conditional proportionality limit $\varepsilon_{0,02}$, then the stresses were determined using the $\sigma_s - \varepsilon_s$ dependence diagram.

$$N_s = \frac{\sigma_s^B + \sigma_s^H}{2} A_s; \quad (1) \quad M_s = \frac{\sigma_s^B - \sigma_s^H}{2} ; \quad (2)$$

$$\text{Shear force (nagel effect)} Q_s = \frac{dM_s}{dx} . \quad (3)$$

The value of the shear force Q_s at the moment of destruction of the beams, depending on the strength of concrete, the amount of longitudinal and transverse steel reinforcement, the length of the shear span and other factors, ranges from 5 – 15 %, and in some cases reaches 25% of the ultimate shear force perceived by the beam.

During the tests, it was found that the experimental longitudinal forces in concrete over an inclined crack, obtained taking into account the actual height of the compressed zone, were less than the experimental forces in the longitudinal reinforcement at the intersection of the inclined crack.

Fig. 5. Distribution of deformations along the length of the longitudinal steel reinforcement in the B-III-1 beam without prestressing:

a) before inclined crack formation (0.3 P разр.); б) before the destruction of the beam (P разр.); — — — deformations along the upper face of the longitudinal steel reinforcement; — — — deformations along the lower edge of the longitudinal steel reinforcement; — • — • — medium deformations

The difference in the magnitude of the longitudinal compressive forces in concrete and tensile forces in the steel reinforcement indicates the presence of additional forces in the inclined section, contributing to their balancing. These forces are the forces of engagement arising along an inclined crack when the rough surface of its edges is displaced with an increase in the external load. The vertical component of the engagement forces increases the shear force absorbed by the beam. The longitudinal and transverse components of the forces of engagement N_3 and Q_3 , are determined from the equations of equilibrium of horizontal and vertical forces obtained from experiments.

$$N_3 = N_{b1} - N_{s2}; \quad (3) \quad Q_3 = Q - Q_{b1} - Q_s - Q_{sw} \quad (4)$$

The values of the vertical component of the forces of engagement, depending on the percentage of transverse reinforcement, the size of the shear span and the force of

compression of concrete by prestressing steel reinforcement, by the time of destruction of the elements ranged within 20÷40 %, and in some cases reaches 55% of the ultimate shear force perceived by the beam.

The greatest value of the shear force from the external load perceived by the longitudinal steel reinforcement (nagel effect) occurs after its intersection with an inclined crack. With a further increase in the load due to the destruction of the protective layer of concrete along the longitudinal steel reinforcement towards the support, the value of the nagel effect decreases. The influence of the forces of engagement of the rough surface of edges arising in an inclined crack when they are displaced, on the strength of bent reinforced concrete elements along inclined sections, on the contrary, increases with an increase in the external load.

The transverse steel reinforcement is made in the form of closed clamps with a diameter of 6 mm from steel of class A-I. On each of the clamps of the transverse steel reinforcement, 6 strain gauges with a base of 20 mm were also glued (3 strain gauges on each branch) (Fig. 6).

Before the formation of inclined cracks at the beginning of loading of the beam, small shortening deformations are observed in the clamps (see Fig. 6). After the formation of inclined cracks, the clamps are deformed unevenly along their length, there are sharp jumps in the elongation deformations at the points of direct intersection of the clamps with these cracks. In beams without prestressing, the attainment of the yield strength in all clamps crossed by an inclined crack was observed at a load of 70 - 85% of the breaking load (see Fig. 6)

In prestressed beams at a load of 85 - 90% of the breaking load, reaching the yield point was observed only in some clamps crossed by an inclined crack, while reaching the yield point in the remaining clamps was observed immediately before and during the destruction of the beams. In beams without prestressing in some clamps, at the stage of fracture, the elongations entered the hardening zone of the steel.

In addition to 24 experimental rectangular beams tested at NIIZhB (Moscow), for the research of the stress-strain state and strength of bent reinforced concrete T-profile elements along inclined sections in the presence of one-, two- and triaxial prestressing of steel reinforcement (Fig. 7 and 8), 48 beams were tested with different cross-sectional dimensions, the number of transverse steel reinforcement, the amount of prestressing, and other factors.

Fig. 7. General view of the installation for testing beams at one -, two - and triaxial prestressing of steel reinforcement.

The research includes a complex process of manufacturing and testing experimental reinforced concrete beams, moreover, in the practice of construction and scientific research both in Russia and abroad, the author of the article was the first to carry out triaxial prestressing of bent reinforced concrete elements.

For experimental research, T-profile beams were made with thin ribs in cross-section (ratio $b/h = 0.18$) and with broadenings in the lower zone designed to accommodate longitudinal steel reinforcement and to ensure the stability of beams during their testing - models of beams of bridge structures. To compare the effect of prestressing in longitudinal steel reinforcement on the strength of beams along inclined sections, similar rectangular beams were made without flanges in the compressed zone of concrete. It should be noted that

in rectangular beams with thin ribs in cross-section, uniaxial prestressing of longitudinal steel reinforcement did not at all increase the strength of beams along inclined sections, or increased insignificantly (by 1.06 times). In similar T-profile beams with thin ribs, prestressing in longitudinal steel reinforcement increased the strength along inclined sections within the range from 1.12 to 1.35 times. With an increase in the relative thickness of the rib in the cross section of the beams, the effect of prestressing of the longitudinal steel reinforcement on their strength along inclined sections increased.

Very valuable and necessary when designing (especially the spans of bridge structures) is the operation of beams under load with triaxial prestressing of the steel reinforcement, in which their brittle fracture is excluded. Despite the heavy loads and deflections in the beams, their destruction occurs plastic.

Fig. 8. Anchoring of prestressing transverse steel reinforcement in compressed flanges (near beam), and also in flanges and ribs (far beam) in bent reinforced concrete I-beam elements.