Strategy for the evolutionary optimization of reinforced concrete frames based on parallel populations evolving

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Abstract. An algorithm has been developed for optimization of reinforced concrete frames with the possibility of forming a structure with a subsequent selection of reasonable section sizes and reinforcement for it. A modified genetic algorithm is used as the main search tool. The overall optimization process is divided into two stages. At the first stage, the topology is synthesized by randomly excluding groups of structural members as well as changing the position in space of the remaining groups. At the second stage, local parallel evolving genetic algorithms are performed for the formed topologies. With a common set of variable parameters, the migration of individuals between parallel populations is not allowed. An example of optimization of the multi-story building frame is considered.

1. Introduction
Optimization of the bearing structures of buildings is one of the urgent problems of modern science and design practice. At the same time, one of the important issues is the design of systems under normal operating conditions. The specific features of building design require that optimization be performed with given discrete sets of variable parameters. For reinforced concrete structures, this is the assortment of reinforcement, grades of concrete, reinforcement and section sizes, selected in accordance with the modular coordination system in construction. For steel structures, these are standard sizes for standard profiles of rolled metal products, sheet thicknesses, etc. One of the best methods corresponding to such optimization is genetic algorithms [1-4]. Currently, there are various options for genetic algorithms as parametric [5-8] and for structural-parametric optimization [9-12]. A number of such algorithms consider both steel [13-15] and reinforced concrete structures [16-18]. Various problems of finding rational parameters with varying cross sections of steel trusses and frames, optimizing such structures taking into account pre-stressing, reinforcing or restoration of bearing capacity have been solved. For reinforced concrete structures, less attention is paid to the problems of parametric optimization [19-21], and the methods of effective structural and parametric optimization have been little studied. This is due to the complexity of the procedures for analyzing the stress-strain state of reinforced concrete, which involves taking into account physical and geometric nonlinearity. Therefore, the creation of methods with a relatively quick preliminary assessment of the performance of reinforced concrete systems is required, which will make it possible to use genetic algorithms more widely and implement structural-parametric optimization schemes. This article proposes one of these schemes.
2. Formulation of the optimization problem

We consider frame structures for which it is planned to vary the combinations of sizes of cross sections of structural elements and the reinforcement schemes associated with these combinations. In addition, we introduce the possibility of varying the structures of the transverse frames, differing in the number of adjacent columns with a fixed span, the number and height of the floors. For each such structure, the discrete sets of variable parameters of the rods are assumed to be the same, and it is also possible to vary the distances between the columns taking into account the symmetry of the object or independently.

To ensure the possibility of varying the structure, we introduce parallel computing threads in each of which a genetic algorithm is performed and its own structure is considered, obtained from a single redundant structure by possibly excluding groups of structural elements. In this case, the interaction between solutions obtained in parallel is excluded.

Setting the number of possible topologies \( T \) to consider, the problem of minimizing the cost \( C \) can be written as the following:

\[
C = f(T, N_T) \rightarrow \min \Rightarrow \begin{cases} 
C_1 = f_1(T, \{Y_s\}, \{Y_{nd}\}) \rightarrow \min \\
C_2 = f_2(T, \{Y_s\}, \{Y_{nd}\}) \rightarrow \min \\
\cdots \\
C_{N_T} = f_{N_T}(T, \{Y_s\}, \{Y_{nd}\}) \rightarrow \min 
\end{cases} \Rightarrow \hat{C} = \min(C_1,...,C_{N_T}). \tag{1}
\]

where \( \{Y_s\} = \{\{y_{s,1}\},...,\{y_{s,n}\}\} \), \( \{y_{s,i}\}(i=1...n) \) is sets of data arrays describing the integral geometric characteristics of combinations of sizes and reinforcement parameters for a structural element \( i \) of the transverse frame of a building. We will use the following data array to describe the varied parameters.

