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OPTIMAL DESIGN OF STEEL FRAME STRUCTURES SUBJECT TO LEVEL OF MECHANICAL SAFETY

Abstracts. The approach to the design of steel frame structures is considered, taking into account the potential risk of occurrence of emergencies associated with their mechanical local damage, and possible material losses. It is proposed to classify these systems according to the safety level of the solution. In accordance with the introduced classification, methods for finding solutions are proposed based on the use of evolutionary modeling with subsequent risk assessment from the onset of an emergency. These methods include a combination of two-level stochastic optimization procedures. At the first level, a search is performed on discrete sets of design parameters of a design variant with a minimum cost. As constraints in the absence of emergencies, regulatory requirements of limit states are accepted, and the strength ratio is regulated. In a possible emergency for the construction is considered a limitation on survivability. At the second level, a heuristic search is performed for the design variant for which the risks of receiving material damage from an accident are minimal while ensuring a minimum of capital investments on the considered stages at building life cycle. Examples of the steel frame design with different levels of safety are given, which demonstrate the efficiency of the proposed approach.

Keywords: evolutionary modeling, accident risks, mechanical safety, survivability, optimization, strength, stiffness, steel frames, building life cycle, emergency actions.

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ОПТИМАЛЬНОЕ ПРОЕКТИРОВАНИЕ СТАЛЬНЫХ РАМНЫХ КОНСТРУКЦИЙ С УЧЕТОМ УРОВНЯ МЕХАНИЧЕСКОЙ БЕЗОПАСНОСТИ

Аннотация. Рассмотрен подход к проектированию стальных рамных конструкций с учетом потенциального риска наступления аварийных ситуаций, связанных с их механическими локальными повреждениями, и возможных при этом материальных потерь. Предлагается классифицировать эти системы по уровням безопасности проектного решения. В соответствии с введенной классификацией предлагаются методы поиска решений, основанные на применении эволюционного моделирования с последующей оценкой риска от наступления аварийной ситуации. Эти методы включают совокупность двухуровневых процедур стохастической оптимизации. На первом уровне выполняется поиск на дискретных множествах параметров проектирования варианта конструкции с минимальной стоимостью. В качестве ограничений при отсутствии аварийных ситуаций принимаются нормативные требования предельных состояний, при этом регулируется запас прочности. В возможной аварийной ситуации для конструкции рассматривается ограничение по живучести. На втором уровне выполняется эвристический поиск того варианта конструкции, для которого риски получения материальных ущербов от аварии являются минимальными при одновременном обеспечении минимума капитальных вложений на рассматриваемых этапах жизненного цикла здания. Приведены примеры проектирования стальной рамы с различными уровнями безопасности, которые демонстрируют работоспособность и эффективность предлагаемого подхода.

Ключевые слова: эволюционное моделирование, риски аварии, механическая безопасность, живучесть, оптимизация, прочность, жесткость, стальные рамы, жизненный цикл, за-проектные воздействия.

Introduction

In modern socio-economic day-to-day realities, the objective of materials saving can be relevant only while ensuring the safety of buildings. The spate of accidents at construction sites associated with man-made impact, including terrorist attacks, domestic negligence, industrial errors, poses the problem of minimizing losses in emergency situations for researchers and designers. One of the quantitative measures giving a comprehensive assessment of the severity of such losses is the risk of an emergency occurrence. The subject of research in the direction of structures calculation taking into account the risk both several decades ago and now is especially relevant. The foundations of this theory, its development and application to various types of structures and structural systems in domestic construction science were laid in the works [1-5] and many others. Foreign scientists are also conducting active research in this field. A number of works [4, 6, 7] are devoted to the search for rational options and the frequency of measures to maintain the functional performance of a structure. Many researches are deal with the risk assessment both in the course of normal operation and when occurring various scenarios of emergency actions [6, 8-14], etc. Among them there are considered wind loads [14], seismic loads [6, 7, 9, 10], and the damage of individual basic (key) structural members [15-21]. An accident risk assessment is performed for corrosion-damaged reinforced concrete [19, 20] and steel [21] structures. When assessing risks, both the overall life cycle of a building and its individual part can be considered [4, 7]. The research level achieved today makes it possible to solve the urgent problem of the optimal design of load-bearing structures considering the specified level of their safety. We know the works those are dedicated to finding optimal solutions for structures with minimal cost. In this case, the probability of failure in structures and, as a consequence, the possible consequences of accidents are not taken into account. The decreasing in the bearing capacity of the elements can lead to significant risks of failures and cannot be considered objectively as the optimum solution throughout the life cycle of the facility. This article proposes an approach to solving this problem for steel structures based on a set of methods that allow obtaining an optimum design solution in terms of cost / risk ratio. Evolutionary modeling is used as a tool for searching solutions at intermediate stages of the computational process [22, 23].

