Cad methods of structural solutions for reinforced concrete frame

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Abstract. Analytical dependences, criteria and bounding conditions numerically describing relations between increasing the compressive strength of concrete and reducing reinforcing steel for both bending and compression-bending elements are given herein under the results of comparative application of concrete and high strength reinforcement in structural elements of the reinforced concrete frame. Computational and analytical dependences to evaluate stress-strain behavior of slabs for the reinforced concrete multistory frame are presented under the multiple computational investigations made for various values of slab and span thickness, real loads, concrete grades and reinforcement. An optimum section model for the reinforced concrete element is CAD developed by criterion for reducing material consumption and proper combination of both concrete and reinforcement grades. The research results are applied in design and construction of a number of reinforced concrete frames for tall buildings in the Republic of Bashkortostan.

Keywords: reinforced concrete, high performance concrete, saving of reinforced steel, CAD, software package.

1. Introduction
High performance concrete with strength properties and concrete mix with modifying additives are widely applied nowadays in cast-in-place construction in the Russian Federation. Now, however, optimization and efficient use of high performance concrete and high strength concrete, especially combined with high grade reinforcement are of vital importance [1, 2]. Furthermore, computing technology has greatly facilitated computation of complicated statically indeterminate systems. It resulted in saving of materials thereby increasing number of buildings and facilities applying reinforced concrete frames.

2. Bibliography
Right proportioning of the concrete mix composition [3], selection and application of standard practice for concrete making and curing, achieving the required quality of concrete elements and reinforced concrete structures in maintenance, handling and control for the normalized level [4, 5] are very important in all steps of making the advanced concrete with strength properties and high
performance criteria. Proceeding from practice of cast-in-place construction, the major part of the applied concrete (80% of total volume) is known to be the concrete with the compressive strength of up to 40MPa [6, 7]. Development of concreting technology, efficiency of both design and technology solutions in concrete and reinforced concrete applying, and optimization in using high quality concrete and elements made from it directly depend on Portland cement and types thereof [8].

3. Materials and methods

Actually applied unmodified concrete mixes with maximum compressive strength of up to 40MPa (V30 grade) have P1 flowability (up to 1-5cm cone slump) and may not be applied in the advanced cast-in-place construction. Concrete mixes of P4-P5 group by flowability (water-binder ratio V/V = 0.3-0.45) that basically meet the requirements of refined technologies of construction including concreting of both thin-walled and densely-reinforced structures are likely to be made on the basis of organomineral modifiers and certain superplasticizers with 50-80MPa strength range (V40-V65 grades) [9]. Concrete mixes with chemical admixtures of P1-P3 (V/V=0.15-0.25) flowability groups enable making concrete of V80 and higher grades (100MPa and more strength). Therefore, searching, development and optimization of new technical, technological and design solutions for the cast-in-place construction are very important requiring further improvement.

Application of high and ultra-high grades of concrete in present-day large-scale construction of frame and cast-in-place buildings requires review of technical and economic efficiency thereof. Such review of the reinforced concrete structures is advisable due to their loading and stress strain behavior [10].

Current approach to efficiency to increase concrete strength by the reinforced steel saving criterion for both compression and bending reinforced concrete elements in certain form is described both in domestic and foreign literature by a number of examples and does not get a general idea of relation between the concrete strength and the reinforcement requirements [11,12].

Increase of the concrete strength is mostly efficient in axially loaded columns and stipulated by saving materials and actually varies with the concrete strength increase. This evaluation is sure to be done considering changes of slenderness ratio in the compression element. At high excentricities of normal force this method efficiency is close to bending elements, and at small excentricities – to axially loaded columns in beam column elements.

Load-bearing capacity of bending (beam, slab) element against bending moment is calculated by formula:

\[ M_{ult} = R_{s0} A_{s0} (h_0 - \frac{R_{s0} A_{s0}}{2R_{b0} b}) \]  

(1)

where, \( R_{s0} \), \( R_{b0} \) – design strength of reinforcement and concrete for the original cross-section;

\( h_0 \), \( b \) – effective height and width of the rectangular cross-section of the element;

\( A_{s0} \) – effective reinforcement area.

