Optimization of steel frame building systems in terms of parameters and reliability requirements

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Abstract. The problem of ensuring safety and reliability of building structures in modern socio-economic conditions is especially urgent. An important aspect of this issue is to determine the rational costs of manufacturing the load-bearing systems. This should take into account the possible emergency situations and their consequences. The purpose of the present studies is to create a methodology for the optimal design of normally operated steel frames considering material and social losses from the possible failure of structural elements. A method for parametric optimization of steel frame systems during selection of rod cross-sections and structure reliability levels is developed. The problem is to minimize structure manufacturing costs and recover damage caused by any material and social losses in the event of possible malfunctions and damage. Constraints on the strength, stiffness, and stability of the frame have all been taken into consideration. A two-stage optimization scheme is proposed. The first stage includes several parametric optimization processes using a genetic algorithm with minimization of construction costs for various system load levels. Then the structure's reliability is assessed within a probabilistic formulation for each of the obtained parameter combinations. Eventually variant of the frame is selected based on the minimum sum of the manufacturing cost and the expected value of material and social losses possible during operation period of the structure, expressed in monetary terms. An example of optimum design of a spatial frame with personnel present in the areas of possible damage is considered.

The presented method allows implementing a comprehensive approach to optimum designing, while taking into account both the manufacturing cost and the possible failures of the constructive system.

1. Introduction
Structural design optimization is one of the growing areas of focus in construction science. Major advances in this sphere have been achieved on the basis of meta-heuristic schemes [1]. Great attention has been devoted to the application of genetic algorithms, which are an approach of evolutionary modeling. A number of studies towards an optimum search for various load-bearing structures with meta-heuristic algorithms took into consideration the reliability characteristics of objects [2-13]. This design concept is what is referred to as reliability-based design optimization (RBDO). Genetic algorithms [11], particle swarm method [10], a combination of Improved Differential Evolution and Single-Loop Deterministic Method [2], a combination of multiple response surface method-based...
artificial neural network and dynamic multi-objective particle swarm optimization algorithm [4], as well as other approaches, were used as tools to implement an optimum search in such problems. Among the load-bearing systems subjected to optimization were steel frames [2], hollow reinforced concrete beams [3], composite stiffened panels [6], steel tailor welded thin-walled structures [7], welded beams [8], and a number of other structures. The minimum weight of the structure [2, 11], minimum cost [8], increased reliability [9], in addition to other characteristics, were considered as objective functions. Various algorithms of multicriterial optimization have been developed as well [3, 4, 6, 7, 10, and others]. For example, in [3] an objective was set to minimize the initial cost of material production and construction, maximize the overall safety factor with respect to the ultimate limit states, and maximize the corrosion initiation time; while in [10] reliabilities are maximized and construction system cost is minimized.

A peculiarity of this paper is the selection of a rational reliability level during structure optimization. This level is determined with a coefficient that corrects the working capacity limitation of a designed structure. At the same time, total production expenditure is minimized, as well as compensatory damages for economic and social losses due to possible emergencies or damage during normal operations. Such an approach allows finding design solutions with economically feasible safety requirements within a single criterion optimization. We consider an example of a tower type supporting frame in a trade and storage building under conditions with the constant presence of people in potentially dangerous areas where load-bearing element failure is possible. The proposed optimization scheme may be considered a Rational Safety Search Strategy (RSSS) within the RBDO framework.

2. The formulation and method of solving the optimization problem

We consider standard steel frames of normal level of responsibility [14] and take into account their operation under ordinary conditions. Taking that the frame elements pertain to the first class of stress-strain state [15], where Von Misses stresses throughout the entire cross-section area do not exceed the design bending resistance of the material. The objective of the optimum design of the structure in RSSS may be formulated as

$$\tilde{N}_v(Y_s, \tilde{\lambda}) = (\tilde{N}_a + C_{zn}) \rightarrow \min,$$

(1)

where $\tilde{N}_v(Y_s, \tilde{\lambda})$ is a total cost function; $Y_s$ is a system of discrete sets of allowable rod cross-sections; $\tilde{\lambda}$ is a parameter used to control allowable stress and displacement values in the structural elements:

$$\tilde{R}_{zn} = \tilde{\lambda} R_{zn}, \quad \tilde{\delta} = \tilde{\lambda} \delta,$$

