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Ecological-Economic and Technical Advantages of Reinforced Concrete Girders with Combined Reinforcement

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Abstract. Changing of usual reinforcement, having, as a rule, welding joints with the pre-stressed joint-free steel has a significant ecological meaning, reducing harmful emissions. Decrease of the concrete consumption is also solving this important ecological issue, since the volume of concrete and concrete dust is reduced. In the compressed elements extreme compressing forces in the reinforcement upon concrete destruction reach 400-500 MPa due to limited concrete compression, which is why use of extra-strong reinforcement in such elements is not reasonable. With the purpose of increase of extreme compressing forces in the reinforcement of compressed elements it is suggested to pre-compress it. Increase of limits of stress in the reinforcement allows to efficiently using extra-strong reinforcement in the compressed zone which will lead to substantial reduction of its consumption. Effect from the pre-compression of the reinforcement is the higher, the bigger is the reinforcement percent. Degree of increase of strength of the elements upon pre-compression of reinforcement with decrease of concrete strength increases.

1 Introduction

As it is known, reinforced concrete girders are the most common types of building constructions and spans of bridges. In such constructions axial forces are mostly operating, which allows to most efficiently use materials. In comparison with steel reinforced concrete girders in the spans of up to 30 meters provide for economy of metal of up to 70%. They are more durable and are distinguished with high fire-resistance and require less operational expenses. Reinforced concrete girders are almost twice lighter than reinforced concrete beams with solid wall.

Taking into consideration the indicated advantages of reinforced concrete girders the task of their improvement, the main trend of which is decrease of consumption of deficit steel and increase of technical, economic and ecological indices, gains special importance[1,2,3,4].

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It should be noted that changing of usual reinforcement, having, as a rule, welding joints with the pre-stressed joint-free steel has a significant ecological meaning, reducing harmful emissions. Decrease of the concrete consumption is also solving this important ecological issue, since the volume of concrete and concrete dust is reduced.

In the known girders the stretched lower chord, and sometimes the utmost rising diagonals are reinforced with extra-strong pre-stretched reinforcement to reduce steel consumption. Other elements of reinforced concrete girder containing non-extra-strong reinforcement are manufactured without pre-stressing.

