Optimal Design of Wall and Ceiling Structures According to the Mechanical Safety and Comfort of the Internal Environment

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Abstract. The article describes an approach to the optimal design of load-bearing structures of walls and ceilings, taking into account not only the factors of strength and stiffness, but also the internal environment of the premises. The problem of optimization of structural systems, taking into account safety, reliability and comfort is currently particularly relevant. Most scientific studies consider each factor separately, which can lead to deterioration of both the functional process in the premises and the onset of the risk of an emergency. An evolutionary modeling scheme is proposed, which operates with discrete sets of parameters and allows to obtain design solutions of minimal cost based on a joint integrated consideration of strength, deformability, thermal protection and acoustic comfort of walls and ceilings. The minimization of the structures cost is assumed as a goal function. Stresses, strains, thermal resistance to heat transfer and the value of airborne sound insulation index are considered as active constraints. Two problem statements are considered. The first one takes into account the design of walls according to the criteria of strength and heat engineering, and the second one is the design of the ceilings with ensuring strength, stiffness and acoustic comfort. Examples of the optimal design of the residential building walls and floors with regard to the conditions considered are given.

1. Introduction

Modern requirements of the regulatory and legal framework in terms of building structures design for buildings and structures imply the fundamental principles of energy and utilities saving and the provision of mechanical, environmental, fire and other types of safety. To solve individual problems within this issue, it is proposed an algorithm based on evolutionary modelling applied to the supporting structures of external walls and floors, the basis of which is reinforced concrete. The problem under consideration can be solved by optimization methods based on evolutionary modelling [1-3]. Such an approach allows designing with the use of discrete sets of variable parameters. Optimum design based on genetic algorithms was effectively applied in solving problems of steel core systems optimization in [4-8]. The issues of reducing material consumption and cost during normal operation [9-12], as well as during accidental impacts were considered. At the same time, the search procedures were adapted to solve some particular problems, for example, prestressing frame structures [13], designing beam structures consisting of steels of various grades [14], increasing the reliability of facilities [15, 16]. Cases of column removal because of mechanical damage [17–19], corrosion [20],
etc. are most often considered as accidental effects. At the same time, the complex issues of optimum design, combining in a single iterative procedure, the constraints associated with the safety and comfort of the internal environment remain almost unresolved.

2. Formulation of the optimization problems
It is considered the problem of minimizing the cost $C_w$ of the walling. It is believed the priority for this design requirements for the strength of the reinforced concrete layer and ensuring the required resistance to heat transfer under the terms of energy saving. In this case, the objective function is represented as:

$$C_w = \sum_{i=1}^{n} C_i \rightarrow \min,$$

where $n$ is number of layers of wall structure, $C_i$ is the cost of $i$- layer at some level of base prices or other conditional representation.

Let’s consider the following constraints.

1. The strength of the concrete layer. Depending on the stress-strain state, using condition on the first and second groups of limit states. So, for compressed wall concrete layers, writing the dependencies:

$$\sigma_b \leq R_b; \quad M \leq M_{crc}; \quad M = N \cdot e,$$

where $\sigma_b$ is stress in concrete determined by the level of strain $\varepsilon_b$, whose values must not exceed the value $[\varepsilon_{b1}, \varepsilon_{b2}]$, determined by Eurocode design standards; $M$ is the bending moment acting from the plane of the wall and determined by random eccentricity $e$, considered as the initial imperfection of the structure, causing its eccentric compression; $M_{crc}$ is the moment of crack formation initiation.

