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Optimization of steel beam structures for frame buildings subject to their safety requirements

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Keywords: building structures, construction safety, column collapse risk, ceiling optimization, buildings durability, steel beams, local damages, emergency actions, transformable structures, evolutionary modelling

Abstract. A method for finding design solutions for discrete sets of design parameters, including a single two-cycle iterative process, has been developed. The evolutionary procedure is a first cycle. Within the framework of this process, a second recurrent cycle is used to calculate the structure in a static nonlinear arrangement. The coefficients are used for correction of the object loading as part of its static analysis to take into account the dynamic effect. Risk assessment for the structure variant also takes part within the framework of the evolutionary procedure. The proposed algorithm has been developed for the structures of buildings of a higher criticality rating, which will allow to increase the mechanical safety of construction objects with the simultaneous rational saving of material costs. As an example of design, a transformed beam structure, equipped with an adaptation system for beyond design effects, is considered. It is shown that during the synthesis of structures of increased durability, the use of adaptation systems in the form of safety elements has an advantage compared to an ordinary increase of the cross section.

1. Introduction

The tasks of optimal design of bearing structures are relevant for construction science. At the same time, in a number of research tasks, they do not take into account the risks of the occurrence of emergencies [1, 2]. This can significantly affect the safety of the object during operation. One of the measures to obtain the most rational design project from the standpoint of estimating the cost of ensuring the safety of buildings and structures is to use approaches based on the risk of material losses during the operation of structures [3–11]. In many studies devoted to this topic, problem statements has been considered, which make it possible to take into account the reliability of the structure, the risks associated with design errors, the level of loading of the object, the nature of loading, etc. Such issues were considered for mechanically [9, 12–14] and exothermically [15, 16] damaged reinforced concrete structures, steel structures under climatic temperature effects [17], and other supporting systems. In some cases, the calculations took into account the full life cycle of the structure [18]. In addition, of interest is the analysis of the risks of material losses with significant wind pressure [10], seismic activity [4–6, 14], floods [7] and other special loads and impacts. Separate attention to the issue of assessing the safety of systems that have damage accumulated during operation is given in [19].

In modern socio-economic conditions, the problem of ensuring the safety of structures comes to the fore. First, this applies to objects of a high level of responsibility. For the supporting structures of such objects, the risks associated with ensuring safety should be reduced to a rational minimum.

In this regard, the solution to the problem of the yield of design solutions to the optimal cost-risk ratio seems to be particularly relevant. It should be noted that so far this problem has not been given enough attention. The reason is the absence, until recently, of both effective methods for optimizing building support

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structures and the computing power of computers that implement them. One of the approaches that allow significant progress in solving this problem is evolutionary modeling or genetic algorithms.

Now they are used in solving problems of assessing the reliability of structures [20–23], searching for parameters for structures of various types, including frames [22], trusses [23], cable-stayed bridges [24], domes and vaults [25], laminates with high energy absorption capacity [26] and many other objects.

The issues of mechanical safety of beam building structures occupy important place herein. Mechanical safety enhancement in case of local damages in the form of emergency actions from the point of view of a design solution can be achieved in two main ways:

– redistribution of internal forces flows generated by abnormal dynamic additional loadings. This can be achieved by the preventive opportunities of modifying the object's structural layout based on the predicted change of the mode of operation of the joint connections, by increasing the cross sections of certain elements, and by introducing additional reinforcement;

– installation of a system of additional safety elements and arrangements actuated by deformable structures or mechanical actuators at the building accident, and redistributing additional loadings from abnormal loads to other structures or foundation. In this case, the safety elements can be destroyed, damping the impact effects.

In a series of contributions about the optimization of building structures, for example [27], the problem of finding the minimum mass, volume, or cost of objects was solved taking into account various factors that did not include risk analysis. In this case, conditions of normal operation were most often considered, some works are devoted to the optimization of structures during emergency action. Researches show that a rational distribution of the material of a structure, which is sought for in optimization problems, in some cases leads to a significant reduction in the safety margins. When considering the actual design conditions (the quality of construction materials, inaccuracies during installation, arrangement of joint connections, improper operation), a reduction in safety margins can create an increased risk of accident and lead to severe economic and social consequences. Therefore, an optimization criterion based only on cost minimization seems to be biased. In this regard, it is necessary to develop approaches related to the risks assessment of accidents and material losses, which will increase the safety of design solutions. It is not consider social losses due to the complexity and individuality of specific cases.