Substituting \( A_s=\mu_0 bh_0 \) in (1) (here \( \mu_0 \) – is ratio of reinforcement for the original cross-section), we get:

\[ M_{ult} = R_{s0} \mu_0 bh_0 (h_0 - \frac{R_{s0} \mu_0 bh_0}{2R_{b0} b}) \]  

(2)

Load-bearing capacity of the alternative cross-section differing from the original one by effective height of cross-section \( (h_{0i}) \), effective reinforcement area \( (A_{si}) \) (coefficient \( \mu_i \), design compressive strength of concrete for alternative grade \( (R_{bi}) \) and tension reinforcement \( (R_{si}) \) will be found by the following dependence under the width stability of the rectangular cross-section b:

\[ M_{ult} = R_{si} \mu_i bh_{0i} (h_{0i} - \frac{R_{si} \mu_i bh_{0i}}{2R_{bi} b}) = R_{si} \mu_i bh_{0i} (h_{0i} - \frac{R_{si} \mu_i bh_{0i}}{2R_{bi} b}) \]  

(3)
Changes of strength properties and relative usage of materials when comparing original and alternative cross-sections may be considered through modification coefficients of the appropriate values:

\[ a_s = \frac{R_{sl}}{R_{s0}}, \quad a_b = \frac{R_{bl}}{R_{b0}} \]  \hfill (4)

\[ \eta_s \] and \( \eta_b \) – of using reinforcement and concrete, accordingly

\[ \eta_s = \frac{\mu_s}{\mu_{s0}}, \quad \eta_b = \frac{h_b}{h_0} \]  \hfill (5)

The strength balance condition therewith will be as follows:

\[ R_{s0}\mu_0 b h_0(h_0 - \frac{R_{s0}\eta_s h_0}{2R_{b0}}) = (R_{s0}a_s)(\mu_0\eta_s)b(h_0\eta_b)(h_0\eta_b) - \frac{(R_{s0}a_s)(\mu_0\eta_s)(h_0\eta_b)}{2R_{b0}a_b} \]

\[ = a_s \eta_s \eta_b R_{s0}\mu_0 b h_0(h_0 - \frac{a_s \eta_s \eta_b R_{s0}\mu_0 h_0}{2R_{b0}a_b}). \]  \hfill (6)

Let us introduce value \( k_0 \):

\[ k_0 = \frac{R_{s0}}{2R_{b0}} \]  \hfill (7)

Substituting \( k_0 \) in (6), we get:

\[ 1 - \mu_0 k_0 = a_s \eta_s \eta_b \left( \eta_b - \frac{a_s \eta_s \eta_b \mu_0 k_0}{a_b} \right) \]  \hfill (8)

Then, correlation of coefficients characterizing efficiency of the alternative cross-section with the changed values (such \( a_s \), concrete strength grade, coefficient of main reinforcement and design strength of tension reinforcement) will be as follows:

\[ a_b = \frac{a_s^2 \eta_s^2 \eta_b^2 \mu_0 k_0}{a_s \eta_s \eta_b^2 - 1 + \mu_0 k_0} \]  \hfill (9)

The resulting dependence (9) is of general character [13,14], and it is presented as dimensionless values (Table 1) and may be applied in solving the following:

1. Reducing application of the reinforced steel by increasing the compressive concrete strength at the same reinforcement strength and the same concrete consumption \((a_s=1, \ \eta_b=1)\);
2. Reducing application of the reinforced steel by increasing the height of the effective cross-section of an element, i.e. increase of specific consumption of concrete at the same strength of concrete and reinforcement \((a_b=1, \ a_s=1)\);
3. Reducing specific consumption of concrete by increasing the compressive concrete strength at the same reinforcement strength and consumption \((a_s=1, \ \eta_s=1)\);
4. Reducing application of the reinforced steel substituting the original grade of steel (e.g. A400) to higher grade of A500C at the same strength and consumption of concrete \((a_b=1, \ \eta_b=1)\);
5. Other issues at simultaneous changing of several values of the cross-section.
4. Results

Computer modeling of optimum alternative cross-section of reinforcement concrete element by criterion for reducing material consumption and rational combination between concrete and reinforcement grades is made [15]. Service limit states are fixed.

The original values to choose the optimum solution when using the program are grade of both concrete and reinforcement, coefficient of reinforcement and solution of the required problem to change the grade of either concrete or reinforcement [16,17]. The program enables computation of optimum reinforcing steel with alternative cross-section at the output when applying high grade concrete up to V90. The calculation is made over the same load-bearing capacity of bending element.