2. Walling energy saving:

$$R_f = \left( \frac{1}{\alpha_{in}} + \sum_{j=1}^{m} R_j + \frac{1}{\alpha_{ext}} \right) \geq R_{f,req}$$

where the value $R_f$ is the actual resistance to heat transfer of the outer wall; $R_{f,req}$ is resistance to heat transfer required by the conditions for ensuring the comfort of the internal environment, $\alpha_{in}, \alpha_{ext}$ $R_j$ $m$ are heat transfer coefficients on the inner and outer surfaces, thermal resistance of the layer and the number of layers, respectively. In terms of real design, the cost of the layer $c_j$ of the wall is determined on discrete sets of thicknesses $t_{j,k}$ materials and mainly depends on the type $k$ of material:

$$c_j = f(\{t_{j,k}\}),$$

The solution of such a problem is associated with a multiple choice of thicknesses of materials of various types, since the variables in constraints 1 and 2 are dependent and the solution of the problem in a deterministic formulation, in our opinion, is difficult. To solve this problem, we propose to use an evolutionary modelling strategy adapted to solving the problem of cost optimization for steel and reinforced concrete structures [18].

It is considered the formulation of the problem associated with the optimization of the flooring structure. For this the task is reduced to the statement (1), taking into account the features of the design solution of the attic. Here conditions (2) are formulated as follows:
- for reinforced concrete parts of structures, the strength and rigidity of the structure should be provided on the basis of the limiting states of the first and second groups.

- for energy saving, the condition (3) is applied, in which \( R_f, R_{o}^{req}, R_f \) are calculated for flooring. For flooring, the requirement for providing an isolation index from airborne and structural noise is added to the conditions for ensuring strength and rigidity. In general terms, these conditions can be written as follows: \( R_{ws}^{f} \geq R_{ws}^{req} \), where \( R_{ws}^{f}, R_{ws}^{req} \) - actual and required noise insulation index. For floorings and coatings, the structure of which is multi-layered (flooring over the ground, solid or hollow flooring of reinforced concrete slabs, etc.), the objective function for solving the optimization problem is (1). If beam floorings or coatings are optimized, we get:

\[
C_{cell} = \min \left( \sum_{i=1}^{n} c_{beam}^{i} + \sum_{j=1}^{m} c_{j} \right),
\]

\( c_{beam}^{i} \) - cost of beams of \( i \)-th type; \( n \) - number of beam types; \( c_{j} \) - the cost of the \( j \)-th layer, including the filing of beams from below, \( m \) - number of homogeneous layers;

\[
\begin{align*}
{A} & = \{A_1, \ldots, A_n\}, \quad \{J_x\} = \{J_{x1}, \ldots, J_{xns}\}, \quad \{J_y\} = \{J_{y1}, \ldots, J_{yns}\}, \quad \{J_z\} = \{J_{z1}, \ldots, J_{zns}\}, \\
\{y; z\} & = \{(y_1, z_1; y_2, z_2; y_3; z_3; \ldots; y_n, z_n)\},
\end{align*}
\]

where \( A \) is beam cross section area; \( J_x, J_y, J_z \) are central moments of torsion and bending relative to the main axes of inertia; \( y, z \) are coordinates of cross-section points furthest from the centre of gravity; \( ns \) is number of beams.

This problem in the formulation of the selection of values from discrete sets will be solved with the help of adapted genetic algorithms, pre-forming a computational model based on solid-state modelling with subsequent discretization of this model into bulk finite elements.

3. **Solving algorithm of optimization problems**

Following the basics of the theory of evolutionary modelling, we form the following stages of the computational process:

1. Collection and setting of initial information for search. At this stage, information is generated on the design model, including:
   - Variant of design solution for the object under consideration;
   - Data on the thickness of the layers, their order, thermal and strength characteristics;
   - Information about the restrictions, including the limiting values of the indicators limited by the calculation, the conditions of fixing, the schematization of the loads; control parameters of the search procedure.

2. Iterative search.

2.1. The initial set of solutions is formed randomly, with the number of variants of facilities being set equal to twice the size of the maximum size of the discrete set for all varied parameters.

2.2. The value of the target function is calculated. For each option from step 2.1, this is done by formula (1) for the wall optimization problem or by formula (5) for the flooring optimization problem.

