Evaluation of the Effectiveness of Alternative Options for Strengthening Inclined Sections of Beams with Prestressing Reinforcement

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Abstract. The article provides an assessment of the effectiveness of technical solutions to strengthen the beams of spans of road bridges and indicates the advantages of using alternative reinforcement options in comparison with known solutions. The necessity of considering the collaboration of concrete and reinforcing elements on the principal planes of the webs of beams of the span is revealed. A method for determining the period of serviceability of a span is presented, as well as the dependence of this parameter on the strength characteristics of concrete beams. Calculated data are presented that allow critically assessing the effectiveness and the possibility of using various options for increasing the period of serviceability of the span of road bridges. The obtained results allow drawing conclusions about the validity and effectiveness of the proposed solutions for strengthening the span, as well as the prospects for using typical structures of previous generations in modern operating conditions.

1. Introduction

The road bridges are technically complex and essential engineering structures. The operational capability of bridge crossings is determined not only by their safety, but also by the level of comfort of drivers and passengers. Compliance of the consumer properties of structures with the requirements of regulatory documents in this case is determined by the calculation in accordance with serviceability limit states, the key factor of which is to ensure crack resistance of the beams of span.

2. Background

The issue of ensuring crack resistance is relevant not only in bridge construction. A.V. Kamenchukov and I.S. Ukrainskiy speak about the importance of maintaining the integrity of the structure of material in publication [1], and the authors of the publication [2] pay attention to the issue of preserving the consumer properties of structures.

In addition, other researchers paid attention to the issues of strengthening the supporting structures: G.I. Berdichevsky in [3], Hu Z, Du R, Sun LZ, Wang S, Wu F, Xiao D and Yuan S in publication [4], and Toniolo G and di Prisco M in [5].

An analysis of publications and the results of experimental and theoretical studies and computational and theoretical works on the issue of increasing the bearing capacity and crack...
resistance of inclined sections of reinforced concrete beams with prestressed reinforcement shows two fundamental directions in solving the problem on this topic.

The solutions of TsNIIS (Central Scientific Research Institute of Construction) and Soyuzdorproekt focus on the use of concrete of higher classes in comparison with typical projects series 3.503.1-81 with an increase in the design resistance $R_{bt,ser}$ and, accordingly, the limiting part of the condition of crack resistance $\sigma_{mt} < 0,85R_{bt,ser}$.

In particular, in the studies of TsNIIS [6], it was shown that it is necessary to take concrete of class B50 to ensure crack resistance of inclined sections of beams in spans with a length of 24 meters under the action of temporary loads A14, N14 according to GOST 32960-2014, and in spans with a length of 33 meters – to take class B45 for the same goals.

In the solutions of PNU (Pacific National University), the condition of crack resistance of inclined sections is provided by reinforcement of the reinforcing nets of the support zones of the beams. A characteristic feature of proposals of PNU is the placement of double vertical bars of stirrups and bars of horizontal reinforcement in the reinforcing nets. The solutions of the authors are presented in detail in publications [7, 8].

3. Statement of the problem

The text of your paper should be formatted as follows:

We can't fail to see that the options for increasing the crack resistance of inclined sections of reinforced concrete beams with prestressed reinforcement, presented even in a draft format, according to their technical implementation of the goal, are alternative options, but they do not reveal the indisputable advantages of any of the options, and in this regard, the assessment of the effectiveness of the presented solutions in providing crack resistance of inclined sections is absolutely topical.

It seems to us that the weightiest argument for a solution is the period of its serviceability.

The period of serviceability of the solution of TsNIIS is obviously determined by the time of wear of concrete, during which the design concrete resistance $R_{bt,ser}$ decreases to the level at which the crack resistance is not provided.

4. Theoretical part

If we consider the condition of crack resistance of the form

$$\sigma_{mt} < 0,85R_{bt,ser}, \quad (1)$$

that is, the following inequality occurs

$$\sigma_{mt} > 0,85R_{bt,ser} \quad (2)$$

If we consider valid the dependence (3.3) of "Methods of computational prediction" [9] in the reflection of degradation processes related to changes in the reduced strength characteristics of concrete, in relation to the type of stress state of interest, we can write

$$R_{bt,ser,Ti} = R_{bt,ser}(1 - k_s k_t \Delta \tau \omega_t) \quad (3)$$

where $R_{bt,ser}$ are the design resistances of concrete by the calculation in accordance with serviceability limit states, corresponding to the accepted concrete class;

$R_{bt,ser,Ti}$ are adequately corresponding to the design resistances $R_{bt,ser}$, the strength characteristic of concrete after full years of operation $t_i$.