\[
\begin{align*}
\text{Designations } & N_T, N, N_g, n_{1,1}, n_{2,1}, \ldots, n_{1,N_g}, n_{2,N_g}, S_1, S_2, \ldots, S_N \\
& \text{where } N_T \text{ is the number (type) of the parameter; } N \text{ is the number of parameter values; } N_g \text{ is the number of groups of structural elements for which the parameter will vary; } n_{1,1} \text{ is the number of elements in group 1; } n_{2,1} \text{ is the number of the first element in group 1. For each group, the numbering of elements must be continuously increasing by one. } S_1 - S_N \text{ are indicators to the type of section.}
\end{align*} \tag{2}
\]

Designations \( S_1, \ldots, S_N \) are integer identifiers for a sectional variant. Let us consider the simplest case when internal force factors include bending moments and transverse forces acting in the plane of greatest rigidity. We present the parameterization of such a sectional variant (Fig. 4.1) and an array of data illustrating its description. We write the elements of the subset as \( \{y_{s,i}\} \)

\[
\{y_{s,i}\} = \{a_{1,i}, a_{2,i}, h_i, b_i, A_{1,i}, A_{2,i}, A_{sw1,i}, A_{sw2,i}, R_{hp,i}, R_{sp,i}, R_{sw,i}, \{ID_s\}\};
\]

\[
\{ID_s\} = \{P, AC_{sw}, M\}; \quad p = \begin{cases} 
0 \rightarrow D_0 \vee U_1 \vee Sym_1 \\
1 \rightarrow D_1 \\
2 \rightarrow U_1 \\
3 \rightarrow Sym_1 
\end{cases} \quad ; \quad AC_{sw} = \begin{cases} 
0 \rightarrow A_{sw1,i} \approx 0, A_{sw2,i} \neq 0 \\
1 \rightarrow A_{sw1,i} \neq 0, A_{sw2,i} = 0 
\end{cases}. \tag{3}
\]
In the formula (3, 4), the values $a_{i,j}, a_{2,i}$ are protective layers of concrete, taken symmetrically equal; $h_i, b_i$ is the height and width of the cross section of the structural element, respectively; $A_{x,i,j}$ is the area of the rods of the longitudinal working reinforcement during bending, which is assigned taking into account the range of reinforcement, the distance between the rods and the actual value $b_i$; $A_{y,2,i}$ is the area of the rods of longitudinal reinforcement in the compression zone during bending, which is assigned constructively $A_{sw,1,i}$. The area of the rods of the transverse working reinforcement during bending. It is assigned taking into account the assortment of reinforcement, the value of the transverse (cutting) force and the pitch of the transverse reinforcement acting in the cross section. The value $A_{sw,2,i}$ is the area of the rods of the transverse reinforcement during bending, assigned structurally. The presence or absence of structural transverse reinforcement is determined by the value of the parameter $AC_{sw}$. If, according to the calculation, the transverse reinforcement is not placed, then it is placed constructively. At the same time, its value and default step are set before the start of the optimization process. Values $R_{b,i}, R_{x,i}, R_{sw,i}$ are the design resistance of concrete, working longitudinal and working transverse reinforcement, respectively. The values of these parameters are used in the absence of parameters associated with the variation of the material classes. An integer $P$ is an indicator to the use of reinforcement scheme (top or bottom or symmetric), see Fig.1. When $P = 0$, any of the schemes can be used. The number $AC_{sw}$, $M$ is, accordingly, an indicator to the need to install the structural transverse reinforcement, if it is not required by calculation and an indicator to using a reinforcement scheme for columns (depends on the value of the longitudinal force $N_x$), when $M = 1$ symmetrical reinforcement is used.

\[
M = \begin{cases} 
0, & \left( M_{x'} \neq 0 \right) \land \left( M_{y'} = 0 \right) \land \left( M_{z'} / N_x < h_i / 30 \right) \rightarrow \left( P = 1 \right) \lor (P = 2) \\
1, & \left( M_{x'} \neq 0 \right) \land \left( M_{y'} = 0 \right) \land \left( M_{z'} / N_x \geq h_i / 30 \right) \rightarrow P = 3
\end{cases}
\]