2 Literature review

Ecological-Economic and Technical Advantages of Reinforced Concrete Girders with Combined Reinforcement is a very actually problem of modern building and constructions. A lot of scientists devote their scientific works to this problem. We can see the parts of this theme in the works of Ch. Alk. Apostolopoulos, M.P. Papadopoulos, Sp.G. Pantelakis; C.A. Apostolopoulos, M.P. Papadopoulos; V. Kumar, U. Kumar Sharma, B. Singh, P. Bhargava; E. Cadoni, M. Dotta, D.Forni, N. Tesio, C.Albertini; P. Dybeł, K. Furtak; P.Desnerck, Janet M. Lees, Chris T. Morley; O. Kelestemur, M. Halidun Kelestemur, S. Yildiz; E. Cadoni, L.Fenu, D.Forni, G. Riganti, E. Cadoni; X. Song, Y. Wu, X. Gu, Ch. Chen; P.Kopas, L. Jakubovičová, M.Vaško, M. Handrik; T. Xu, A. Castel ; J. Toribio, B. González, J.C. Matos, F.J. Ayaso; Michael D. Sangid, Garrett J. Pataky, H. Sehitoglu, Reginald F. Hamilton, Hans J. Maier; J. Yin, W. Wang, Z. Man, S. Khoo; R.R. Bhargava, S. Hasan; C. Xue, An He, H. Yong, Y. Zhou; M.V. Menshykova, O.V. Menshykov, Vita A. Mikucka, I. A. Guz; R.K. Joki, F. Grytten, B. Hayman, B.F. Sorensen; Di-Hua Tong, Xue-Ren Wu; M. El-Zeghayar, T.H. Topper, K.A. Soudki; Doo-Ho Cho, An-Dong Shin, Nam-Su Huh, Hyun-IkJeon; C. Fischer, C. Schweizer, T. Seifert; C. Mang, L. Jason, L.Davenne; M. Bruggi; M.Nematzadeh, A. Salari, J. Ghadami, M. Naghipour; Y. Xing, Q. Han, J. Xu, Q. Guo, Y. Wang ; P. Li, Yu-Fei Wu at their articles : Tensile behavior of corroded reinforcing steel bars BSt500s [1]; Stress concentration and fatigue of profiled reinforcing steels [2]; Tensile and low cycle fatigue behavior of corroded reinforcing steel bars S400 [3]; Effect of temperature on mechanical properties of pre-damaged steel reinforcing bars [4]; Mechanical behaviour of quenched and self-tempered reinforcing steel in tension under high strain rate [5]; The effect of ribbed reinforcing bars location on their bond with high-performance concrete [6]; Bond behaviour of reinforcing bars in cracked concrete; Improvement of Mechanical Properties of Reinforcing Steel Used in the Reinforced Concrete Structures [7]; Strain rate behaviour in tension of austenitic stainless steel used for reinforcing bars; Numerical simulation of the high strain-rate behavior of quenched and self-tempered reinforcing steel in tension [8]; Bond behaviour of reinforcing steel bars in early age concrete [9]; Fatigue Resistance of Reinforcing Steel Bars [10]; Modeling the dynamic stiffness of cracked reinforced concrete beams under low-amplitude vibration loads [11]; Effect of sudden load decrease on the fatigue crack growth in cold drawn prestressing steel [12]; High resolution analysis of opening and sliding in fatigue crack growth [13]; Modeling and analysis of gear tooth crack growth under variable-amplitude loading [14]; Crack-tip-opening displacement for four symmetrically situated cracks with coalesced interior yield zones [15]; Crack tip opening displacement in a linear strain hardening material; Interface cracks with initial opening under harmonic loading [16]; Determination of a cohesive law for delamination modelling – Accounting for variation in crack opening and stress state across the test specimen width [17]; Analysis of crack opening stresses for center- and edge-crack tension specimens [18]; A model of crack opening stresses in variable amplitude loading using smooth specimen fatigue test data for three steels [19]; Engineering estimates of crack opening displacement for non-idealized circumferential through-wall cracks in pipe [20]; Assessing steel strains on reinforced concrete members from surface cracking patterns [21]; Numerical limit analysis of steel-reinforced concrete walls and slabs [22]; A crack opening stress equation for in-phase and out-of-phase thermomechanical fatigue loading [23]; Crack opening estimate in reinforced concrete walls using a steel–concrete bond model [24]; A numerical method to generate optimal load paths in plain and reinforced concrete structures [25]; Stress-strain behavior of freshly compressed concrete under axial compression with a practical equation [26]; Experimental and numerical study on static behavior of elastic concrete-steel composite beams [27]; Stress–strain behavior of actively and passively confined concrete under cyclic axial load [28].

3 Ecological-Economic and Technical Advantages of Reinforced Concrete Girders with Combined Reinforcement

In the compressed elements extreme compressing forces in the reinforcement upon concrete destruction reach 400…500 MPa due to limited concrete compression, which is why use of extra-strong reinforcement in such elements is not reasonable. With the purpose of increase of extreme compressing forces in the reinforcement of compressed elements it is suggested to pre-compress it. This will lead to increase of compressing forces in the reinforcement upon concrete destruction by the value of pre-compressing forces. As the resultlimits of stress will be equal$R_{sc} + \sigma'_{sp}$, where$R_{sc}$is design resistance of reinforcement to compression, and$\sigma'_{sp}$is pre-compressive stress. Increase of limits of stress in the reinforcement allows to efficiently use extra-strong reinforcement in the compressed zone which will lead to substantial reduction of its consumption.

Decrease of steel consumption is explained by increase of limits of compression stress in the reinforcement of the compressed chord by the value of pre-compression of reinforcement. In extra-strong reinforcement of compressed chord of the girder limit compression stress equals to$R_{sc} + \sigma'_{sp}$,which will lead to decrease of steel consumption compared to elements without pre-stressing by$\left(R_{sc} + \sigma'_{sp}\right)/R_{sc}$times.

Besides, pre-compression of compressed chord reinforcement upon drawback of pre-stressing leads to girder bending which is substantially bigger than pre-stretch of lower chord reinforcement. It enables also increase of cracking resistance of the lower stretched chord [1,2].

Pre-stretched reinforcement could be produced from any extra-strong steel (rod, wire, cable, wire-rope), and reinforcement frame of the upper chord is manufactured from longitudinal extra-strong working rods and closed stirrups.

