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OPTIMAL STRUCTURAL DESIGN BASED ON APPLICABILITY IN PRACTICE

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Abstract

Although numerically correct, methods for optimal structural design presented in the literature usually do not consider applicability of obtained solutions in practice, at the building site, because the only optimality criterion is minimal total price of structure. This means that relatively simple and easily achievable solution would be eliminated just because it is the 'second best', even if its total amount of materials is infinitesimally larger than in insignificantly cheaper but remarkably more complicated one, which would be automatically accepted as the optimum. This assumption was confirmed by the field research which showed that variation of only 3% in total amount of steel in the reinforced concrete beam can result in new reinforcement pattern that would demand as much as 50% lower amount of time needed for placing and fixing and thus strongly affect the accurate estimation of man-hours and required number of rebar fixers, which are both important parameters in dynamics plans making. Purpose of this paper is an attempt to abridge a gap between theory and practise in the field of structural design by introducing applicability criterion as the additional constraint in optimization process. Test results confirmed that proposed approach can help a designer to choose the most applicable solution among several theoretically acceptable ones and also to be successfully used in solving complex optimization problems.

Key words

Optimization; reinforced concrete; reinforcement pattern; structural design

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1 INTRODUCTION

Common practise in structural design of the reinforced concrete structures includes choice of cross-sectional dimensions and reinforcement that would meet the requirements proscribed by a given code of practise considering primarily strength and serviceability, as well as other imposed demands that result from the environment, architectural requirements etc. If the requirements are not met, than the cross-sectional dimensions and/or amount of the reinforcement have to be iteratively modified until all the required criteria are satisfied. In real engineering practise, this iterative process is usually carried out without deeper consideration of prices of concrete, steel, formwork and human labour. Therefore, it is obvious that the practicing engineers need an efficient designing method that would give results which would be not only satisfying considering given legal standards but also considering optimality criteria.

The search for an effective and applicable method for optimal design of the concrete structures is not a new subject, but the most of developed applications and procedures were aimed at finding the optimum (minimal) weight of a structure, although decision making process is usually, if not always, aimed at minimal price. Material and labour costs are important issues in design and construction of the reinforced concrete structures, as well as the applicability of obtained solution in practice, i.e. at the building site. Until the information technology was not developed enough to support very complex calculus models and procedures, problem of optimal reinforced structures design was usually solved by finding optimal cross-sectional dimensions and total amount of the reinforcement, while the problem of bars placing within a concrete members remained almost untouched or was avoided by introducing too generalized assumptions. If the basic optimality criterion is minimal price, regardless of applicability of a given solution at the construction site, a simple and easily achievable solution would be eliminated just because it is the 'second best', even if its total amount of the steel is infinitesimally larger than in pattern that requires less reinforcement but is much more complicated, which would be automatically accepted as the optimum. Besides that, the same set of reinforcing bars can be placed in a given cross section in several different patterns that would all have approximately equal bearing capacity but will remarkably vary considering possibility of efficient and exact placing and fixing.

Purpose of this paper is an attempt to abridge a gap between theory and practise in the field of optimal design of the reinforced concrete structures and to enable researchers and practitioners to assess obtained solutions from the practical point of view. Based on empirical data gathered in the field research at the on-going building sites, the functional correlations between different reinforcement pattern features were developed as well as the coefficient for numerical assessment of applicability of different reinforcement patterns in practice.

The second section of the paper provides short overview of insofar researches and results available in the literature. Mathematical formulation of the problem and its practical aspects are explained in the third section and proposed methodology is presented in the fourth section. The fifth section provides numerical example that illustrates how presented reinforcement pattern coefficient can successfully be used as an optimality criterion in decision-making process when there are several feasible patterns with approximately same amount of steel. Concluding remarks are given in the last section.