This article discusses the approach to the optimal synthesis of design solutions for beam ceiling and roof structures of increased durability with safety elements from the perspective of minimizing the risks associated with accidental impacts. At the same time, the search for variants of the design solution is carried out taking into account the rational minimum of costs for the supply and construction of these structures.

2. Methods

2.1. Formulation of the problem

It is considered a deformable beam structure of the building having a mechanism for adapting to emergency actions (a safety system), providing or at least enhancing the durability of the system in an accident. Risks from a possible accident are considered only at the stage of operation of the structure. The task of finding the optimal solution for any variant of such a structure depends on the levels of local damage. Here are these damage levels:

– normal level of damage (NLD), when local damage does not create any significant risk of loss of the durability of the object during the operation of the safety system of the structure.

– higher level of damage (HLD), when the safety elements system with a high probability will not be able to prevent the destruction of the structure in all possible damage cases.

In this case, the optimization task falls into two subtasks. For the NLD formulation, the design parameters should be chosen in such a way as to deliver at least the following functionality:

$$C + C_s(y_s) - R(y_s,\, p) \to \min, \quad R = pU(y_s), \tag{1}$$

where C is the initial cost of the structure without safety system;

C_s is a cost of the safety system;

R is the absolute risk factor of an accident with the material losses;

y_s is a discrete set of variable design parameters of the safety system;

p is a failure probability of the structure under the condition of accident;

U is damage from material losses in monetary terms.

For HLD formulation the optimization problem can be formulated as:

$$C(y)+C_s(y_s)-R(y,\,y_s,\,p)\to \min,\quad R=pU(y,\,y_s), \tag{2}$$

where y is a discrete set of variable design parameters of the structure, excluding the elements of the safety system, values U, C, C_s, y_s, R, p are the same as in the formula (1).

Active (checkable during the iterative process) constraints in solving extreme problems (1), (2) are:

– the condition of durability, it is interpreted for the structures under consideration as a prohibition of significant changes in geometry during the accident;

– the condition for the prevention of local destruction of the material of structural elements, leading to a general destruction along critical sections with their dynamic additional loadings.

As passive constraints (checkable after the iterative process of finding a solution), it is considered the restrictions on limit states regulated by the relevant standards (codes, state standards) for various types of structures. It also fulfils the design requirements for ensuring local strength, flexibility, support conditions, etc.

The modular system for dimensions coordinating in construction and the design of beam structures require the definition of design parameters in the form of discrete sets:

$$y=\{\vec{y}_1,\,\vec{y}_2,\,...,\,\vec{y}_n\},\quad y_s=\{\vec{y}_{s1},\,\vec{y}_{s2},\,...,\,\vec{y}_{sm},\}, \tag{3}$$

where $\vec{y}_i,\ i\in[1...n]$ is the vector of i-th variable design parameter, specified by the components from the range of acceptable values for the values selection used in solving the problem;

$\vec{y}_{sj},\quad j\in[1...m]$ is similar, but for the safety system;

n, m are the numbers of variable parameters for the structure and its safety system, respectively. For example, for steel beam structure, vector $\vec{y}_1,$ bonded to a specific beam structural element can be represented in the following form:

$$\vec{y}_1=(\{A\}_1,\{J_x\}_1,\{J_y\}_1,\{J_z\}_1,\{X\}_1,\{Y\}_1), \tag{4}$$

where A, J_x, J_y, J_z, X, Y are respectively, the area, the moments of inertia and the coordinates of critical points in sections in the local coordinate system of the element. The sizes of the sets of areas and moments of inertia are determined by the number G of variable values for the considered parameter, and the dimensions of the coordinate sets X, Y – by the number P of considered critical points for the cross section, otherwise the set $\{A\}$ = $\{A_1, \ldots, A_G\}$, $X = \{X_1, \ldots, X_G\}$, $X_1 = \{x_1, \ldots, x_P\}$. The other sets have a similar view.

Structure calculations will be performed on the basis of the finite element analysis. The review of modern methods for the optimal design of technical objects for discrete sets of design parameters allows choosing the most effective approach to solve the problems posed, based on the evolutionary search.

2.2. Constraints

The time of the normal operation period for steel structure is considered. The strength of the ceiling (or roof) bearing beams of the first stress-strain state class (with the avoidance of plastic deformation for use in floors or coatings) [28]:

$$\frac{M}{W_nR_y\gamma_c}\le 1;\quad \frac{QS}{JtR_s\gamma_c}\le 1, \tag{5}$$

where M is a bending moment;

W_n is the section net resistance;

R_y is the design bending resistance;

γ_c is the working conditions factor of the structure;

Q is a shear force;

S is the static moment of the shear part of the cross section;

J is the moment of inertia in the bending plane;

t is the thickness of the shear part section;

R_s is the design shear resistance.