In the formula (3, 4), the values $a_{i,j}, a_{2,i}$ are protective layers of concrete, taken symmetrically equal; $h_i, b_i$ is the height and width of the cross section of the structural element, respectively; $A_{x,i,j}$ is the area of the rods of the longitudinal working reinforcement during bending, which is assigned taking into account the range of reinforcement, the distance between the rods and the actual value $b_i$; $A_{y,2,i}$ is the area of the rods of longitudinal reinforcement in the compression zone during bending, which is assigned constructively $A_{sw,1,i}$. The area of the rods of the transverse working reinforcement during bending. It is assigned taking into account the assortment of reinforcement, the value of the transverse (cutting) force and the pitch of the transverse reinforcement acting in the cross section. The value $A_{sw,2,i}$ is the area of the rods of the transverse reinforcement during bending, assigned structurally. The presence or absence of structural transverse reinforcement is determined by the value of the parameter $AC_{sw}$. If, according to the calculation, the transverse reinforcement is not placed, then it is placed constructively. At the same time, its value and default step are set before the start of the optimization process. Values $R_{b,i}, R_{x,i}, R_{sw,i}$ are the design resistance of concrete, working longitudinal and working transverse reinforcement, respectively. The values of these parameters are used in the absence of parameters associated with the variation of the material classes. An integer $P$ is an indicator to the use of reinforcement scheme (top or bottom or symmetric), see Fig.1. When $P = 0$, any of the schemes can be used. The number $AC_{sw}$, $M$ is, accordingly, an indicator to the need to install the structural transverse reinforcement, if it is not required by calculation and an indicator to using a reinforcement scheme for columns (depends on the value of the longitudinal force $N_x$), when $M = 1$ symmetrical reinforcement is used.

The set of coordinates $\{Y_{nd}\}$ in the general case for a plane frame can be represented by the following group of subsets:

$$\{Y_{nd}\} = \{\{X\}_1 : \{Y\}_1\} \ldots \{\{X\}_{nB1} : \{Y\}_{nB1}\},$$

where $\{X\}$, $\{Y\}$ – is the set of permissible horizontal and vertical coordinates for a group of elements; $nB1$ – is the total number of groups of structural elements with the possibility of exclusion.
We take into account, as active constraints, the strength of structural elements along normal and sloping sections, the rigidity of the crossbars based on aesthetic requirements, the horizontal displacements of the columns and crossbars in the level of coating of the frame should not exceed 1/500 of its height. The crack resistance constraint is set. The absence of pre-stressing of the crossbars imposes a constraint on their maximum span, which is not allowed more than 12 m. As a passive constraint, it is accepted to ensure overall stability.

3. Optimization method

We will present it in the form of a block diagram in Fig. 2 and briefly explain the contents of the given blocks. At the first stage, the synthesis of the frame topology is performed, the rational step of the columns is determined; the geometry of the sections of structural elements with preliminary reinforcement is selected. This results in several different structural schemes with different step of columns. Reinforcing elements at this stage is performed according to the maximum forces acting within the group of structural elements. At the second stage, for the obtained solution, a regrouping of elements is performed; including for the crossbars the selection of the groups of finite elements located in the supporting and span parts of the crossbars. This grouping is carried out in accordance with the points of theoretical breakage of the upper and lower reinforcement. For columns, it is possible to change the overall dimensions of the section within several floors in height. Let's consider the first stage in more detail. After the data of block 1 for solving the optimization problem is gathered, the stage of synthesis of the frame structure begins. In this case, the number N of structures that can be considered in parallel computing threads is initially specified. If several different structures cannot be obtained, then the topology of the redundant structure needs to be processed.

Identification of non-coincident structural A options can be performed on the basis of the template in the form of a line with the code:

\[ A: (g_{1i}, \ldots, g_{nBi}), \quad g_1 = [0; 1], \quad g_{nBi} = [0; 1], \quad i = 1; 2. \]  

(6)

Here \( g_{1i} \) - \( g_{nBi} \) is the identifier associated with the group of structural elements to be excluded. When \( g_{1i} = 0 \) group No. 1 of the elements is excluded, when \( g_{1i} = 1 \) – the group is present in the design scheme.