(2)

$\tilde{R}_{zn}, \tilde{\delta}$ are the corrected values of characteristic bending resistance and allowable displacements for the rod cross-section under consideration; $R_{zn}, \delta$ are the characteristic bending resistance and allowable structure displacement as per regulations; $\tilde{N}_a$ is the direct costs of the construction of the structure; $C_{zn}$ is the expected value of construction and repair works and indemnities of social damages due to possible failures. For the system of sets $Y_s$ the structural and technological requirements shall hold.

At that, limitations for the first and second group of limit conditions [15] have been taken into consideration in accordance with the allowable stress and displacement values as corrected with the coefficient $\tilde{\lambda}$ . We assume that analysis of the stress-strain state of the rod structures is performed with the finite element method within the framework of a displacement method based on design rod model. In a general case, we take tension-compression strain, bend in two main planes, and pure torsion into consideration when analyzing the rods. The influence of longitudinal forces on bending is taken into account, thus providing a check-up of overall stability of the rod system on the basis of
displacement limits [16]. There are provisions that the local strength and stability requirements are satisfied with the assignment of allowable rod cross-sections and additional local reinforcements of the variant resulting from the optimum structural design search.

Direct construction costs for the supporting frame of the structure are estimated with the dependence

\[ \tilde{N}_\alpha = (1 + k_1 + k_2) \sum_{i=1}^{n} c_i m_i, \]  

(3)

where \( k_1, k_2 \) are the coefficients that consider the operating costs of construction machinery and personnel payroll respectively; \( n \) is the number of the rods; \( c_i, m_i \) are the cost of a unit mass of material and the weight of the \( i \)-th rod.

The value \( C_{zn} \) is determined in the following way:

\[ \tilde{N}_{zn} = \sum_{m=1}^{m_0} Q_{Rm}(U_{Rm} + U_{pm}) , \]

(4)

where \( m_0 \) is the number of structural elements (rods, nodes, constraints, etc.), for which a possibility of failure or destruction is considered; \( Q_{Rm} \) is the probability of failure of an element \( m \) during normal operation of the structure; \( U_{Rm} \) is the amount of material damage compensation due to failure of the element; \( U_{pm} \) is the monetary value of social losses due to such failure.

The value \( Q_{Rm} \) is estimated via the following steps [17]:

1. For each structural element \( m \) a mathematical expectation is calculated for load-carrying capacity reserve \( \Delta_m \) and summarized mean-square deviation of random generalized load and resistance value for the material \( \delta_{\Delta m} \):

\[ \bar{\Delta}_m = \bar{L}_m - \bar{R}_{ym_m}, \delta_{\Delta m} = \sqrt{S_F^2 + S_R^2} , \]

(5)

where \( \bar{L}_m \) is a mathematical expectation of a load effect random component; \( \bar{R}_{ym_m} \) is a mathematical expectation of the characteristic bending resistance for such effect; \( S_F, S_R \) are mean-square deviations for load effect and the characteristic bending resistance of the material.

2. The reliability index \( \beta_m \) and the value of \( Q_{Rm} \) are calculated:

\[ \beta_m = \frac{\bar{\Delta}_m}{\delta_{\Delta m}}, \quad Q_{Rm} = 1 - (0.5 + \Phi(\beta_m)) , \]

(6)

where \( \Phi \) is Laplace's function.

The value of \( U_{Rm} \) is determined via the equation

\[ U_{Rm} = U_{tm} + U_{nm} + U_{rm}, \]

(7)

where \( U_{tm} \) is the cost of an element \( m \); \( U_{nm}, U_{rm} \) are respectively the cost of temporary guys, props and bracing, and the cost of works for replacements of the element.