Strength of second and third stress-strain state classes for beams (assuming plastic strain) is determined [28]:

$$\frac{M}{c_x \beta W_n R_y \gamma_c} \leq 1; \quad \frac{Q}{A_w R_s \gamma_c} \leq 1, \tag{6}$$

where c_x, β are coefficients, that take into account the cross section shape and the level of tangential bending stresses respectively;

A_w is the shear area.

Beam stiffness due to structural safety and aesthetic requirements

$$f \,/\, L \leq \Omega_L, \tag{5}$$

where f is a deflection of the structure;

L is the span;

Ω_L is the coefficient determined by the L value. For example, for L = 6 m, it is assumed Ω_{LL} = 0.005, for L = 12 m, Ω_L = 0.004, and so on.

General and local sustainability conditions are met by design requirements. For this purpose, the shape of the section, the setting of stiffeners, the fixing from the plane of bending are specially set.

For the conditions of an accident, the presence of plastic stress σ_{yeld} is allowed, the value of which does not exceed the limit values $\sigma_{\lim}$ corresponding to the formation of cracks or rupture of structural steel:

$$\frac{\sigma_{yeld}}{\sigma_{\lim}} \leq 1. \tag{7}$$

Limiting the deflection of the transformed system. In an accident, after the mechanical safety system is activated, the transformed frame structure is deformed. The deflections f_e of this system should not exceed the allowable values f_{ult} sufficient for the safe evacuation of people and equipment from the building. The value f_{ult} is taken as $f_{ult} = 0.7H$, where H is the height of the floor, but not less than 2 m.

This constraint is used as an active for simplified evaluation of design structures. At the same time, for the final design solution, a calculation must be performed taking into account geometric nonlinearity, in particular, the proposed V.F. Mushchanov et al. [27, 28], as well as monitoring the rationality of the resulting geometry to ensure the evacuation of people and equipment [29].

2.3. Method for solving the problem

The general scheme of the computational process is presented in Figure 1. Such stages of the computing iterative process are carried out.

2.3.1. Construction of a finite element model and the formation of sets of variable parameters. At this stage, the information on the discretized model of the object, including the topology, material, loads, and reference restrictions is entered. Sets of varying parameters and identifiers are represented in the form of matrices, connecting these sets with the finite element model of the system.

2.3.2. Formation of initial sets of variants of structures in the form of data arrays. First set V is current and contains a description of the variants of structures represented in a coded variable I:

$$V = \{I_1, I_2, ..., I_N\}, \quad I_1 = \{a_{11}, a_{12}, ..., a_{1n}\}, ..., I_N = \{a_{N1}, a_{N2}, ..., a_{Nn}\}, \tag{8}$$

where N is the number of structures in the set;

a_{ij} is the value number of j-th parameter of variant i, ($i \in [1…N]$, $j \in [1…\mathrm{n}]$), determining the characteristics of a parameter from the sets $\{A\}_j$, $\{J_x\}_j$, $\{J_y\}_j$, $\{J_z\}_j$, $\{X\}_j$, $\{Y\}_j$. That is, if $a_{11} = 3$ for the rod, associated with variable parameter 1 of the first variant of (I_1) structure from the set V, the characteristics $\{A_3\}_1$, $\{J_{x3}\}_1$, $\{J_{y3}\}_1$, $\{J_{z3}\}_1$, $\{X_3\}_1$, $\{Y_3\}_1$ will be assigned.

The variants of structures for the initial set V are formed according to the principle of decreasing identifier numbers a_{ij}, with the components of the vectors $\vec{y}$ to be sorted by ascending values of geometric characteristics. At the same stage, similar to the set structure V the V_{best} data set structure is formed, which will be used to save the best solutions. The size of this set usually contains 15–20 structures variants. Initial set V_{best} is empty.