2.3. The database of elite structures is filled or edited. The conditions for placement in this base are based on the logic of the process of "elitism"

\[
\begin{align*}
C_{N} & < \max \{C_{P}\} \\
\Omega(C_{N}) & \notin \Omega, \forall \Omega \in [\Omega_{i} \ldots \Omega_{N}]
\end{align*}
\]
where $C_N$ is the value of the objective function for the structure placed in the base, $C_p$ is the maximum value of the objective function that is in this database, $\Omega(C_{N})$ is coded current facility $\Omega_i$ is facility from the database of elite facilities in coded form, $\tilde{N}$ is number of elite structures.

2.4. The formed set of solutions by the crossover and mutation operator’s transformation known in evolutionary modelling.

2.5. Repeat steps 2.2 - 2.4 until the condition for exiting the iterative process is fulfilled.

The condition for exit from the process is based on an empirical criterion, expressed in the absence of changes in the database of elite facilities. In the general case, this criterion is associated with the convergence of the search problem and depends on the total number of variable parameters, the number of values allowed for selection by varying parameters, the number $\tilde{N}$ and, we suppose, from some other factors. When solving this cross-task, the search process stops if there are no changes in the database of elite facilities during 50 iterations of the search.

4. Results of optimum design

1. Search for solutions for self-supporting wall structure. Given a multi-layer enclosing structure consisting of facing, thermal insulation and structural layers (Fig. 1.). Energy saving conditions were set at the location of the facility in Moscow. Since the wall does not take the load from the flooring, the strength conditions are assumed to be provided. The sequence of layers shown on Fig. 1, during the optimization process does not change. Discrete sets $t_{j,k}$, varied during the search for a solution are presented in Table 1. In total, 7 types of materials varied, each of which provided for a choice from 2 to 5 values.

![Figure 1. Wall layout example: 1 – face layer, 2 – brick protective layer, 3 – heat insulation layer, 4 – brick bearing layer](image)

In the course of solving the problem of forming a three-layer enclosing structure with an area of 1 m$^2$, 936 variants of wall structures were considered to meet the heat transfer requirements. The graph of convergence of the iterative process is presented in Fig. 2. When calculating the values $C_w$ the market method was used to determine the cost of materials at current (projected) prices in Moscow and the Moscow region. As a result, the minimum cost of a three-layer building envelope was determined equal to 1000.97 RUB per 1 m$^2$, satisfying the requirements of heat transfer and bearing capacity, taking into account the load only from its own weight, and consisting of two layers of expanded clay concrete with a thickness of 200 mm and polystyrene foam 20 mm.
2. Search for solutions for the flooring structure. Two variants of internal flooring on a monolithic reinforced concrete slab are considered. The first (a) with the use of lag, the second (b) without (ref. to Fig. 3). The sets of variable parameters are shown in table 2. We assume that the finishing layer of the flooring does not vary, we adopt parquet as an example.

Table 1. Discrete sets of variable parameters.

| Layer t₁ material | Brick | Claydite | Aerated concrete | Foam concrete |
|-------------------|-------|----------|------------------|-------------|
|                   | 120   | 200      | 200              | 200         |
|                   | 200   | 230      | 300              | 300         |
|                   | 250   | 240      | 400              | 400         |
|                   | -     | 280      | 500              | 500         |

| Layer t₂ material | Foam glass | Mineral wool | Styrofoam |
|-------------------|------------|--------------|----------|
|                   | 50         | 50           | 20       |
|                   | 60         | 100          | 30       |
|                   | 80         | -            | 40       |
|                   | 100        | -            | 50       |
|                   | 120        | -            | 100      |

| Layer t₃ material | Brick | Claydite | Aerated concrete | Foam concrete |
|-------------------|-------|----------|------------------|-------------|
|                   | 120   | 200      | 200              | 200         |
|                   | 200   | 230      | 300              | 300         |
|                   | 250   | 240      | 400              | 400         |
|                   | -     | 280      | 500              | 500         |

Figure 2. Convergence of the iterative process.
Figure 3. Ceiling layout example: 1 – layer material 1 (table 2); 2 – layer material 2; 3 – layer material 4; 4 – floor logs, 5 – parquet.

