Metaheuristic optimization of building structures with different level of safety

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Abstract. A methodology for solving the optimal synthesis problems of bearing and enclosing structures is proposed, including for steel frames, column reinforced concrete foundations, heat-transmission shell using genetic iterative diagrams and triangulation procedures. The approaches to finding solutions for buildings of normal and increased levels of responsibility are considered. A three-stage diagram is proposed that includes, at the first stage, the synthesis of the topology of the steel frame, at the second stage, the optimization of its shape and parameters of the rods, and at the third stage, the consideration of possible emergency situations. For buildings with a normal level of responsibility in the particular case, the use of the first two stages is allowed. The structure of the frames is synthesized by using the algorithm of plane triangulation of a set of points, which are meant as structural joints. The design parameters are selected using an improved genetic algorithm adapted for solving problems of this type. An example of the synthesis of the building structure of a weighted vehicle is considered, illustrating the performance and high efficiency of the approach under consideration.

1. Introduction

For the traditional design of load-bearing systems, in some cases, structural solutions can have a significant materials cost overrun. To minimize the material consumption of the structure, it becomes necessary to calculate its stress-strain state. Moreover, for complex statically indeterminate systems, the selection of a rational distribution of stiffness occurs very difficult. In addition, scenarios of potential accidents should be considered for buildings with an increased level of responsibility. Due to the high complexity of the work, optimization of design solutions for such structures based on generally accepted designing approaches becomes almost impossible. Currently, the problem of design building structures operated under normal conditions, as well as in the event of possible emergency situations, has become essentially urgent [1-4]. The idea of synthesis of structural systems of buildings and structures based on metaheuristic approaches has been developed for many years [5, 6]. However, in view of the high scope of calculations for complex building structures, the search for rational solutions was difficult.

In the last decade, with the growth of computer performance, it is able to advance in the optimal synthesis of buildings and structures. In particular, iterative diagram concepts were proposed for optimizing deformable systems of various types with discrete sets of design parameters, based on the use of evolutionary modelling [7-11], particle swarm [12-15]. In this article, an example of buildings
with steel frames, offers an approach to topological and parametric optimization of structures, taking into account both normative and emergency actions, which is based on the joint use of the evolutionary procedure [16, 17], flat triangulation [18] and procedures of considering the survivability of structural systems in emergency situations [19].

Formulation of the optimization problem

Let us consider a structural system with a steel frame, enclosing structures and a reinforced concrete foundation, the synthesis of which is performed on discrete sets of possible topologies of the frame, standard sizes in cross-sections of rods, heat transfer parameters of the enclosing structures, foundation geometry and reinforcement. Three main phases are being implemented.

At the first stage taking into account the space-planning solution of the facility, the topology (structure) of the frame is formed. The extreme task of minimizing the cost of frame rods material is solved, excluding the cost of building enclosing structures, the installation of units and foundations.

\[ C_i(Y) \rightarrow \min, \]  

where \( Y \) – the set of possible structures of facilities, determined by the positions of the structural nodes and the presence or absence of rod elements. Moreover, the parameters of the cross sections of the rods in this structure are selected under the assumption that the base and foundation are absolutely solid bodies. To form the topology, we will use methods of eliminating rods from the base redundant structure and plane triangulation on a set of points.

At the second stage the cost of bearing and enclosing structures of the buildings is minimized:

\[ C_{st}(Y_1) + C_{jn}(Y_2) + C_{pd}(Y_3) \rightarrow \min; \]

\[ C_{st}(Y_1) = C_s(A,T,G_s) + C_j(V_m) + C_{ws}(V_{ws}), \quad C_{jn}(Y_2) = C_b(V_b,G_b) + C_A(V_A,G_A) + C_{ad}(V_{ad},G_{ad}) + \]

\[ + C_{wb}(V_{wb}), \quad C_{pd}(Y_3) = C_{sp}(V_{sp}) + C_p(V_p,G_p) + C_{wp}(V_{wp}), \quad Y_1 = \{A,T,G_s,V_m,V_{ws}\}, \]

\[ Y_2 = \{V_b,G_b,V_A,G_A,V_{ad},G_{ad},V_{wb}\}, \quad Y_3 = \{V_{sp},V_p,G_p,V_{wp}\}, \]

where \( C_s(Y_1) \) is a cost of load-bearing steel structures, including the cost of element materials \( C_s \), nodal joints \( C_j \) and construction works \( C_{ws} \); \( C_{jn}(Y_2) \) is a cost of reinforced concrete foundations, consisting of concrete costs \( C_b \), reinforcement \( C_A \), steel inner joint plates \( C_{ad} \) and foundation works \( C_{wb} \); \( C_{pd}(Y_3) \) – is a cost of enclosing structures; \( A,T,G_s \) are sets of variable parameters for cross sections of rods, plate thicknesses, steel grades, respectively; \( V_{ad},V_{ws} \) are the volumes of materials and work necessary for the installation of unit joints; \( V_b,G_b,V_A,G_A,V_{ad},G_{ad} \) are accordingly, volumes and classes of concrete, reinforcement, volumes and grades of steel inner joint plates; \( V_{wb} \) is the scope of work needed to calculate the cost of foundation construction; \( V_{sp},V_p,G_p \) are respectively, the volume of materials for walling (layers of wall structures excluding insulation), effective insulation; \( G_p \) the set of types of insulation, \( V_{wp} \) is the scope of work on the arrangement of enclosing structures.