The cost of the social losses due to failure in element \( m \) may be determined in the following way:

\[ U_{pm} = (\bar{N}_m + \bar{Z}_m)C_P , \]

(8)

where \( \bar{N}_m \) is a mathematical expectation of the number of people constantly working in the area affected by a possible failure of element \( m \); \( \bar{Z}_m \) is a mathematical expectation of the number of
bystanders in the affected area; $C_p$ is the legally defined average compensation of social injury per injured person.

Let us decompose the optimization problem by introducing a certain discrete set of values $\bar{\lambda}$: $\bar{\lambda} = \{\lambda_1, \lambda_2,...,\lambda_{i_0}\}$, where $i_0$ is the number of such values. For each $\lambda_i$, we apply evolutionary modeling to solve the intermediate optimization problem

$$\tilde{N}_a(Y_i) \rightarrow \min.$$  \hspace{1cm} (9)

Function $\tilde{N}_a(Y_i)$ is then minimized with the help of the genetic algorithm scheme presented in [18], which applies combined approaches to the operations of selection and mutation. This computational procedure for an optimum search provides a high accuracy of solutions on discrete sets of parameters without distorting the objective function with penalty functions to factor in the limitations. Next, a search is performed with respect to the value $i:\n
$$\tilde{N}^{(i)}_V = \left(\tilde{N}^{(i)}_a + C^{(i)}_{zn}\right) \rightarrow \min,$$  \hspace{1cm} (10)

where $\tilde{N}^{(i)}_a$ is the value of $\tilde{N}_a$, achieved during optimization of the value of $\bar{\lambda}_i$; $C^{(i)}_{zn}$ is the cost of $C_{zn}$, corresponding to the parameters of the cross-sections obtained in the optimization.

3. Results of optimum design

RSSS was used to optimize the space frame of the tower type supporting frame (Fig. 1,a) of a civil building with a retail warehouse function. The rods of the structure were manufactured in steel with a characteristic bending resistance of $R_{sm} = 245 \text{ MPa}$. A uniformly distributed load of $q = 6.15 \text{ kPa}$ was factored in. A set $\bar{\lambda} = \{0.7; 0.85; 1.15; 1.3\}$ was considered. The numbers of personnel and construction machinery used during construction are usually defined in the Work Execution Plan. Thus, the shares of costs $k_1$ and $k_2$ in this case may be assumed approximately with consideration for the relevant values of shares of costs taken from the Work Execution Plans with similar structural systems and erection methods. Based on experience with similar structures in Bryansk, we took: $k_1 = 0.2$; $k_2 = 0.35$. The average price of universal sheet metal was considered at the level of current prices as 650 conventional units/tn. Uniform divisions of rods into finite elements were introduced. Each column was separated into 5 finite rod elements, and each beam into 12 elements. The search for structural elements of the frame was performed in the set of 18 combinations of different cross-sections of rectangular welded tubular rods (Fig. 1,b), shown in Table 1. The rods were grouped, and their cross-section was considered the same within a group. Grouping of the structural elements is shown in Fig. 2,a. The results of the facility synthesis for each value of $\bar{\lambda}$ are given in Table 2.

When determining costs $C_{zn}(Y_i)$ we assumed that the random values of characteristic bending resistance and load are normally distributed. Sample sets of 20 instances were considered for these random values. Statistic data of strength testing of structural elements are taken from H-section certificates provided by their manufacturer. The dispersion $S_{sm} = 7.8 \text{ MPa}$ was calculated from these values. Load dispersion calculations modeled a situation where the frame underwent 20 steps of loading with a diverse set of goods with a total weight corresponding to the average working load of 2.9 kPa. Statistical treatment resulted in the value of $S_q = 0.3 \text{ kPa}$.