It should be noted that pre-compression of the extra-strong reinforcement in compressed girder elements is reasonable not only in girders with parallel chords, but in other types of girders. For example, in composite girders of trapezoidal and rectangular profile pre-stretching of lower chords and pre-compression of upper ones is carried out separately for each half, which before assembly are joined by welding of embedded and mounting steel elements.

In eaves girder it is convenient to pre-compress reinforcement of compressed chord and outmost vertical posts[3,4].

Elements of reinforced concrete girders containing pre-compressed and pre-stressed reinforcement, as a rule, have non-stressed reinforcement, as well, availability of which in the elements increases resistance of the latter upon transfer of strength of pre-stressing from the reinforcement to the concrete, allowing to increase the pre-stressing force.

For quantitative evaluation of relative content in the cross-section of pre-stressed reinforcement coefficients of stretching pre-stress K_p and compressing pre-stress K_c are introduced, numerical values of which are determined by formulas:

$$K_p = \frac{\sigma_{0.2}^{sp} A_{sp}}{\sigma_{0.2}^{sp} A_{sp} + \sigma_{0.2}^{sc} A_{sc} + \sigma_{0.2}^{s} A_s}, \tag{1}$$

$$K_c = \frac{\sigma_{0.2}^{sc} A_{sc}}{\sigma_{0.2}^{sc} A_{sc} + \sigma_{0.2}^{sp} A_{sp} + \sigma_{0.2}^{s} A_s}, \tag{2}$$

where $\sigma_{0.2}^{sp}$; $\sigma_{0.2}^{sc}$; $\sigma_{0.2}^{s}$; are conventional liquid limits of pre-stretched, pre-compressed and non-stressed reinforcement;

A_{sp}; A_{sc} and A_s are areas of cross-sections of pre-stretched reinforcement located in the stretched (or less compressed) zone of the element.

Similarly coefficients K'_p and K'_c are determined, characterizing relative content of pre-stretched, pre-compressed and non-stressed reinforcement located in the compressed zone of the element.

Values of pre-stressing coefficient lay within the limits from 0 to 1.

For evaluation of efficiency of centrally compressed elements during pre-compression of the reinforcement let's review the element having symmetrically located pre-compressed and non-stressed reinforcement.

Resultant of pre-stress in the reinforcement will be equal to:

$$P_c = \sigma_{spc} A_{sc} + \sigma'_{spc} A'_{sc} + \sigma_{so} A_s + \sigma'_{so} A'_s, \tag{3}$$

σ_{spc} and σ'_{spc} – are pre-compressing stresses;

$\sigma_{so} = \sigma_8 - \sigma_{6,9}$; $\sigma'_{so} = \sigma'_8 - \sigma'_{6,9}$ are stresses in non-stressed reinforcement, numerically equal to algebraic sum of losses from concrete shrinkage σ_8 (leading to compressing stress in the non-stressed reinforcement) and concrete creep (quickly creeping or long) $\sigma_{6,9}$ and $\sigma'_{6,9}$. Stresses σ_{so} and σ'_{so}, as a rule, are compressing, since losses of pre-stress from shrinkage are more than from creep upon stretching by 2…4 times.

Before application of external load concrete section under the influence of force P_c will turn out to be stretched. Destructing external compressing force N upon central force application ($e_{ON} = e_{OP} = 0$ will be equal to:

$$N = R_B A + \varepsilon_{BR} E_s (A_{sc} + A'_{sc} + A_s + A'_s) + \sigma_{spc} A_{sc} + \sigma'_{src} A'_{sc} + \sigma_{sc}(A_s + A_{sc}) + \sigma_{sc}(A'_s + A'_{sc}), \tag{4}$$

and in case of absence of pre-stressing –

$$N_1 = R_B A + \varepsilon_{BR} E_s (A_{sc} + A'_{sc} + A_s + A'_s) + \sigma_8 (A_s + A_{sc} + A'_s + A'_{sc}), \tag{5}$$