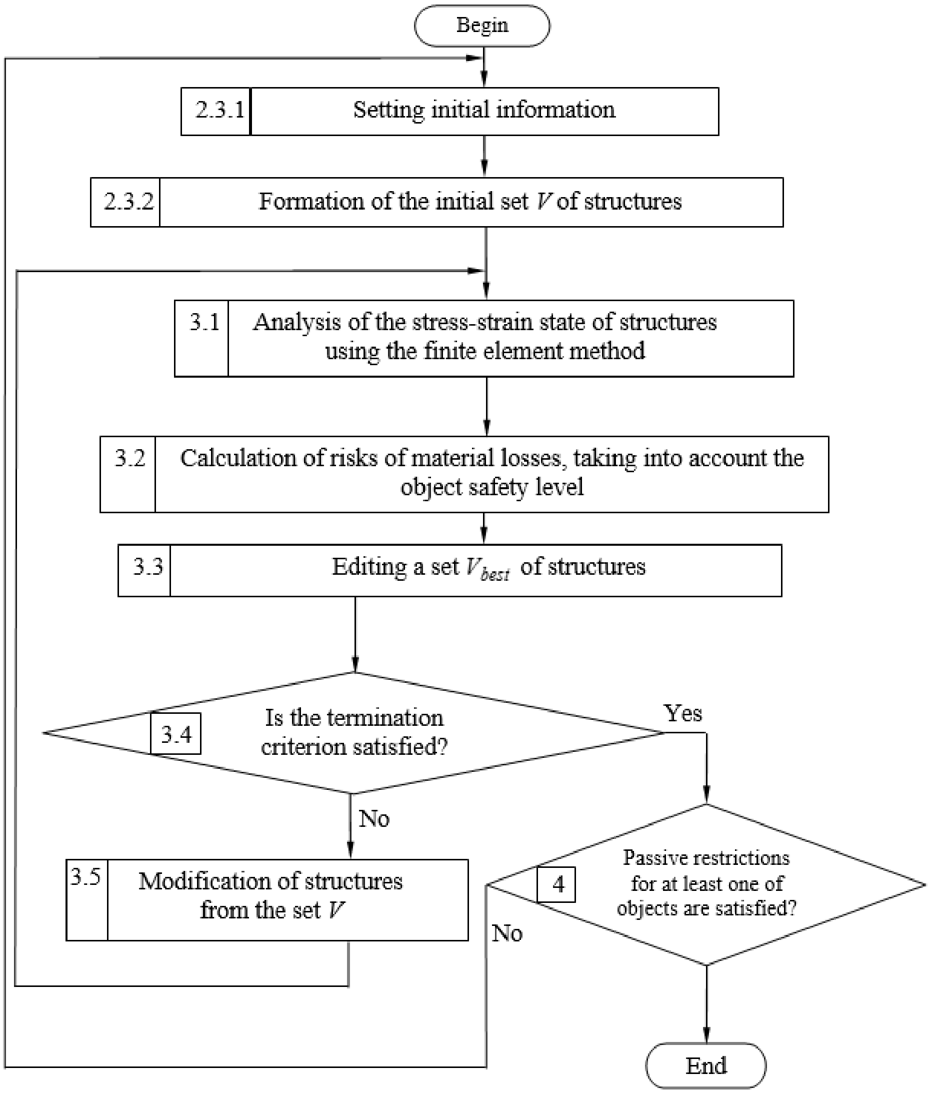


Figure 1. The sequence of finding the optimal solution.

2.4. Iterative process of finding solutions

2.4.1. Calculation of structures variants. Since the considered systems can have local damages, their calculation should be performed in a formulation that takes into account both physically and structurally nonlinear effects, as well as large displacements. Since the analysis of the structure in the dynamic formulation within the framework of the evolutionary approach is not possible due to the very high computational capacity of the process, we will use the simplified approach, which consists in a quasistatic nonlinear calculation with internal iteration cycles not related to the external cycles of the evolutionary algorithm. Dynamic effects in this calculation will be approximately taken into account by dynamic coefficients, the magnitude of which increases the loading level of the system. For this calculation, you can use the algorithm from the [30] or the NX Nastran solver. In this case, we consider the final position of the adaptation system, corresponding to the maximum activation after local damage to the system.

In the genetic algorithm for the analysis of the stress-strain state, the elements of the “Beam” type (NX Nasrtran) are used, which provide for the possibility of taking into account the plastic flow of the material with hardening. At the end of the search process, for the analysis of the resulting system, single-layer shell elements (“Plate”) are used.

It is defined dynamic coefficients outside the evolutionary search process as follows. For each variant of accident effect, we perform calculations of the damaged system in dynamic and static arrangement, determining the maximum equivalent stresses σ_D and σ_S respectively. We take into account the physically and geometrically nonlinear behaviour of the object. We do not consider the transient dynamic process of the adaptation system activation. As a result, the dynamic coefficient $k_D = \sigma_D / \sigma_S$.

If, as a result of the calculation, it is determined that the structure has durability, then we consider it at the next stage of the iterative process. If, based on the results of the calculation, it is determined that none of the structure variants is durable, then we go to the stage 1.