The third stage provides for the solution of optimal design problems for various emergencies. Moreover, the main criterion for optimality is a minimization the social economic consequences of possible emergency situations. One of the conditions for this is to ensure the survivability of the structural system with local damage of its key elements.

During the first stage of the synthesis of the structural system for the method of redundant structure, the following main constraints are made:

1. Geometrical invariance of the basic design. The invariance assessment is performed for the
finite element model using the analytical features: the global stiffness matrix must be positively determined and well conditioned.

1.2 The equilibrium of the discretized computational model nodes. A system of linear equations of the finite element method is solved.

For the planar triangulation method, we consider the following constraints:

1.3 The maximum possible overall dimensions of the structure.
1.4 Positions of nodes, whose coordinates do not change during the synthesis of topology.
1.5 The Delaunay condition for the plane triangulation of a set of points, which consists in complying with the emptiness of the diametrical ball for any three adjacent nodes.

During the second stage for a structure whose topology is synthesized, the following main constraints are made:

2.1 The strength and stability condition for the rods in accordance with the requirements of Russian standards for steel structures.
2.2 The strength condition of the plates.
2.3 The Stiffness of design elements.
2.4 Overall structural stability, local strength and stability of plate-rod structural elements.
2.5 Unification by parameters. For a group of variable parameters, the same parameter value can be assigned, for example, the same standard sizes of rod cross-sections or nodal coordinates.
2.6 Symmetry conditions of the structure.
2.7 Design limitations (overall dimensions, the possibility of using certain assortments, etc.).
2.9 Element-by-element requirements for thermal protection of the facility. For each i-th type of enclosing structure the following inequality is valid

\[ R_i \geq R_{i0} \]  

where \( R_i \) is the conditional resistance to heat transfer of a homogeneous part of a heat-transmission shell of the building, \( R_{i0} \) – standardized value of reduced resistance to heat transfer of the enclosing structure.

2.10 Strength, rigidity and stability of enclosing structures (if necessary).

At the third stage when considering the possibility of emergencies, the following constraints are used:

3.1 The absence of cracks and collapse of the elements, expressed in the prevention of reaching the level of deformation above the limit values of the strain.
3.2 Prevention of significant changes in the geometry of the deformable system, which is approximately interpreted as the state of survivability of the structure with local damage.

2. Methods

Each of the three design stages is carried out as part of a separate iterative process. In this case, at the second or third stage, the topology of the structure with the initial locations of nodes is used. The main computational procedures of the first stage of synthesis of a structural system are presented in Figure 1.

The block diagram of the second stage of the synthesis of the facility is shown in Figure 2. For parametric optimization, a method is used based on the use of an extraordinary diagram of population formation [17], taking into account the possibility of modifications depending on the types of design features.

The third stage. For the design variant with the best value of the goal function obtained in the second stage, possible scenarios of local damage are formed (options for removing supports, eliminating elements, ties). Next, the calculation of the damaged structure in dynamic and static settings is performed taking into account physical, geometric and structural nonlinearities.

The dynamic coefficient \( k_{id} \) for the i-th design basis emergency action is determined:

\[ k_{id} = \frac{P_{is}^{up}}{P_{id}^{up}} \]  

(4)
where \( P_\text{is}^{P} \) and \( P_\text{id}^{P} \) are limit values of load generalized vectors, perceived by a damaged structure under static and dynamic loading. After calculating the dynamic coefficients, the method of evolutionary optimization is implemented when calculating design structures taking into account physical nonlinearity. In the framework of this method, the performance of structures is assessed by calculations in a quasistatic setting, taking into account the obtained values \( k_{id0} \).

![Figure 1. Block diagram of the topological synthesis of the rod system](image)

For the resulting design optimization, the coefficients \( k_{id} \) are calculated. If \( k_{id} \approx k_{id0} \), then it is checked if the resulting solution satisfies the conditions of durability (resistance to progressive destruction), otherwise it is necessary to accept \( k_{id0} = k_{id} \) and do the evolutionary synthesis again. If the survivability of the structure is ensured, then it is necessary to verify the compliance with normative requirements and, if the result is positive, consider the problem solved.