For each structural element $m$ the cost of temporary guys, props and bracing, and the cost of repair works were estimated from the prices of contractors employed in Bryansk for construction and repair work in similar facilities with the help of the following equations: $U_{unm} = 0.05 U_{um}$; $U_{im} = 0.4 U_{um}$. When estimating the monetary values of social injuries, it was assumed that the process (packaging of products) within the frame during its normal operation requires the constant presence of 2 employees in each of the 4 cells (see Fig. 1,a).
Figure 1. Structure, fastening, and loading schemes of a space frame (a); rod cross-section (b): 1 – pillars; 2 – cross-beams; 3 – floor slab

Table 1. Characteristics of variate parameters

| Designation of the size combination | Cross-section (cm) | Designation of the size combination | Cross-section (cm) |
|------------------------------------|--------------------|------------------------------------|--------------------|
|                                    | $d_1$  | $d_2$  | $t_1 = t_2$ | $d_1$  | $d_2$  | $t_1 = t_2$ |
| $T_1$                              | 14.4   | 16     | 0.2        | $T_{10}$ | 48.6   | 55     | 0.6     |
| $T_2$                              | 18     | 20     | 0.2        | $T_{11}$ | 50     | 60     | 0.7     |
| $T_3$                              | 23     | 25     | 0.2        | $T_{12}$ | 60     | 70     | 0.8     |
| $T_4$                              | 28     | 30     | 0.2        | $T_{13}$ | 60     | 80     | 0.9     |
| $T_5$                              | 32.6   | 35     | 0.3        | $T_{14}$ | 80     | 100    | 1       |
| $T_6$                              | 37.6   | 40     | 0.3        | $T_{15}$ | 80     | 120    | 1       |
| $T_7$                              | 38     | 40     | 0.3        | $T_{16}$ | 100    | 140    | 1.2     |
| $T_8$                              | 40.2   | 45     | 0.4        | $T_{17}$ | 100    | 160    | 1.2     |
| $T_9$                              | 43.6   | 50     | 0.5        | $T_{18}$ | 120    | 180    | 1.2     |

Table 2. Optimization results for different values of $\tilde{\lambda}_i$

| $i$ | $\tilde{\lambda}_i$ (Thousand conventional units) | $C^{(i)}_u$ | Rod cross-section by group |
|-----|---------------------------------------------------|-------------|---------------------------|
| 1   | 0.7                                               | 4.947       | $T_1$ $T_3$ $T_6$ $T_9$ $T_{11}$ $T_1$ $T_1$ |
| 2   | 0.85                                              | 3.803       | $T_6$ $T_5$ $T_7$ $T_8$ $T_{10}$ $T_1$ $T_1$ |
| 3   | 1                                                 | 3.343       | $T_1$ $T_2$ $T_3$ $T_8$ $T_{10}$ $T_1$ $T_1$ |
| 4   | 1.15                                               | 3.144       | $T_6$ $T_3$ $T_3$ $T_7$ $T_9$ $T_1$ $T_1$ |
| 5   | 1.3                                               | 2.960       | $T_5$ $T_1$ $T_3$ $T_7$ $T_9$ $T_1$ $T_1$ |
Unnecessary people are restricted from entering the working area. For these conditions, the values are $\overline{N}_m = 2$, $\overline{Z}_m = 0$. The value of $U_{pn}$ was assumed as being equal to 14,286 conventional units/person (1,000,000 rubles/person), with considerations for actually paid compensations referenced in the law of the Russian Federation [19, item. 2,e].

Results of costs $\hat{N}^{(i)}_a$, $C_{cr}(Y_i)$, $N^{(i)}_v$ estimation for the variants of the structure are given in Table 3. The minimum value of the target function $\hat{N}_v$ is achieved when $i = 3$ ($\lambda_i = 1$). The variant of the frame corresponding to $\lambda_i = 1$ is shown in Fig. 2.b.