2.4.2. Calculation of the building fail risks of an accident. For the automated calculation of the risks associated with material damage from accidental effect, we introduce the following data sets:

$$S = (\{N_s, \{N_e\}, L, D\}_1, ..., \{N_s, \{N_e\}, L, D\}_{ns}), \tag{9}$$

where S is the array of information about structural elements, the number of which is ns, and each element of which contains the number of the structural element N_s and a list $\{N_e\}$ of the numbers of finite elements constituting this structural element, the length of the structural element L and binary damage identifier D. If in any finite element we detect stresses equal to or exceeding a certain critical level (for example, for steel this is the yield strength), then we consider the structural element to be damaged, and $D = 1$, otherwise $D = 0$. Within the same structural element, the sections of all finite elements are assumed to be similar.

Thus, the loss U_s from the failure of the structure rods and the safety system, can be determined by selecting all structural elements having damage from the array S:

$$\forall S_i \big| D = 1:\ U_{si} = k_w C_s L_i A_i \rho_i,\quad U_s = \sum_{S_i|D=1} U_{si},\quad i \in [1...ns], \tag{10}$$

where U_{si}, C_s, L_i, A_i, ρ_i are respectively loss from damage of i-th structural element, the cost of its unit of mass, length, cross-sectional area and density of the material;

$k_w = 1,02..1,1$ is the coefficient taking into account the cost of welding.

The loss $U_{\tilde{s}p}$ from the failure of equipment and floor structures (coatings) can be determined based on the selection of data from the array $\tilde{S}$:

$$\tilde{S} = \{\{N_p, \{N_k\}, C_{\tilde{s}}, C_p\}_1, ..., \{N_p, \{N_k\}, C_{\tilde{s}}, C_p\}_{np}\}, \tag{11}$$

where N_p is the number of span in which the damaged structure is located;

$\{N_k\}$is a list of structural elements limiting this span;

$C_{\tilde{s}}, C_p$ are the costs of equipment and floors that were exposed to emergency actions, before they are damaged. If we consider a multi-storey object, the spans are numbered on each floor. If there are damaged structural elements in span N_p from the list $\{N_k\}$, we also consider the equipment and floors as damaged, otherwise we assume $C_{\tilde{s}} = 0, C_p = 0.$

Thus

$$\forall \tilde{S}_i \big| \{C_{\tilde{s}} \neq 0\} \vee (C_p \neq 0):\ U_{\tilde{s}p} = \sum_{np} C_{\tilde{s}i} + C_{pi},\ i \in [1...np], \tag{12}$$

where np is the number of spans.

The total material loss will be:

$$U = U_s + U_{\tilde{s}p}. \tag{13}$$

The risks of damage from an accident are divided into two groups. The first group (I) is associated with the failure of the structure in normal operating conditions, the second – with failures during emergency actions. When calculating the probability p_I of failures of the first group we take into account the variation of mechanical characteristics and loads due to their statistical variability. This probability of failure is calculated based on a well-known approach using the Laplace formula under the assumption that random variables are distributed according to normal rule. This probability of failure significantly depends on the actual safety margin of the elements [31, 32] and nodal joints [33]. The probability p_{II} of risk of damage of the second group (II) is determined based on the analysis of statistics of accidents and disasters at construction sites.

Thus, the total risk of material loss at the stage of operation of the structure will be defined as:

$$R = R_I + R_{II} = U_s p_I + U_{\tilde{s}p} p_{II}. \tag{14}$$

Further, depending on the levels of local damages NLD and HLD, for each structure considered at this stage of the evolutionary algorithm, we calculate the value of the objective function $C(I)$ according to the formula (1), (2).

2.4.3. Filling the set V_{best}. All structures considered at the previous stage are checked for compliance with the conditions of fitting the set V_{best} in accordance with the strategy of "elitism" known in genetic algorithms. Any variant from the set V, if it is not in the set V_{best}, fit into it provided that $C(I \in V) \leq C(I \in V_{best})$.

2.4.4. Termination the end condition of iterations [1]. If during a certain number of iterations there are no changes in the set V_{best}, it means termination of the evolutionary cycle. This number of iterations depends on the number of variable parameters and the number of values of these parameters allowed for use in the search process. It is determined empirically at the stage of formal problem solving.