Table 2. Characteristic of variable parameters.

| Flooring type in Fig. 2 | Material                                      | δ, mm |
|------------------------|-----------------------------------------------|-------|
| a                      | Material 1                                    |       |
|                        | Reinforced concrete slab 80mm for beams 120x230mm (span 1500mm) | 80    |
|                        | Reinforced concrete slab 120mm for beams 130x270mm (span 2100mm) | 120   |
|                        | Reinforced concrete slab 120mm for beams 130x290mm (span 2400mm) | 140   |
|                        | Material 2                                    |       |
|                        | Mineral wool ROCKWOOL                         | 50, 60, 70, 80 |
|                        | Mineral wool ISOVOL-L                         | 50, 100 |
|                        | Technikol TECHNOFLOOR Standard                | 50, 60, 70, 80 |
|                        | Material 3                                    |       |
|                        | Fibre building boards                          | 25, 32, 40 |
|                        | Wood chip boards                              | 25, 36, 40 |
| b                      | Material 1                                    |       |
|                        | Reinforced concrete slab 80mm for beams 120x230mm (span 1500mm) | 80    |
|                        | Reinforced concrete slab 120mm for beams 130x270mm (span 2100mm) | 120   |
|                        | Reinforced concrete slab 120mm for beams 130x290mm (span 2400mm) | 140   |
|                        | Material 2                                    |       |
|                        | Mineral wool ROCKWOOL                         | 50, 60, 70, 80 |
|                        | Technikol TECHNOFLOOR Standard                | 50, 60, 70, 80 |
|                        | Floor beams: bar 50x50 or 50x100               | 50, 100 |
|                        | Material 3                                    |       |
|                        | Fibre building boards                          | 25, 32, 40 |
|                        | Wood chip boards                              | 25, 36, 40 |

The airborne noise insulation index is defined by simplified dependency. $R_{ns}^f = 37lg m + 55lg K - 43$, $m$ - material surface density, $K$ - empirical coefficient depending on the type of material. Compliance with the requirements of noise protection is taken equal to the level
During the study, 360 options were considered. In the study, the market method was used to determine the cost of materials in current (forecast) prices in the territory of Moscow and the Moscow Region. The graph of convergence of the iterative process for ceiling on fig. 3,a is presented in Fig. 4.

As a result, the most effective was the flooring with the cost of 1213.7 USD per 1 m², satisfying noise insulation requirements (Rw = 53 dB), consisting of a monolithic reinforced concrete slab with a thickness of 80 mm with secondary beams with a section of 120x230mm, a ROCKWOOL sound insulation layer with a thickness of 50 mm and a fibre building board with the thickness of 25 mm. Requirements for reinforcement, strength and crack resistance for this design are also satisfied.

5. Discussion
The considered approach does not allow us to state unequivocally that the found designs are optimal, because we did not take into account the possibility of changing the sequence of layers. In this case, from the point of view of thermal physics, it may be necessary to construct a vapour barrier or change the structure as a result of assessing the probability of condensation in the insulation layer. In addition, it seems relevant to take into account the reliability of materials of constructional layers in time. These issues will be considered in the course of further research.

6. Conclusions
The general methodology of search engine optimization of constructive solutions for multilayer carrier and enclosing structures, based on the use of adapted algorithms for evolutionary modelling, has been developed. In the framework of this approach, two methods of finding solutions are implemented. The first allows you to optimize the thickness of the layers of self-supporting outer walls, the second thickness of multilayer floorings. The presented developments have prospects for use in computer-aided design systems, as well as adaptation to new types of multi-layer structures of walls, floorings, coatings and roofs.

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