2 LITERATURE REVIEW

Numerous researchers have investigated possibilities in optimal design of reinforced concrete girders and structures. Friel [1] derived an equation for determining optimal ratio of steel to total concrete area in a singly reinforced beam, while Chou [2] used Lagrange multiplier method for minimizing total cost of the T-shaped beam. Kirsch [3] presented iterative procedure in three levels of optimization for minimizing the cost of continuous girders with rectangular cross section, in which the total amount of the reinforcement is minimized at the first level, cross-sectional dimension are minimized at the second level, while the third level of optimization is minimizing the design moments. Lakshmanan and Parameswaran [4] derived a formula for direct determining of optimal span to cross-sectional depth ratio so the iterative trial and error procedure can be avoided, while Prakash et al. [5] based their cost-minimization method on Lagrangian and simplex methods.

Kanagasundaram and Karihaloo [6,7] introduced the crushing strength of concrete as an additional variable along with cross-sectional dimensions and steel ratio to optimize the cost of simply supported and multi-span beams with rectangular and T-sections using sequential linear programming and convex programming. Chakrabarty [8,9] presented cost-optimization method for rectangular beams using the geometric programming and Newton–Rapson method, while Al-Salloum and Siddiqi [10] proposed optimal design of singly reinforced rectangular beams by taking the derivatives of the augmented Lagrangian function with respect to the area of steel reinforcement. Coello et al. [11] proposed the cost optimal design of singly reinforced rectangular beam using Genetic Algorithms by considering cross-sectional dimensions and the reinforcement area as variables.

More detailed overview of literature on cost-optimization of reinforced concrete structures up to 1998 can be found in [12].

One of the first papers that deal with reinforcement placing details was presented by Koumousis and Arsenis [13]. This method is based on multi-criterion optimization using Genetic Algorithms for finding a compromise between minimum weight, maximum uniformity and the minimum number of bars for a group of members. After that, researchers have started to introduce reinforcement detailing data as variables in optimization methods, usually by using one of two basic approaches. In the first one, reinforcement spacing demands are included into calculus as constraints, while the other one uses previously developed data base of possible reinforcement patterns. Constraints in the first approach are based on maximum allowable number of reinforcement layers (usually one or two) and maximum allowable number of bars per layer (usually up to four or five). The second approach is in fact simplification of the first one because the data-base of allowable reinforcement patterns is developed by introducing the same limitations and demands proposed by a given code of practice.

Overview of the most important works in this field in the last fifteen years, including corresponding codes of practice and basic assumptions, is presented in Table 1.

It can be observed that the main problem in comparing efficiency and applicability of different approaches is the fact that they are based on different codes of practice, i.e. on different reinforcement placing rules and restrictions. Because of that, and as opposite of the steel structures, there are no standard benchmark problems for testing a given method so the parametric sensitivity analysis is the only available tool for the applicability assessment.

The other problem, and the more substantial one, is the great variety of different basic assumptions such as maximal allowed number of rows and number of bars per row. For example, limiting the number of bars per row on four or five is acceptable for cross sections with width up to 35 cm, but there is no reason to use such restriction for wider cross sections. Besides that, limitation of maximally one row of the reinforcement has no practical excuse, especially when dealing with narrow but tall cross sections.

Even the one of the most advanced approaches, proposed by Govindaraj and Ramasamy [14,15], has its limitations. Although based on the most relaxed constraints, allowing as much as three different bar diameters in the same cross section, this method uses previously developed data base of possible reinforcement patterns is based on assumption that the number of rows is limited to three and the number of bars per row is limited to five.