2.4.5. Editing the set V. Those structure variants that do not have the property of durability are replaced by randomly generated new variants. Half of the variants, for which the durability condition is satisfied are edited using the following statements:

– random change of parameter value. Let's consider a structure variant presented in coded form (8): $I_1 = \{a_{11}, a_{12}, ..., a_{1n}\}$. The work of the function is as follows. The parameter number for changes is randomly selected, and then the number of the parameter value is also random. In evolutionary modelling terminology, this function is called a simple single-point mutation. For definiteness, we consider the number of variable parameters equal to 3, and the ranges of change codes as $a_1 = \{1, 2, 3\}$, $a_2 = \{1, 2\}$, $a_3 = \{1, 2, 3, 4\}$. When changing the original structure variant $I = \{3, 2, 1\}$ with this function, the following variants may occur: $\tilde{I}_1 = \{1, 2, 3\}$, $\tilde{I}_2 = \{2, 2, 4\}$, $\tilde{I}_3 = \{3, 1, 4\}$, $\tilde{I}_4 = \{3, 2, 1\}$ and etc. In the first two variants, the value of the first parameter randomly changed, in the third – of the second, in the last – of the third;

– exchange of parameters (crossover) [1]. To implement it, you must select two variants for the object. The work of the function consists of two stages. First stage: randomly select the parameter number, for which the exchange will take place, the second stage is the exchange of parameters. In the terminology of evolutionary modelling, this function is called single point crossover. To illustrate the work of the function, we give an example presented in the table. Here, parameter 3 is initially selected, with respect to which the exchange is performed.

Table 1. An example of the parameter exchange function.

Before exchange	After exchange
$I_1 = \{a_1, a_2, a_3, a_4, a_5, a_6,\}$ $I_2 = \{b_1, b_2, b_3, b_4, b_5, b_6,\}$	$\tilde{I}_1 = \{a_1, a_2, a_3, b_4, b_5, b_6,\}$ $\tilde{I}_2 = \{b_1, b_2, b_3, a_4, a_5, a_6,\}$

The other half of the structure variants, for which the durability condition is satisfied, is replaced with the variants from the set V_{best}, selected in ascending order of the objective function *C* and edited only by the random change function of the parameter value.

4. Check of passive constraints. If the passive constraints are satisfied, then the solution is obtained; if not, then you can check their satisfaction for the structure variants obtained as a result of the search that are closest in terms of the objective function value.

As a result of the algorithm, we obtain several best solutions by criterion (1) or (2), which means optimality in terms of the cost-risk ratio. If it is required to maximize the safety of the structure, then this algorithm can be used by specifying such a formulation of the objective function:

$$\begin{cases} R \to \min \\ C(y) + C_s(y_s) \to \min \end{cases} \quad \text{or} \quad ((C(y) + C_s(y_s))k_1 + Rk_2) \to \min, \tag{15}$$

where k_1, k_2 are coefficients that are defined as unit fractions, which determine the degree of importance of taking material loss risk into account.

The designer when agreed with the project investor assigns these coefficients. If an investor wants to insure himself against potential risks, then $k_1 > 1$, the value of k_1 is assigned large if the investor does not need a safety system $k_2 = 0$.

If risk consideration for a designer does not seem significant (for example, at low cost, quality assurance of construction materials and low probability of accidents), then the problem of structural optimization can be solved using evolutionary modelling based on [34].

3. Results and Discussion

3.1. Results of steel ceiling beam optimization

The design of a beam structure with an adaptation system for emergency actions, the concept of which by a patent for an invention is protected (pat. No. 2556761 RF, MPK E04B 1/24, Figure 2).

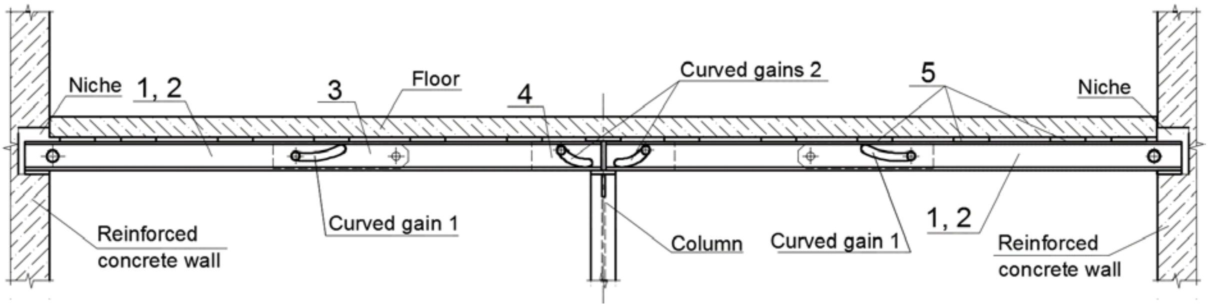
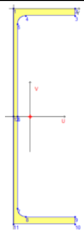
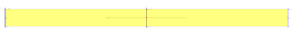


Figure 2. The ceiling beam and preventive safety system.