Problem definition

The steel frame system is considered, which is operated under normal conditions. When assessing the stress-strain state of this structure, taking into account only regulatory requirements. When assessing the risks of material losses, possible emergencies associated with local damage to the supports or their parts, as well as failures due to the statistical nature of the physical and mechanical characteristics of the materials and the variability of the loads, are considered. Let us introduce the following safety levels of the design solution: I - minimum, II - medium, III - high. The criterion for classifying the structure to the level of safety is the value of the “danger” of investment, estimated by relative risk:

$$\zeta_s = \sum_{i=1}^n (R_i / C_i), i \in [1..n], \quad (1)$$

where R_i – is an indicator of the absolute risk of an emergency occurrence, accompanied by financial loss; C_i – is the amount of the capital investments; i – is the number of the life cycle stage; n – is the number of such stages considered in the risk assessment.

When assessing the stress-strain state of the structures, we take into account the active constraints for strength and stability of the frames, structural rigidity and flexural stability for girders. The local stability of the flanges and webs of the open section rods is a passive constraint (it is checked outside the main computing process). The search for solutions for which the calculation of the value ζ_s is performed with a set of sizes and types of the frame sections using the modification

of the genetic algorithm [23].

Methods

To obtain a design solution with the target safety level, it is necessary to perform the following sequence of actions:

1. Performing an optimal search for a solution considering the normal operation and risks associated with failures of structural members as a result of statistical variability of materials and existing loads. For this, it is necessary to form a discrete set of a parameter that regulates the value of the structural safety reserve. Such a parameter can be the permissible equivalent stress determined by the designer $\sigma = \{\sigma_1, \dots, \sigma_e\}$, where e – is an integer number of values of the permissible stress. It is obvious that any of the permissible stresses should not exceed the design resistance of the structure. Then for each of the elements of the set σ it is necessary to perform the following steps:

- parametric synthesis of the structure using the discrete sets of variable parameters with constraints on the considered stress from the set σ . The algorithm for such a synthesis is described in the section of the evolutionary model for finding a solution given below in this paper;
- calculation of the probability of structural members failure;
- calculation of financial loss associated with an emergency in case of the failure;
- determination of the number of considered stages of the structure life cycle and calculation of relative risks.

After that for the obtained structure options, the minimum value of $F = C + pr$ is determined. Here C is the cost of the structure, r is the amount of the financial loss associated with its failure, p the probability of failure. The structure for which the value F is minimal will be rational in terms of costs and risks. For this structure, value ζ_s is calculated.

2. Assessment of the risk of accidents resulting from local damages. Initially, possible damage scenarios is considered. We will form them proceeding from the following: the main scenario (A) is a quick failure of the construction of one support. Such a scenario is already included in some design standards for reinforced concrete structures. We also consider additional scenarios (B, C ...): partial or complete damage to one of several supports together with the failure of one support.