Tab. 1: Literature overview, 1998–2013

Author	Code of practice	Basic assumptions
Koumousis & Arsenis [13]	Greek Code 1991	Maximum one row with not more than for bars of the same diameter.
Govindaraj & Ramasamy [14,15]	Indian Standard Code of Practice	Data base, maximum 3 rows with maximum 5 bars per row, maximum 3 different diameters.
Rajeev & Krishnamoorthy [16]	Indian Standard Code of Practice	Data base with 14 possible reinforcement patterns.
Matouš et al. [17] Lepš & Šejnoha [18]	EC2	Maximum 3 rows, maximum 31 bars per row, same diameters.
Camp et al. [19]	ACI99	Data base, maximum one row with maximum 4 bars, same diameters.
Lee & Ahn [20]	ACI99	Data base, maximum 2 rows with maximum 4 bars, same diameters.
Ferreira & Barros [21]	EC2	Only total steel area is considered.
Praščević [22]	PBAB87	Only total steel area is considered.
Yokota at al. [23]	Not specified	One row, number of bars between 3 and 10.
Barros at al. [24]	EC2	Only total steel area is considered.
Sahab et al. [25,26]	British Standard BS8110	Only columns are considered, one bar in each corner.
Guerra & Kiousis [27]	ACI05	Only total steel area is considered.
Kwak & Kim [28,29]	Korean Code	Data base, maximum 2 rows, maximum 5 bars, same diameters.
Perera & Vique [30]	ACI05 + EC2	Only total steel area is considered.
Alqedra et al. [31]	ACI08	Number of bars between 4 and 12, same diameters.
Kaveh and Sabzi [32]	ACI08	Data base, maximum 2 rows with maximum 6 bars, same diameters.
Barros et al. [33]	EC2	Only total steel area is considered.
Bekdas & Nigdeli [34]	ACI2005	Maximum 2 rows with maximum 5 bars, same diameters.
Jahjouh et al. [35]	ACI 2008	Maximum 8 bars, same diameters, detailed pattern is not considered.
Yousif & Najem [36]	ACI 2008	3 data bases: 2 rows with a) same diameters, b) diferent diameters, c) both a) and b)

3 PROBLEM FORMULATION

Numerical methods for optimal design of the reinforced concrete structures are based on finding cross-sectional dimensions and corresponding reinforcement that would result in minimum price of a given structure. Therefore, mathematical model of this optimization problem can be formulated as follows:

$$\min F = W_c p_c + A_f p_f + W_s p_s \tag{1}$$

where W_c, A_f and W_s are amounts of concrete, formwork and reinforcement given in m^3, m^2 and kg, respectively, while p_c, p_f and p_r are unit prices including the price of material as well as the price of work.

The main difficulty in solving this task is the applicability of obtained optimal solution in reality. After calculating required amount of the reinforcement for a given cross section, a designer is supposed to choose proper combination of reinforcing bars which would have the total area as close as possible to the calculated one, and to specify their exact positions in a cross section in accordance with rules and requirements from a given code of practice. Having in mind that reinforcement bars come in more than ten different diameters, this task is not as easy as it is usually considered. Although codes of practice can vary more or less between different countries, they all generally come down to the same set of requirements because what is obligated in one country usually is accepted as a rule of thumb in another and vice versa. In general, if bars with different diameters are used, greater diameter should be placed closer to the bottom edge and sides, and total steel area in the lower row should be greater than or equal to the area of bars in the upper row. Combinations of significantly different diameters should be avoided and therefore the difference between the largest diameter and the smallest one should be limited by the maximal acceptable value, usually 5− 6 cm or three bar sizes. Proper pouring and vibrating of the concrete mixture should be enabled by defining minimal clear horizontal and vertical spacing between the bars which should not exceed value specified in a code, nor the maximum bar diameter. While an experienced engineer would easily make a choice between similar reinforcement patterns with approximately same bearing capacity or amount of steel, the computer would always opt for the one that would result in mathematical minimum of a given criterion, regardless of its applicability.

One possible relevant criterion for assessing applicability of any given reinforcement pattern in reality might be the time needed for its placing at the building site. However, productivity rates for man-hours calculation for in-situ reinforcement fixing are too generalized and based only on total amount of reinforcing steel [37-39], regardless of the pattern complexity which can greatly affect time needed for proper placing, tying and control. For example, patterns consisting of 11Ø16, 8Ø18 and 6Ø22 bars, respectively, would all give approximately the same total amount of steel and consequently the same theoretical amount of man-hours, although it is obvious that such result would not be realistic. This conclusion was confirmed by the field research (described in the following section) that showed that variation of only 3% in total amount of steel can result in changes of as much as 50% in real amount of labour (time) and thus strongly affect the accurate estimation of number of man-hours and required number of rebar fixers, which are both important parameters in dynamics plans making. Besides that, productivity rates can significantly wary from country to country [40-42].