**Table 3. Results of cost estimation**

| $i$ | $\hat{N}^{(i)}_a$ (Thousand conventional units) | $C_{cr}(Y_i)$ (Thousand conventional units) | $N^{(i)}_v$ (Thousand conventional units) |
|-----|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|
| 1   | 4.947                                         | 0.009                                         | 4.956                                         |
| 2   | 3.803                                         | 0.0329                                        | 3.836                                         |
| 3   | 3.343                                         | 0.111                                         | 3.454                                         |
| 4   | 3.144                                         | 0.321                                         | 3.466                                         |
| 5   | 2.960                                         | 0.597                                         | 3.557                                         |

**Figure 2.** Grouping and orientation of the rod cross-sections (a); Results of optimum design of the frame from the rod cross-section selection (b): I-VII are rod group designations; $T_1$-$T_{10}$ are numbers of cross-section size combinations

4. **Discussion**

The proposed approach to RBDO allows taking into account the factor of feasible structure reliability selection from an economical point of view, and may serve as a tool for improvement of regulatory requirements for building structures. Further studies shall make possible gathering information on random loads acting upon construction systems; mechanical characteristics of materials; amount of monetary compensation for social damages; processes requiring the presence of personnel in areas of possible failure; the effects of failure on people in the failure-affected areas.
5. Conclusions
A strategy of parametric optimization of building structures has been developed, which varies reliability level and parameters of the supporting system to minimize the costs of the structure with considerations for building cost, together with social and economic losses from possible failures under normal operating conditions. An algorithm is proposed for performing such optimization for steel frame structures via the help of an evolutionary calculation procedure. Performance of this optimization procedure has been illustrated with the example of a space frame of an industrial building retail warehouse.

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References
[1] Magalhães-Mendes J, Greiner D 2015 Evolutionary Algorithms and Metaheuristics in Civil Engineering and Construction Management. Springer International Publishing AG p 127
[2] Linh A, Le T, Bui-Vinh V, Ho-Huu T N 2017 J. of Constr. Steel Res. 138 pp 389–400
[3] Garcia-Segura T, Yepes V, Frangopol D M, Yang D Y 2017 Eng. Struct. 145 pp 381–391
[4] Song L, Fei C, Wen J, Bai G 2017 Aerospace Sc. and Techn. 64 pp 52–62
[5] Hao P, Wang Y, Liu C, Wang B, Wu H 2017 Comp. Meth. in Appl. Mech. Eng. 318, pp 572–93
[6] Liu Y, Jeong H K, Collette M 2016 Comp. & Struct. 177 pp 1–11
[7] Song X, Sun G, Li Q 2016 Thin-Walled Struct. 109 pp 132–142
[8] Meng Z, Zhou H, Li G, Yang D 2016 Comp. & Struct. 175 pp 65–73
[9] Mella M A, Zio E 2016 Reliab. Eng. & Sys. Saf. 152 pp 213–227
[10] Zhang E, Chen Q 2016 Reliab. Eng. & Sys. Saf. 145 pp 83–92
[11] Kumari J R, Valsarajan K V 2016 Int. J. of Eng. Res. Dev. 12 pp 01–06
[12] Lopez R H, Torii A J, Fleck L, Miguel1 F, Eduardo J, De Cursi S 2015 Mech. & Ind. 16 p 603.
[13] Kharmanda G, Mothsine A, Makloufi A, El-Hami A 2008 Int. J. Simul. Multidisci. Des. Opt. 2 pp 11-23
[14] SP 16.13330.2017 Steel structures. Rulebook. The updated version of SNiP II-23-81* (approved by the order of the Ministry of Construction and Housing and Communal Services of the Russian Federation of February 27, 2017 No. 126 / pr)
[15] Raizer V D 2009 Reliability of Structures: Analysis and Applications Backbone Publishing Company p 146
[16] Raizer V D 2009 Reliability of Structures: Analysis and Applications Backbone Publishing Company p 146
[17] Serpik I N, Alekseytsev A V 2016 Magazine of Civ Eng. 1 (61) pp 14–24
[18] Serpik I N, Alekseytsev A V, Balabin P Y 2017 Period. Polytech. Civ. Eng. 61 (3) pp 471-482
[19] Rules for allocating a budget from the reserve fund of the Government of the Russian Federation for the prevention and liquidation of emergency situations and consequences of natural disasters. As revised by the Government of the Russian Federation, 2015