To assess the risks resulting from emergency actions, we will follow these steps:

- analysis of dynamics of the damaged system. Two ways are possible here. With a simplified approach, it is possible to calculate dynamic coefficients for each of the possible options for local damage. For this, it is convenient to use the method of G.A. Geniev [16]. If a detailed study of the stress-strain state is required, then a damaged system can be calculated using approaches involving the analysis of local calculation schemes, for example [26], or other methods implemented in software systems. Such calculations take into account possible non-linear effects and loss of stability;

- parametric synthesis of design solutions subject to the constraints of the survivability of the structure with emergency damage effects. The survivability criterion is defined in works [17, 18]. For the frame structures, we consider the survivability provided if the conditions are met:

$$f_{tot} \leq [f]_{np}, \varepsilon \leq \varepsilon_{np}, \quad (2)$$

where f_{tot} – is the maximum displacement in the damaged structure after damping oscillations; $[f]_{np}$ – is the limiting displacement (deflection) of the structure, set by the designer due to the condition of ensuring the possibility of evacuation of people and equipment; ε – is maximum relative deformation in the structure material under uniaxial tension; ε_{np} – is ultimate plastic deformation of the material.

Essentially, conditions (2) mean the prevention of relatively large changes in the geometry

of the damaged structure, and the formation of plastic hinges in it during deformation is allowed. For steel structures, the condition $\varepsilon \leq \varepsilon_{np}$ means preventing the formation of cracks. Survival loss is approximately determined by us as a violation of one of the inequalities of condition (2).

If the structure does not have survivability during the implementation of any or all of the damage options from scenario A beyond the design basis effects, then it belongs to safety level I, if it does, then to level II. When providing survivability for one or more options of scenarios B, C, etc. - safety level is III.

- calculation of the risks of an emergency occurrence according to scenarios of emergency actions. In calculating these risks, we will consider the financial loss. In the general case, the total risk because of the occurrence of accidents consists of the risks calculated for each stage of the life cycle:

$$R_{tot} = (p_{C1}^A U_{C1}^A + \dots + p_{Cn}^A U_{Cn}^A) + \dots + (p_{C1}^m U_{C1}^m + \dots + p_{Cn}^m U_{Cn}^m), \quad (3)$$

where p_{C1}^A – is the conditional probability of the emergency damage occurrence under scenario A from m group of scenarios, provided that it is implemented at the stage C1 of the life cycle consisting of n stages; U_{C1}^A – is the financial loss owing to the local damages under scenario A at the stage C1.

The remaining values in the formula have a similar interpretation. If the right-hand side for R_{tot} attributed to the corresponding capital investments at the stages of the life cycle, then we get the value ζ_s .

3. The choice of the optimum design solution with the specified level of mechanical safety. For structures with safety level I, the design solution will be optimum if the conditions $F = C + pr \rightarrow \min$, described in paragraph 1 are met. To select the optimum design solution from the point of view of safety at levels II and III, one should consider as many hazardous options as possible from the point of view of loss of survivability of local damage. That structure variant that has survivability for any kind of emergency actions related to the corresponding group of scenarios (A, B ... etc.) will be optimum from the point of view of safety. Obviously, this option will not have a cost close to the cost of the structure, designed on the basis of the traditional approach.

When analyzing the design options that are survivable when implementing the number V_s of emergency actions from the considered group of scenarios, but do not have survivability when implementing other variants from this group, the risk value should be adjusted. For this, a coefficient of $k = V_s / V_{tot}$ is introduced, V_{tot} – is the total number of local damage options in the scenario. The risk is adjusted by dividing by this coefficient.

4. The evolutionary model of finding a solution.

In the case of designing separate relatively simple constructions, it is advisable to use a modification of a simple genetic algorithm containing such computational procedures:

- generation of the initial group of design solutions using a discrete set of variable parameters of the sections of the frames. These sets are defined by integral geometric characteristics. For steel structures, these values are selected by assortment or calculated by direct calculation, and for reinforced concrete structures, these characteristics are reduced to concrete using a coefficient that reflects the ratio of the elastic moduli of concrete and reinforcement.

- then the iterative process begins, including work with two groups of design solutions. The first group contains current solutions (CS) that are changed during the evolutionary search, and the second group contains the best or elite solutions (ES). During the iteration process, the following steps are performed:

- the structure efficiency check, taking into account the established constraints for strength, rigidity, stability. In this case, the calculation is performed on the basis of the finite element method or on the basis of mathematical models set forth in the design standards;

- editing an ES group according to the conditions for including the best solutions and exclusion of the worst ones (elitism strategy) [22];

- modifications of the CS group by genetic operators.