4 PROPOSED SOLUTION

In order to develop an adequate quantitative method for evaluating applicability of any given reinforcement pattern in reality, a field research was carried out with aim of gathering data about real time needed for placing and fixing reinforcement in different formations. The results were normalized by dividing the obtained time by amount of steel per bar, row and the whole pattern respectively and thus transformed into man-hours.

Comparison of data obtained in the field research confirmed logical assumption that the time needed for placing and fixing is affected by the following reinforcement pattern features: number of rows, number of bars per row, number of bars in the last row and presence of bundles. Because of that, different patterns with approximately same bearing capacity would all theoretically be feasible solutions, but the time needed for their placing and fixing can significantly wary.

Based on these findings, the reinforcement pattern coefficient C_r was developed in order to include all important features of a given reinforcement pattern, namely: number of rows (n_r), number of bars per row (n_b), number of bars in the top row (n_{bl}) and number of different bundles (n_d), as follows:

$$C_r = \left(An_r^2 + Bn_r + C\right)\left(1.0 + 0.1n_d\right)10^{-3} \tag{2}$$

where:

$$A = -25 - 5n_b \tag{3}$$

$$B = 825 + 115n_b - 10n_{bl} \tag{4}$$

$$C = -110(n_b - n_{bl}) \tag{5}$$

Note: If all bar or bundles are the same, than n_d is 0.

Calculated this way, the reinforcement pattern coefficient can be used both in design and in different optimization algorithms in case of different applicable and feasible reinforcement patterns with approximately equal bearing capacity.

5 EXAMPLE

Proposed methodology will be illustrated by an example that shows how reinforcement pattern coefficient can be used as an optimality criterion in situation where the same set of bars can be arranged in different patterns and the designer (or computer) is supposed to choose the most appropriate, i.e. the optimal one (Fig. 1). Since all proposed patterns consist of the same set of bars, total amount of steel cannot be taken as the optimality criterion. Although bearing capacity might be helpful in decision making, in this case it would not be adequate criterion because all solutions are feasible, i.e. all of them have sufficient and approximately equal bearing capacity. Because of that, computer would not be able to make a difference between proposed possibilities in order to recommend one as the ‘optimal’, and even an experienced designer would have difficulty in estimating applicability of proposed solutions at the building site.

Including reinforcement pattern coefficient as the optimality criterion would make the decision-making process much easier, because it is obvious that solution *i)* requires the smallest amount of time for placing and fixing the bars without compromising the bearing capacity.