Table 1. The results of solving principal problems to evaluate efficiency of high grades concrete and reinforcing steel

| No | Problem content | Relative values | Value relationship formulae characterizing the efficiency |
|----|-----------------|----------------|-------------------------------------------------------|
| 1  | Efficiency of concrete strength increased by criterion for reducing reinforcing steel at the same concrete consumption | $a_b = \frac{\eta_s^2 \mu_b k_0}{\eta_s + \mu_b k_0 - 1}$ | $\eta_s = a_b \pm \sqrt{a_b^2 - 4 \mu_b k_0 + 4 \mu_b^2 k_0^2 a_b}}{2 \mu_b k_0}$ |
| 2  | Optimization of relationship between specific consumption of concrete and reinforcing steel in slab elements | $\eta_b = \frac{\mu_b k_0 - 1}{\eta_s^2 \mu_b k_0 - \eta_s}$ | $\eta_s = \frac{\eta_b^2 - 4 \mu_b k_0 + 4 \mu_b^2 k_0^2}{2 \mu_b k_0 \eta_b}$ |
| 3  | Efficiency of concrete strength increased by criterion for reducing concrete consumption | $a_b = \frac{\eta_s^2 \mu_b k_0}{\eta_s^2 - 1 + \mu_b k_0}$ | $\eta_b = \frac{a_b \mu_b k_0 - a_b}{\mu_b k_0 - a_b}$ |
| 4  | Saving of reinforcing steel substituting the original steel grade to the higher grade at the same strength and the same concrete consumption | $\eta_s = 1 \pm \sqrt{1 - 4 \mu_b k_0 + 4 \mu_b^2 k_0^2}}{2 \mu_b k_0 a_s}$ |
| 5  | Efficiency of concrete strength and reinforcing steel increased by criterion for reducing reinforcing steel at the same concrete consumption | $\eta_s = a_b \pm \sqrt{a_b^2 - 4 \mu_b k_0 a_b + 4 \mu_b^2 k_0^2 a_b}}{2 \mu_b k_0 a_s}$ |

The program enables alternative quantitative evaluation of the reinforcing steel for reinforced concrete bending elements without prestressing when changing compressive concrete strength and reinforcing steel grade.
The program is applied to design of the reinforced bending elements [18]. The computation is made over the same load-bearing capacity of bending element.

The latest official version of the program makes computation by all four values of the cross-section: effective height of the cross-section \(h_0\), main reinforcement area \(A_{si}\) (coefficient of main reinforcement \(\mu_i\)), design compressive strength of concrete for alternative grade \(R_{bi}\) and that of reinforcement for tension \(R_{si}\).

The user is to choose an alternative cross-section value to be changed (concrete grade, reinforcement grade, concrete or reinforcement usage). Algorithm for the program and GUI are given in Figure 2.

Multiple numerous investigations of possible structural concepts were made to fix practical boundaries for the proposed method and program. The spans, slab thickness, concrete and reinforcement grade were varying. Bending elements were analyzed.

The proposed program will enable quantitative evaluation of efficiency and reasonable areas for high performance concrete to be applied in the reinforced concrete bending elements to make feasibility study in the design step which is more important at engineering of reinforced concrete frame facilities [19].

Principal forces were defined, computation of load-bearing capacity for frame elements was made and reinforcing specifications were fixed under the SCAD-Office and LIRA-CAD software (Figure 1).

![Figure 1. Computational models, design load moments and ratio of reinforcement](image)

The analysis data to save A400 main reinforcing steel, as well as A500C reinforcement demonstrate that application of high performance concrete is extremely effective for bending (slab)
elements at about 25%. It follows therefrom that the critical level to increase concrete strength is V40-V50 grade at initial V20-V25 grade [20]. Application of higher grade concrete (V50-V60) in bending (slab) elements to save reinforcing steel is not effective which is confirmed by figure 2.

Computations in the service limit state (deformations and crack resistance) have finally revealed rational areas for high grade concrete application for compressive strength and A500C reinforcement depending on thickness of bending elements and main reinforcement (%) usage [21, 22]. The results of these computations are given in figure 2.

![Figure 2. Dependences of ratio of reinforcement of slab thickness, concrete grade and column grid of frame](image)

5. Conclusion

Multiple numerous investigations and proposed design models for stress and strain behavior of cast-in-place concrete elements in frames of buildings with variations in slabs, thickness, load, and concrete and reinforcement grades enabled us to significantly amend design values specifying load-bearing capacity thereof. All the computations have confirmed accuracy of previously made provisions on boundaries and criteria (areas) to reduce material consumption (reinforcement and grade) applied to the frame elements. Automated software complexes enabling efficient solving of problems for optimization and making cast-in-place concrete frames have been elaborated and registered in the Russian Agency for Patents and Trademarks under the above research applying economic and mathematical methods. Using the proposed analytical tool to evaluate and find appropriate areas for high performance concrete application in both compressed and bending reinforced concrete elements it has been found that saving of reinforcing steel in V40 concrete and less is appropriately to be applied in spans up to 6m long, and in V50 and less if spans are longer than
The results of the research are applied in design and construction of a number of cast-in-place concrete frames for tall buildings thereby actually saving materials and costs up to 20-30%.

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