Considering the accepted symbols $R_{bt,ser,Ti}$ and $R_{bt,ser}$, the previously given inequality (2), as a reflection of the violation of the condition of crack resistance, should be represented in the following form

$$\sigma_{mt} > 0,85R_{bt,ser,Ti} \quad (4)$$

Then, using the accepted symbols, the condition of crack resistance in the inclined section of a beam of the structure with a service life of $t_i$ years should be as follows:

$$\sigma_{mt} < 0,85R_{bt,ser,Ti} \quad (5)$$
Replacing the factor $R_{bt,ser} T_i$ on the right side of expression (5) with the first part of expression (3) we obtain

$$\sigma_{mt} = R_{bt,ser} \cdot 0.85 \cdot (1 - k_s k_t \Delta R \omega t_i)$$

(6)

and further

$$\frac{\sigma_{mt}}{0.85 R_{bt,ser}} = (1 - k_s k_t \Delta R \omega t_i)$$

(7)

Whence, considering the known operating conditions that determine the values of the influencing parameters $k_s, \Delta R, \omega$, we find the period of serviceability $t_i$, at the end of which the condition for fulfilling (5) will still be ensured:

$$t_i = \frac{\sigma_{mt}}{0.85 R_{bt,ser}} - 1$$

(8)

5. Practical significance

Before assessing the option of strengthening the inclined section according to the proposals of PNU as an alternative to the previously considered option according to the proposal of TsNIIS, we will point out the conditions for ensuring the practical implementation of the option of strengthening according to the proposal of TsNIIS, taking as a basis the results of the checking calculation of the crack resistance of inclined sections of a beam with a length of 24 meters as part of the span G-10+0.75+2.25 m under the load A14, N14 according to GOST 32960-2014, given in the publication [10].

Further, based on the materials of publication [10], the values of stresses $\sigma_{mt}$ are given for the sections of the beam $x$, and from the condition of crack resistance $\sigma_{mt} < 0.85 R_{bt,ser}$ we find

$$R_{bt,ser} = \frac{\sigma_{mt}}{0.85}$$

(9)

and the class of concrete $B$ corresponding to the found $R_{bt,ser}$.

According to the publication [10], we have:

| $x$, m | $\sigma_{mt}$, kgf/cm² | $R_{bt,ser}$, kgf/cm² | $B$, MPa |
|--------|-----------------------|-----------------------|---------|
| 5,43   | 19,1                  | 22,5                  | 45      |
| 4,20   | 20,8                  | 24,5                  | 55      |
| 3,63   | 21,5                  | 25,3                  | 60      |
| 2,70   | 23,0                  | 27,0                  | 60      |
| 2.40   | 21,1                  | 24,8                  | 60      |
| 5,43   | 19,1                  | 22,5                  | 45      |

Thus, the data obtained from the publication [10] regarding the class of concrete of the values $B_{45}$, $B_{55}$, $B_{60}$, which are quite significant in comparison with the data of a typical project series 3.503.1-81, give reason to note the following: the development and modernization of individual technological operations of the production of reinforced concrete spans are probably necessary to ensure the required high class of concrete providing working capacity in their supporting structures by creating a more perfect concrete structure that successfully resists the factors influencing concrete wear and reducing its strength characteristics in the form of expression (3), in the form of coefficients $k_s$, $k_t$, $\Delta R$, $\omega$, mainly of a statistical nature.
And in this regard, it seems to us that proposals of PNU have greater guarantees of preservation of working capacity, because they are focused on quite real constructive additions to the internal structure of the web, and in the design part on building a design model in which the key condition of ensuring the crack resistance of concrete on the principal planes of inclined sections is the collaboration of concrete and vertical bars of transverse reinforcement as well as horizontal bars of reinforcing nets of the webs in their support zones.