As genetic operators from a variety of their diversity, we use single-point crossover and mutation.

- checking the condition for termination of the search.

The criterion for ending the iterative process is the absence of change in the ES group for several tens or hundreds of iterations. This number is established empirically depending on the total number of possible structure options. If the search termination condition is fulfilled, then after satisfying the passive constraints, we consider the solution obtained. If not, a new iterative process cycle begins. If passive constraints are not fulfilled, then the evolutionary search process must be repeated by correcting the set of variable parameters.

Results and discussion

Example 1. Design of a double-span steel frame of the first (I) safety level. The considered frame structure (figure 1) consists of welded rods of the I-beam section.

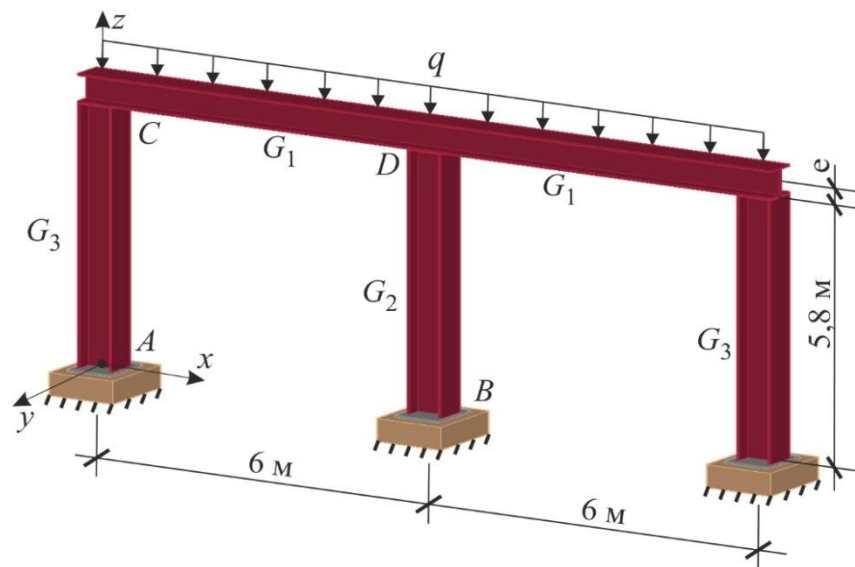


Figure 1 –The steel frame of the structure

The supporting nodes are considered as hinged ones, the other ones are rigid. The frame is made of structural steel C245. Elemental load on beams is $q = 90 \text{ kN/m}$. The support assembly units are hinged-fixed. In the process of parametric synthesis, combinations of sizes of welded I-beam sections of the rods were varied. Moreover, within each group G_1, G_2, G_3 the cross-section of the rods is assigned the same. The grouping takes into account the symmetry conditions of the object relative to the vertical axis. For the beams of the frame, the permissible profiles for selection in sections are shown in the table 1, for - columns in table 2.

The conditions of strength and stiffness were taken into account in accordance with the requirements of the code of SP 16.13330.2017. The calculation is performed according to the finite element method, discretizing the object into spatial rod elements of 1 m long for girders and 1.16 m long for racks. When varying the parameters, the change in the height H of the profile was taken into account by the size $e = H/2$ of the vertical rigid insert for the finite elements of the beam.

The structure at two stages of the life cycle is considered: erection (E) and operation (O). When calculating the risks associated with failures caused by the variation of mechanical characteristics, the methodology was used [24]. Statistical data on the variation of the mechanical characteristics of structural steel was obtained according to the data of the supplier plant, according to the

loads by the method of statistical tests. For normally distributed values of the calculated resistance R_y and load q the dispersions $S_R = 7,8$ MPa, $S_q = 3,5$ kPa are calculated. When calculating financial loss, we take into account the cost of damaged frame elements and the presence of equipment worth 1 million rubles in each of its span. The cost of the beams material, taking into account welding work, is accepted 60,000 cu for 1 t. The set is formed: $\sigma = \{80, 120, 160, 200, 235\}$. For each of the elements of this set, is performed a parametric synthesis of the structure based on the evolutionary model of finding a solution by the criterion of minimizing the cost (p.4).