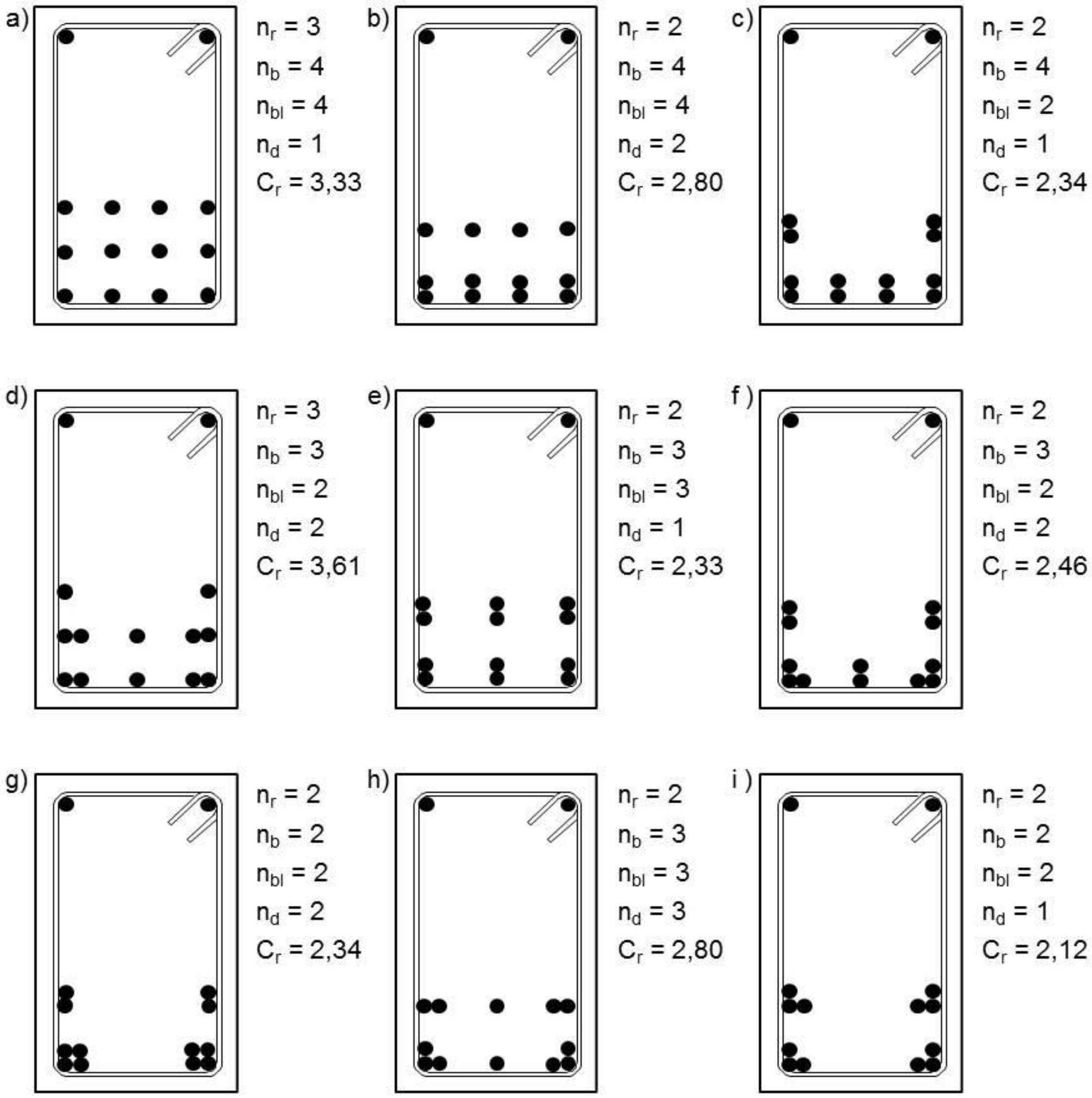

Fig. 1: Reinforcement patterns consisting of 12 bars

Presented methodology can also be included in the above mentioned data bases with different cross sections and patterns, because number of feasible solutions for a given girder span and load, even within relatively narrow interval of allowable cross-sectional dimensions, can be even more than ten thousands. In such cases, computer would automatically opt for the solution with absolute minimum of reinforcement, although there might be a solution with almost the same price but much easier for achieving at the building site. Besides that, this example shows that man-hours calculation should not be based only on total amount of steel (as it as usually done in practice) because different reinforcement formations, even when consisting of same bars, simply cannot be considered as equivalents. Therefore, presented coefficient can be helpful in both the traditional design process and the optimization software tools.

6 CONCLUSION

Adequate choice of the reinforcement pattern is an important step in design of the reinforced concrete structures and therefore should not be based only on intuition. Applicability of any given reinforcement pattern should be considered during the design process because it can significantly affect the amount of time required for placing and fixing at the building site. Field research showed that norms for productivity rates for in-situ reinforcement fixing are too generalized and that calculation of man-hours based only on total amount of reinforcing steel is not realistic. Besides that, total computer-based optimization would be possible only if we find a way to 'teach' computer how to make distinction between similar reinforcement patterns and to imitate reasoning of an experienced designer.

Methodology presented in this paper offers solution for these problems by introducing the reinforcement pattern coefficient as an additional criterion in making a choice among several similar feasible solutions. It can also be included into different kinds of software for reinforced structures design, which would be a step forward total computerization of the design process.

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