### 6. Research results

A key condition in ensuring the crack resistance of concrete on the principal planes of inclined sections is the collaboration of concrete and vertical bars of the reinforcing nets of the webs in their support zones. The outline model is reflected in the analytical solution in a closed form, presented in publication [10].

So, considering the collaboration of concrete with the reinforcing elements of the reinforcing net of the web, the analytical solution for assessing tensile stresses on the principal planes of the concrete part of the inclined section of the beam depending on the main tensile stresses $\sigma_{mt}$ according to clause 7.104 of SP 35.13330.2011 (Set of rules) has the following form:

$$
\sigma_{mt,b} = \frac{\sigma_{mt}}{\left(1 + \frac{E_s n_x A_{sx}}{E_b u_y b} l \cos^3 \alpha_1 + \frac{E_s n_y A_{sy}}{E_b u_x b} l \sin^3 \alpha_1\right)}
$$

The collaboration of concrete and reinforcing elements of reinforcing nets is represented by the summands of the denominator of expression (10), in which the structure of horizontal reinforcement is characterized by the vertical step of horizontal bars $u_y$, the number of horizontal bars in one horizontal plane $n_x$, and the cross-sectional area of one horizontal bar $A_{sx}$.

In a similar way, the structure of transverse reinforcement is characterized by the horizontal step of the stirrups $u_x$, the number of stirrups in one vertical plane $n_y$, and the cross-sectional area of one stirrup $A_{sy}$.

Explanations for the construction and justification of the calculation model are presented in Figure 1.

**Figure 1.** Calculation model

- a – equilibrium condition on a unit area,
- b – scheme for determining the forces in the bars of horizontal and vertical reinforcement.
The naturalness of the proposed design model for the collaboration of concrete and reinforcing elements of horizontal and vertical reinforcement follows from the analysis of the operation of a fragment of the web of a beam pierced by an inclined crack, which reveals the participation of horizontal and transverse reinforcement bars in the force interaction of the left and right parts of the beam, separated by an inclined crack (Figure 2).

![Figure 2. The participation of reinforcing elements in the work of concrete.](image)

In the same way, it is obvious that the effectiveness of this participation depends on the step of setting of the vertical and horizontal bars $u_x, u_y$ and their assortment $A_{sx}, A_{sy}$.

Returning to the assessment of the efficiency of the analyzed version of reinforcement based on the intensification of the reinforcement of the support zones of the beams, one should probably consider the degradation processes associated with the operation, which lead to a decrease in the strength of concrete of inclined sections, for which the condition crack resistance of the type of the following form is relevant

$$\sigma_{mt} < 0,85 R_{bt,ser} t_i$$

as well as initiating corrosion processes in reinforcement with a decrease in the area of the bars from the initial values $A_{sx}, A_{sy}$ to the values at the end of the period of serviceability $A_{sx}^*, A_{sy}^*$. Then, for the end of the period of serviceability with the required duration $t_i$, the expression (10) as a source for determining $t_i$ should have the following form

$$\sigma_{mt,b} = \frac{\sigma_{mt}}{\left(1 + \frac{E_{sx} A_{sx}^*}{E_b u_y b} l \cos^3 \alpha_1 + \frac{E_{sy} A_{sy}^*}{E_b u_x b} l \sin^3 \alpha_1\right)} < 0,85 R_{bt,ser} t_i$$

It follows from the analysis of inequality (12) that it is extremely difficult to find the period of serviceability of the analyzed option of strengthening directly from the expansion of inequality (12), due to the absence of an analytical relationship that establishes a connection between degradation processes in concrete and reinforcement with time factors, and therefore it is proposed to expand the
inequality (12) based on an iterative process, initially taking in the first approximation the period of serviceability equal to $t_i$ found from (8), with the following estimation of $R_{bt, ser} T_i$ for the right-hand side of (12), taking into account the duration of corrosion processes, specifying the cross-sectional areas of reinforcing elements $A_{sx}^*$, $A_{sy}^*$, the subsequent substitution of the found values in (12) and test of inequality (12).

7. Conclusions
Thus, the value $t_i$ found as a result of iteration sets the duration of the period of serviceability of the option of strengthening according to the proposals of PNU. The advantage of the analyzed options of strengthening according to the proposals of TsNIIS and PNU is determined based on the comparison of the $t_i$ and $t_i$ found according to (8).

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