Table 1 – Permissible combinations of beams cross-sectional sizes

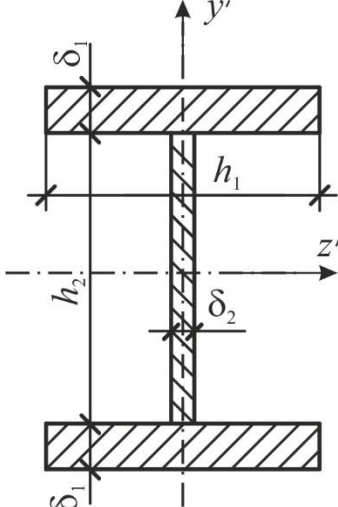
Combination mark	The cross-section shape	Размеры, см			
		h_1	δ_1	h_2	δ_2
W1		16	2,0	15	0,8
W2		20	2,0	18	0,8
W3		25	3,0	20	1,0
W4		28	3,0	25	1,0
W5		30	3,0	27	1,0
W6		32	3,0	29	1,0
W7		34	3,0	31	1,0
W8		36	3,5	33	1,2
W9		38	3,5	35	1,2
W10		40	4,0	36	1,2
W11		42	4,0	38	1,2
W12		46	4,0	42	1,4
W13		50	4,0	46	1,4
W14		55	5,0	50	1,6
W15		60	5,0	55	1,8

Table 2– Permissible combinations of column cross-sectional sizes

Combination mark	The cross-section shape	Dimensions, cm			
		h_1	δ_1	h_2	δ_2
W1	Welded I-beam (table1)	16	2,0	15	0,8
W2		20	2,0	18	0,8
W3		25	2,0	20	1,0
W4		28	3,0	25	1,0
W5		30	3,0	27	1,0

Moreover, for the final options based on the finite element method, we check the overall stability of the facility. The obtained solutions are presented in table 3.

Table 3 - Results of an optimal search for frame assigned to safety level I

Project No.	σ , MPa	C , c.u.	pr , c.u.	Combination mark for the group		
				G_1	G_2	G_3
D1	80	220631	$2,1 \cdot 10^{-2}$	9	2	W1
D2	120	174345	0,67	W7	W1	W1
D3	160	158519	9,52	W5	W1	W1
D4	200	150607	2133	W4	W1	W1
D5	235	137607	843686	W3	W1	W1

Obviously, in this case, under the abstract condition of zero probability of emergency actions for the first level of safety, the solution D4 will be the most rational. A further desire to reduce material consumption leads to a significant increase in the risk of failure, see solution D5 table 3.

If local damage effect occurs, then this solution will have even greater risks, and obviously, to increase the level of structure safety, an additional increase in the material consumption of the system is required.

Example 2. Design of the structure of II and III safety levels. We form scenarios of local structural damage. For an object of safety level II, in the case of a calculation with the main survivability constraint, we provide the following options for local damage (scenario S1):

- exclusion of the support *A* (see figure 1);
- exclusion of the support *B*.

The destruction of the joints *C* and *D* for this structure is considered conditionally equally hazardous to the corresponding damage to the supports. An object of safety level III must maintain the survivability property during the implementation of scenario S1 and such emergency actions (scenario S2):

- exclusion of the support *A* and the single support connection of the support *B* in the *x*-axis direction of the global coordinates (see figure 1);
- exclusion of the support *B* and the single support connection of the support *A* in the *x*-axis direction of the global coordinates. When considering other options for excluding support connections, the system either turned out to be geometrically variable, or these schemes were similar in degree of danger.