In the figure, the following designations are introduced: 1, 2 – are continuous and split channel beams; 3, 4 – plates, 5 – ties, welded to a continuous channel beam. The beam is made of structural steel C245. Spans are 3 m. Support joints are hinge-fixed, with the possibility of free rotation of the split channel beam in a niche. In case of accident removal of the middle support, the system is transformed into a frame structure. Running load q=30 kN/m. The dimensions of the standard profiles of the rods of channel beams 1 and 2, and the cross sections of plates 3 and 4 were varied independently. The durability condition in this case involves the transformation of the structure into a frame system and ensuring the condition of not exceeding the maximum deflection, which it is assumed to be 6 cm. Strength conditions were taken into account in accordance with the requirements of [31]. The structure is attributed to the 3rd class of the stress-strain state, under which the formation of conditional plastic hinges is allowed during the deformation. The characteristics of variable parameters for the structure and its adaptation system to accident are presented in the Table. 2.

The calculation is made by the finite element method using spatial rods, while taking into account the effect of buckling of the flat shape of the bend. Statistical data on the variation of the mechanical characteristics of structural steel and loads are taken from [34]. Design requirements were imposed on the dimensions of the plates and channel beams, consisting in coordinating the heights of these elements to ensure the operation of the adaptation mechanism.

Table 2. Allowable combinations of cross-sectional column dimensions.

Element in the Figure 1	Section shape	Profile grades and plate dimensions, m
Channel beams 1 and 2 (S1)		Channel beam with parallel edges of the rims according to GOST 8240–97: 1) 20P; 2) 24P; 3) 30P; 4) 36P; 5) 40P.
Plate 3 (P1)		1) 1.0×0.2×0.008; 2) 1.0×0.24×0.01; 3) 1.0×0.3×0.01; 4) 1.0×0.4×0.01;
Plates 4 (P2)		1) 1.2×0.2×0.02; 2) 1.2×0.24×0.02; 3) 1.2×0.3×0.03; 4) 1.2×0.4×0.04;

Analysis of the dynamic effect in case of local damage to the middle support was calculated “extensive” for a fully transformed state of the system (Figure 3) without taking into account its damping properties during transformation. The coefficient of the beam dynamics without adaptation mechanism when removing its middle support turned out to be equal to 1.95. In the presence of a transforming safety system to be equal to 1.52. These coefficients were obtained based on the energy approach of G.A. Geniev. The coefficient of dynamics in this case is calculated as $k = 2D - S$, D is the value of the maximum dynamic stress in the cross section of the transformed system with local damage; S is the value of this stress obtained in a static finite element analysis.

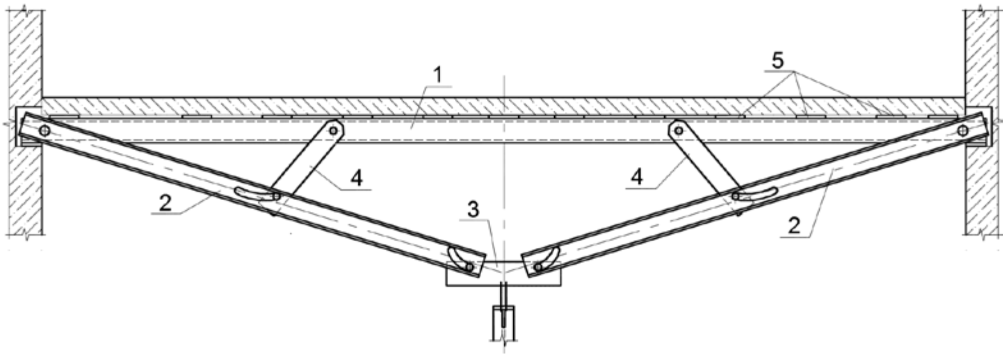


Figure 3. Beam system diagram transformed into a frame system.

When calculating the material loss, the cost of damaged elements of the beam and equipment worth 500 th. cu was taken into account. The cost of the material of beams, elements and parts of the safety system, taking into account the welding work, was assumed to be 60 th. cu per 1 ton. When calculating the risk of loss as a result of emergency actions, the probability of its occurrence was taken to be 0.01. In sets V, V_{best} 5 structure variants were used. The search process took not more than 20 iterations. Search results are shown in the Table. 3.