Thus, element strength could be as a sum

$$N = N_1 + N_2, \tag{6}$$

where N_1 is a force taken up by the same element, but without pre-stress and determined by formula (5) with consideration to compressing forces σ_8 from concrete shrinkage; N_2 is the additional force nulling the pre-stressing stretching force in the concrete and being strength growth of the element in pre-compression of the reinforcement, it equals:

$$N_2 = \sigma_{spc}A_{sc} + \sigma'_{spc}A'_{sc} - \sigma_{6.8}(A_s + A_{sc}) - \sigma'_{6.8}(A'_s + A'_{sc}), \quad (7)$$

It should be noted that if steel of low classes with physical liquid limit is used for non-stressed reinforcement, there might be a case when deformation in the reinforcement by the liquidity beginning will turn out to be less than limit compression of concrete $(\varepsilon_y < \varepsilon_{BR})$. In this case, rarely met in practice, in the formulas (4) and (5) stresses in the non-stressed reinforcement$A_s$andA'_sshould be taken as equal to liquid limitσ_y (instead of$\varepsilon_{BR}E_s$).

It should also be noted that formula (4) is true under the condition that summarized compressing stresses in the reinforcement upon element's destruction do not increase the conditional limit of reinforcement tension, i.e. subject to the condition$\left(\sigma_{spc} + \varepsilon_{BR}E_s\right) \leq \beta\sigma_{0.2}$, where$\beta = \sigma_{el}/\sigma_{0.2}$. Otherwise, which is rarely met in the practice of compressed elements designing, non-linear dependence should be used between stresses and deformations in the reinforcement.

Let us show on the example of centrally compressed short (non-flexible) element the efficiency of pre-compressing of reinforcement. Ratio of forces taken up by the longitudinal reinforcement and concrete upon depletion of strength of elements equals to:

$$\frac{N_s}{N} = \frac{\mu(R_{sc}+\sigma_{spc})}{R_B+\mu(R_{sc}+\sigma_{spc})}; \quad (8)$$

$$\frac{N_B}{N} = \frac{R_B}{R_B+\mu(R_{sc}+\sigma_{spc})}, \quad (9)$$

where$N$, $N_s$and$N_B$are stresses taken up by the reinforced concrete element, longitudinal reinforcement and concrete, correspondingly; $\sigma_{spc}$are value of pre-compression of the reinforcement.

With concrete of the classB30 and reinforcement with design compression resistance$R_{sc} = 400\ MPa$,If the reinforcement is not pre-compressed $(\sigma_{spc} = 0)$, dependence of the indicated stresses from the percentage of reinforcement is shown with slightly curved lines. By these lines it is seen that even with$\mu = 2\%$only 30% of total stress is taken by the non-stressed reinforcement. If this reinforcement is pre-compressed to reach resistance $\sigma_{spc} = 400\ MPa$, the stress taken up by it rises to 50%, and bearing capacity of the element increases by more than 30%.

Let us analyze the influence of various factors on the degree of increase of strength of reinforced concrete elements with pre-compressed reinforcement. In central compression of elements with symmetrical reinforcement strength of the element containing pre-compressed reinforcement, will be equal to:

$$N_c = R_BA + R_{sc}(A_s + A_{sc}) + \sigma_{spc}A_{sc}, \quad (10)$$

where the first two summands of the first part represent the strength of element without pre-stress N. Ratio

$$\frac{N_c}{N} = 1 + \frac{\sigma_{spc}\mu_{sc}}{R_B+\mu R_{sc}}, \quad (11)$$

depends on the prism strength of concreteR_B, value of pre-compression of the reinforcement$\sigma_{spc}$and reinforcement coefficient – summarizedμand of pre-compressed reinforcement μ_{sc}.

4 Conclusions

With increase of values of pre-stress coefficientsK_c, i.e. relative content of pre-compressed reinforcement, from 0.25 to 1 with$\mu = 2.55\%$relative strength of elements rises by 20…25%. Effect from the pre-compression of the reinforcement is the higher, the bigger is the reinforcement percent – with its increase from 0.65% to 2.55% relative strength of the element rises by 17…22%. Degree of increase of strength of the elements upon pre-compression of reinforcement with decrease of concrete strength increases. Thus, with $\mathrm{K}_c = 1$and$\mu = 2{,}55\%$decrease of concrete strength $R_B$from 40 to 20 MPa leads to growth of relative strength of the element by 13%, and with$\mu = 1{,}13\%$ - by 6%.

Thus, use of reinforced concrete girders of the suggested construction allows increasing technical, ecological and economical indices of such constructions.

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