Block 2 forms a database of structures, which is edited according to the principle of comparing options in an encoded form (5), if there is no structure option in the database, then it is placed in it, otherwise, for A option, the identifier value is changed from 0 to 1 or vice versa for a randomly selected the numbers of groups whose numbers are also randomly selected. The criterion for the optimality of the structure in this database is the minimum total length of the rods obtained as a result of the exclusion of elements.

Next, the optimization problem is decomposed into N parallel thread (blocks 3), each of which carries out a simple genetic algorithm, or its modification depending on the type and computational capacity of the problem being solved. The parameters of the cross sections and the location coordinates of the structural elements vary depending on the adopted grouping system.

Upon reaching the stopping condition of the genetic algorithm, we obtain N solutions using the same optimality criterion. In block 4, based on expression (1), the best solution is selected. Then, in the framework of a separate implementation of the genetic algorithm, in block 5, discrete sets of parameters are formed and grouped in order to obtain the optimal distribution of the material. For structural reasons, the cross-sections of the crossbars along their length do not change, but the area of the working reinforcement on the selected parts of the crossbar varies. Such a grouping can be performed by assigning the same reinforcement of the crossbar in the near supporting parts of the length \( l/4 \) and in the span part \( l/2 \). In accordance with the work of the crossbar in the frame in these parts, the calculated moments differ by about 2 times. For medium columns, the cross section can be changed within several floors in height. After receiving a design solution at the second stage, passive constraints are checked for it.
4. Results
Consider an example of optimization of a 5-story plane frame of a building 48 meters wide. The excess structure of this construction is shown in Fig. 3.a. When varying the structure, it is possible to exclude columns within all floors, united in groups 1-6, outlined by circles. If there is a group in the structure of the calculation scheme for it, the genetic algorithm provides for the selection of one of 5 possible positions along the axis \( x \) on the interval \( L_1 \), shown in relative coordinates in Fig. 3.b. The module adopted by us is 1.2 m. We take into account the structural constraint of the crossbar span, which, from the condition of the absence of pre-stressing, should not exceed 12 m.
As the variable parameters of the cross sections, we will use combinations of sizes indicated in the table. Moreover, for groups of 1-6 columns, square sections with symmetrical reinforcement were used. We consider the nodes of the crossbars and columns to be rigid, therefore, in accordance with an approximate estimate of the distribution of the diagram of bending moments, each crossbar was divided into 4 parts, within which the reinforcement schemes \( U, D \) (Fig. 1) and the presence / absence of structural transverse reinforcement were varied (Fig. 3, c). Transverse reinforcement is by designer installed for elements 2, 3, and for elements 1-4 it is assigned by calculation. When changing the position of the columns in accordance with the local coordinates in Fig. 3,b, the coordinates of the nodes \( u_1-u_3 \) are recalculated (Fig. 3,d).

For all the rods, the concrete class is varied, it was allowed to use B20, B25, B30, B40, B50, the reinforcement class did not vary, but A500 was specified. Consider the results obtained. At the stage of synthesis of the structure, we set \( N = 4 \).

As a result of optimization, several solutions were obtained. One of the best is shown in Fig. 4.
Figure 4. Some optimization results
When performing a simple genetic algorithm, at each iteration, in each of the parallel threads, 25 variants of the object were considered. The database of the best solutions included 20 objects. To take into account physical nonlinearity, 5 internal iterations were used. The search for a solution lasted no more than 350 iterations.

5. Discussion
The proposed methodology for the search for constructive solutions can be used both for single-objective and multi-objective optimization. Moreover, the use of a genetic algorithm with one current population significantly reduces the possibility of choosing rational structures and can lead to a local optimum associated with a particular structure [22-27]. If it is possible to use the proposed algorithm for multi-objective optimization, it seems relevant to organize the migration of individuals between parallel populations as well as weak interaction between them.

6. Conclusion
A methodology has been developed for the normally operated reinforced concrete frames design, taking into account the possibility of topology/shape/size and reinforcement parameters optimization. This technique is based on a strategy of parallel evolving populations with the prohibition of the migration of individuals between populations. The considered example of frame optimization shows the efficiency of the proposed approach.

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