Table 3. The solutions obtained are similar to objective function.

Project No.	Codes of parameter values from the Table 1.			Objective function $C(I)$
	S1	P2	P1	
D1	1	1	3	7106
D2	1	2	3	7334
D3	1	3	3	7825

In the absence of an accident prevention system and ensuring the durability of the structure during an accident (with the same deflection of the damaged system) for the beam, it is necessary to use a section having a profile 36 P of channel beam. Table 4 shows a comparison of the obtained design solutions for structures with the presence and absence of an accident prevention system. The cost of these structures differs 1.3 times. The risk of material loss for them within the error of 13 % is similar.

Table 4. Comparison of the results of the structure synthesis.

Project No.	Structure cost $\breve{C}$, cu	Risk of material loss, cu	Codes of parameter values from the Table 1.		
		R	S1	P2	P1
D1	12730	5624	1	1	3
D*	16555	5012	4*	–	–

* Project for a beam without a safety system.

3.2. Discussion

The issues of adaptation and improvement of genetic algorithms for solving the considered problems are also investigated. This is primarily an increase in the effectiveness of the search for a solution at the initial stages of the iterative process [35], the use of a combined scheme of constraints accounting [36]. The concepts of genetic algorithms that use the basics of game theory to search for solutions on several optimality criteria, in particular based on D. Nash equilibrium, G. Stackelberg game models and optimality by V. Pareto [37] are promising.

The dynamics coefficients obtained in this example can be found more accurately, based on the provisions of [38]. The proposed iterative procedure can be implemented for other types of thin-walled structures, for example, [39]. However, when assessing the bearing capacity of objects, various features of deformation and types of such systems should be taken into account: these are non-uniform torsion [40], types of profiles [41], strength and stability of nodes [42], as well as the value of welding stresses [43]. A separate issue is the applicability of such an iterative scheme to the optimization of concrete and reinforced concrete structures [44].

It should be noted that the proposed approach to estimating the life cycle cost of operating structures is somewhat simplified. This is primarily due to the significant difference in the complete data on the provision of normal operating conditions for structures of various types. For example, to estimate operating costs for lattice structures, one can use the results of work [45]. But these results may not be fully used for other systems. For constructions of new types such data are practically absent.

4. Conclusions

1. A method to search for design solutions for frame building structures based on the joint use of evolutionary modelling, risk theory and calculations in a physically and geometrically non-linear formulation, which makes it possible to obtain cost-effective and safe systems based on sets of design parameters specified in a discrete form, has been developed.

2. The proposed method allows to take into account the peculiarities of the design of building structures related to the availability for production in specific conditions of standard sizes of rod profiles, the use of certain materials and to consider both one and several stages of the structure life cycle.

3. The considered example of design a ceiling beam system of increased durability shows that the arrangement of prevention safety systems, includes allowing the structure transformation, is more preferable from the point of achieving safety and economy goals.

4. The considered algorithm has limitations on the use in terms of estimating operating costs for various types of structures. Overcoming these limitations requires additional research, reflecting the features of operation, maintain measures, general repairs and reconstruction of these systems.

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Оптимизация балочных конструкций каркасных зданий с учетом требований к их безопасности

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Ключевые слова: строительные конструкции, оптимизация, механическая безопасность, риск, живучесть, локальные повреждения, запроектные воздействия

Аннотация. Разработан метод поиска проектных решений на дискретных множествах параметров проектирования, учитывающий риски материальных потерь при авариях и начальную стоимость конструкции и включающий единый двухцикловый итерационный процесс. Первым циклом является генетическая итерационная процедура. В рамках этого процесса вводится многократно повторяющийся второй цикл, используемый для расчета конструкции в статической нелинейной постановке. Для учета динамического эффекта используются коэффициенты, вычисляемые с использованием методов прямого интегрирования уравнений движения поврежденной системы, с помощью которых корректируется нагруженность объекта. Оценка рисков для варианта конструкции происходит также в рамках эволюционной процедуры. Предлагаемый алгоритм предусматривает возможность учета степени безопасности объекта, что позволит повысить до необходимого уровня сопротивляемость авариям несущих конструкций с одновременной рациональной экономией материальных затрат. В качестве примера проектирования рассмотрена трансформируемая балочная конструкция, оборудованная системой адаптации к запроектным воздействиям. Показывается, что при синтезе конструкций повышенной живучести использование систем адаптации в виде страховочных элементов имеет преимущество по сравнению с простым увеличением сечений элементов.

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