When assessing the stress-strain state of objects with local damage, we restrict ourselves to the quasi-static method for taking into account dynamic effects on the basis of the method proposed in the paper [25]. The analysis of the static states of the frame under consideration showed that for all types of local damages, the dynamics coefficient turns out to be close to 2.0. Therefore, we perform the stage of parametric synthesis of the damaged structure with the value of the effective load of 180 kN/m. In this case, the formation of plastic hinges in the rods was allowed, and the maximum displacements of the damaged system were limited to 300 cm, which ensured a free span of 2.8 m, ensuring the evacuation of people and equipment. The design schemes of objects and those obtained as a result of parametric synthesis of the grade of rod sections in cases of their local damage are shown in figure 2.

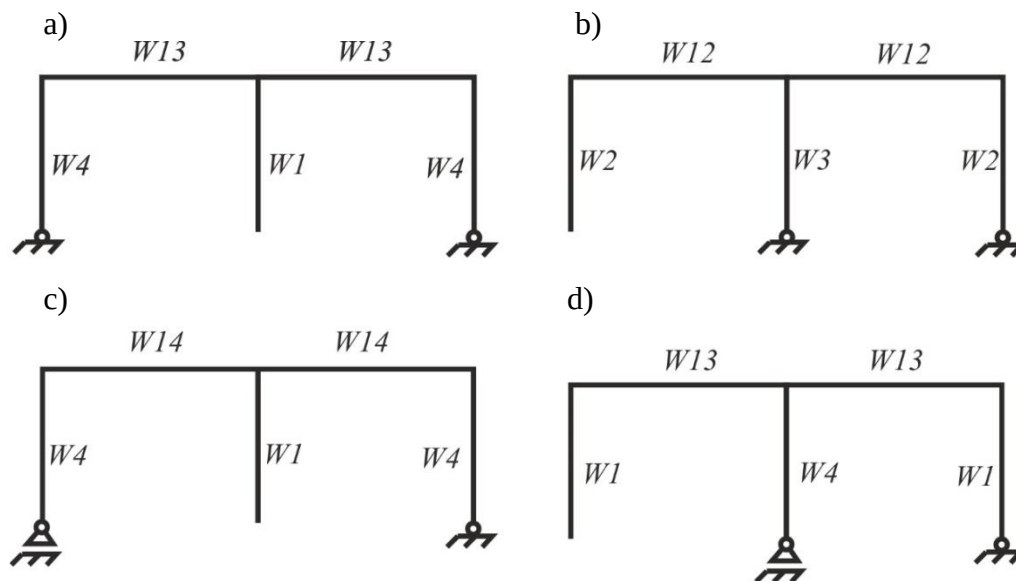


Figure 2 – The results of calculations for local damages in the implementation of scenario S1 (a, b) and scenario S2 (c, d)

As a result of the analysis of figure 2, we obtain solutions with survivability under any effect within the framework of the specified level of safety (see table 4). When calculating the risks for an object of I, II, III safety levels, empirically selected values of the probabilities of emergency actions presented in tables 5, 6, 7 were taken into account.

Table 4 – The results of parametric synthesis

Project No.	Safety level	C , c.u.	Combination mark for the group		
			G_1	G_2	G_3
DS1	II	361147	W13	W3	W4
DS2	III	461523	W14	W4	W4

Table 5 – Estimated probabilities for calculating the risks of accidents at projectD4 (I safety level)

Failure Scenario	p	$p(O)$	$p(E)$	Conditional probability	
Normal operation S0	10^{-8}	0,05	0,05	$p(O S0) \approx 0$	$p(E S0) \approx 0$
Scenario S1	0,(3)	1	0,05	$p(O S1) = 0,47$	$p(E S1) = 0,23$
Scenario S2	0,(3)	1	0,05	$p(O S2) = 0,47$	$p(E S2) = 0,23$

The following designations are used in the tables: p –probability of the accident; $p(O)$, $p(E)$ – the probability that any event from the group of failure scenarios is realized at the stage of operation (O) or erection (E) of the life cycle; $p(O|S0)$ –the conditional probability that the accident from scenario S0 (if it is successfully implemented) will occur precisely at stage (O).