**Results**

Let’s consider the synthesis of a building for vehicles weighting. The building consists of three transverse frames with a span of 5.5 m, installed at interval of 6 m on monolithic column foundations (Figure 3). The enclosing structures of the external walls, including 150 mm thick Ventall-S sandwich panels, end elements 1 made of 50x40x3 pipes, strapping beams 2 of 80x60x3 pipes and 3 braces of 70x3 pipes did not vary, their cost was considered as fixed. The roof structure was adopted to be made of S-20 profiled flooring, 0.8 mm thick, laid along the span of 70x3 pipes installed on the upper belt of the truss structure at interval of 1.25 m (not shown conventionally in Figure 3). The building is unheated, therefore, the design of a heat-insulating shell in this particular case is not considered. The symmetry of the building was taken into account in the longitudinal direction relative to the axis \( \text{O-O} \) (Figure 3) and in the transverse direction relative to the middle transverse frame. Under normal operating conditions, the current standard loads and ground conditions described in Rulebooks «SP 20.13330.2016 Loads and actions» and «SP 22.13330.2011 Soil bases of buildings and structures» are taken into account when the facility is located in the city of Bryansk. In the synthesis of the crossbar
topology at the first stage, the planar triangulation method with Delaunay constraints [18] was used.

The roof truss topology was built by constructing triangles at the nodes $U$ (ref. to Figure 3), the coordinates of which did not vary at the points $U_0$ with variable coordinates. Two units $U_0$ were considered, which could be placed in a grid of squares 1.5x1.5 m. In each square of the grid $S$ only one node $U_0$ can be located. There are five positioning points $A_k$ in the grid square for the node is allowed. In Figure 3, b-e, possible topology options are shown, while only the structure variants in Figure 3b and in Figure 3e satisfies the Delaunay condition. Option in Figure 3e is less rational, since a small angle of the rods jointing therefore, as the base at the second stage of optimization, it is used the structure shown in Figure 3 b.

At the second stage of optimization for the structure shown in Figure 3b, the independently
varied parameters presented in the table 1. Nodes with variable coordinates are connected from the plane of the frames by step rods. The cost of rod joints in the optimization process was calculated based on the accepted layout shown in Figure 4 and marked in Figure3.

Figure 3. Sets of variable parameters for the first and second stages of structural synthesis:

a) - the initial structure of the frame; b)-e) - variants of the truss topology synthesized by triangulation with varying positions of two nodes; e) - design diagram used in the second stage of synthesis

At the third stage of optimization, the possibility of local damage to one of the column supports G1 or G2 because of a possible collision with a car or other technological impact is considered.

To prevent damage to expensive cargo as a result of such an accident, Z beams were introduced to localize the collapse of the roof. When calculating a damaged system, dynamic coefficients \( k_{G1} = 1.65 \), \( k_{G2} = 1.89 \) are obtained. These coefficients were used to obtain a design solution for a structural system of increased survivability. The cost of a structure variant designed in the traditional way, taking into account normal operation, turned out to be equal to 950 thousand RUB. As a result of optimal synthesis of the normal level of responsibility structure, the variant with a cost of 830 thousand RUB was found. Providing an increased level of responsibility of the structure, the cost amounted to 1,340 thousand RUB.
Table 1. Description of independently variable parameters

| Group of elements at (Figure 3, f) | Allowable parameter values |
|-----------------------------------|-----------------------------|
| $W_1; W_2$                        | Rectangular pipes: 1) 45x30x2 2) 50x40x2; 2) 80x60x2.5; 3) 80x70x3; 4) 120x80x3; 5) 180x140x5; 6) 240x120x4; 7) 240x150x6; 8) 260x140x8. |
| $Z_1; Z_2$                        | Foundation base dimensions, m: 1.5x1.8; 1.8x2.1; 1.8x2.4; 2.1x2.7; 2.4x3.0. Concrete grade: B15, B20, B25, B30, B35. Reinforcement class A300, A400, A500. |
| $F_1; F_2$                        | Concrete grade: В15, В20, В25, В30, В35. Reinforcement class А300, А400, А500. |
| $U_1$                             | y-axis coordinate, mm: 1) 4700; 2) 5000; 3) 5300; 4) 5600; 5) 5900; 6) 6200. |
| $U_2$                             | y-axis coordinate, mm: 1) 4400 2) 4450 3) 4550; 4) 4575; 5) 4600; 6) 4625; 7) 4650; 8) 4675. |
| $R_1; R_2; R_3$                    | Rectangular pipes: 1) 45x30x2 2) 50x40x2; 2) 80x60x2.5; 3) 80x70x3; 4) 120x80x3; 5) 180x140x5; 6) 240x120x4; 7) 240x150x6; 8) 260x140x8. |

Figure 4. The joints of structural elements and the results of the optimal synthesis for building with high survivability: $I_{W1} - I_{W2}$ marks of weld lengths; 1-7 – numbers of sections from table 1.
3. Discussion
It should be noted that the given algorithm has the possibility of optimizing buildings with structures in the shape of regular flat frames, and the minimum cost criterion may not always objectively meet the requirements for structural safety.

4. Conclusion
Based on a metaheuristic search, a methodology for the topology-parametric synthesis of design solutions for buildings including steel bearing frames, foundations on a natural base and a heat-transmission shell has been developed. The proposed approach to optimal design allows the selection of rational form and parameters of the facility, taking into account operation under normal conditions and the possibility of emergency actions. The basic optimization procedure can be used in design automation systems at the stage of pre-design and design studies.

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