Table 6– Estimated probabilities for calculating the risks of accidents at projectDS1 (II safety level)

Failure Scenario	p	$p(O)$	$p(E)$	Conditional probability	
Normal operation S0	≈ 0	≈ 0	0,05	$p(O S0) = 0$	$p(E S0) = 0$
ScenarioS1	10^{-6}	≈ 0	0,05	$p(O S1) = 0$	$p(E S1) = 0$
ScenarioS2	0,(3)	1	0,05	$p(O S2) = 0,5$	$p(E S2) = 0,5$

Table 7– Estimated probabilities for calculating the risks of accidents at projectDS2 (III safety level)

Failure Scenario	p	$p(\mathcal{O})$	$p(B)$	Conditional probability	
Normal operation S0	≈ 0	≈ 0	0,05	$p(O S0) = 0$	$p(E S0) = 0$
ScenarioS1	≈ 0	≈ 0	0,05	$p(O S1) = 0$	$p(E S1) = 0$
ScenarioS2	10^{-6}	10^{-6}	0,05	$p(O S2) \approx 0$	$p(E S2) \approx 0$

Since the object DS1 has survivability during the implementation of local damage from the scenario S1, the probability of significant damage is close to zero. The probability of failure in the S0 scenario is also close to zero, because the object during normal operation should have significant

safety margins. In the table 7 the probabilities of an accident for an object of level III safety are given. Object DS2 has survivability for all variants of emergency actions; therefore, the probability of the risk of an emergency in all cases is close to zero.

When calculating financial loss, the same conditions were taken into account as in example 1. During the operation of the structure, the costs of maintaining their operability were also taken into account. It was believed that the period of operation of the structure is 50 years, and the costs of maintaining the structure take place from the 5th year of operation and are equal to 8,000 cu per year. At the same time, the change in these costs over the years was taken into account. The results of the calculation of relative risks for the objects with the considered safety levels are presented in table 8.

Table 8 - Indicators characterizing the safety of design solutions

Project No.	Safety level	Relative operational risk			Relative risk during the construction phase			ζ_s
		$\frac{R(O)_{S0}}{C(O)}$	$\frac{R(O)_{S1}}{C(O)}$	$\frac{R(O)_{S2}}{C(O)}$	$\frac{R(E)_{S0}}{C(E)}$	$\frac{R(E)_{S1}}{C(E)}$	$\frac{R(E)_{S2}}{C(E)}$	
П4	I	6,3	159,8	159,8	4,3	4,3	4,3	338,8
П61	II	0	0	152	31,3	31,3	31,3	245,9
П62	III	0	0	0,1	50,4	50,4	50,4	151,3

The following legend is used in table: $R(O)_{S0}...R(O)_{S2}$ – the absolute values of the risks associated with financial losses resulting from failures at the operation stage according to scenarios S0-S2; $R(E)_{S0}...R(E)_{S2}$ – the same for the construction erection stage; $C(O)$ – the amount of capital investment, including the cost of the structure and the maintenance of its operability at the operation stage; $C(E)$ – the cost of the structure installation. The obtained structure options for the frame D4, DS1, DS2 are optimum in terms of cost-risk ratio at their safety level. Moreover, if we globalize the goal of minimizing possible risks, obviously we need to choose the project DS2. The cost of this option compared with the object D4, designed with the assumption of a significant risk in case of accidents, is 3 times higher.

Conclusions

1. A methodology for the calculation and optimum design of steel frame structures is proposed taking into account their safety level, including criteria for minimizing risks associated with possible key-elements failures leading to significant financial loss. The methodology is based on the joint application of the methods of evolutionary modeling and structural analysis subject to the constraints of ultimate conditions and survivability under emergency actions.

2. A proposal has been formed to classify the safety levels of structures, based on the calculation of the integral values of relative risk, taking into account the initial design reliability and the degree of survivability of the facility.

The considered example of the design of a steel frame confirms the operability of the proposed methodology and indicates that the design of structures of this type based on only the criterion of minimizing the cost can significantly reduce its level of safety both during normal operation and during accident conditions.

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