Mathematical and computer modeling in the design of steel rod structures

A Vasilkin
Moscow State University of Civil Engineering, Yaroslavskoye Shosse, 26, Moscow, 129337, Russia

e-mail: Vasilkinaa@mgsu.ru

Abstract. The article considers the problem and search solution of an optimal variant of the design of steel structures based on the use of computer technology and mathematical modeling. As a method of search of the optimal solution, the method of parametrical optimization is used. The application of the method is illustrated on the example of a flat rod design - a truss construction. The variable parameters were selected to build a grugh for changing the target function. The novelty of the study lies in the fact that as a criterion of optimality, the cost of its production was adopted, at that time, how often is the weight of the structure taken. As a result of the conducted research it was found that the difference in production cost at application of different types of outlines of belts makes up to 20%. For criteria of an optimality metal consumption and production cost were received various versions of the optimal solution that tells about the important role of the chosen criterion and the need of the accounting of bigger quantity of elements to compose the optimality criterion. Efficiency and expediency of use of computer technologies to design steel structures is shown. That gives the engineer necessary information for adoption of reasonable design decisions on the basis of the analysis of alternative options.

1. Introduction
One of important components of a problem of design of building constructions is process of synthesis and the choice of the design decisions meeting the set conditions. It is known that poor quality of design decisions is economically inefficient and influences on safety of functioning of a designed object [1].

In order that the choice of the design decision was based not only on an intuition and experience of the designer, but also on some quantitative and quality indicators, it is necessary to define criterion for the choice of option. Besides, synthesis of alternatives is characterized by existence of various restrictions narrowing area of admissible values which can be expressed as accurately formulated requirements or conditions. At a small amount of restrictions, it is possible to receive a set of versions of alternative decisions, each of which will be admissible that will increase the choice options of the designer. Comparing admissible design decisions any quantitative assessment, it is possible to choose the most effective decision.
2. Problem statement

In technical literature, the similar tasks are known as problems of optimum design [2,3], alternative design [4,5,6], management of behavior of building constructions [7]. Process of optimum design consists in the choice of one effective decision from a number of admissible decisions [8] by method of parametrical optimization - when specialists carry out search of such parameters of a design which use allows to receive extreme values of the criterion function [9,10,11] or structural optimization consisting in search of optimum topology [12,13].

The traditional approach at design of steel building constructions consists in synthesis of an initial design and its consecutive improvement in the relation of some indicator called criterion of optimality. Most often metal consumption is used as similar criterion to design steel structures [14,15], however, the more components of the criterion the objective function takes into account, the more global the extremum will be.

When using a method of parametrical optimization, the area of admissible values depends on complexity of criterion of an optimality [16] and quantity of variables of design [17,18] therefore at increase of them both we expand the field of search for the optimal solution.

This article is about the task to find the optimal design solution of a flat rod design - a rafter truss, by method of parametrical optimization, by criterion of an optimality "the production cost".

The rafter trusses represent the rod design pivotally connected in knots pivotally (conditionally) and are used as the bearing designs for the organization of overlapping and a covering of buildings. On the basis of constructive use the trusses can be light or heavy.

The trusses can be classified by an outline of belts, according to the static scheme, and lattice system.

One of the most significant signs for division of trusses into separate types is the outline of belts on which influences on metal consumption and labor input of production depends.

3. Methods and results of the study

Designs of steel farms have to meet the following conditions:
- durability requirements;
- stability requirements;
- rigidity requirements
- dimensional restrictions for the determined design parameters (maximum length, possibility of transportation across public roads);
- classes and brands of steel are limited to norms of design depending on the area of construction and working conditions;
- the restrictions caused by requirements of production, installation or operation of a design.

Conditions of durability are included into the mathematical description of a problem in the form of inequalities. A condition of durability of the stretched truss elements:

\[ R_y f - N/A \geq 0 \]  

where \( R_y \) - the settlement resistance of steel on compression, stretching, and bending; \( f \) - working condition coefficient; \( N \) - longitudinal force; \( A \) - cross-sectional area.

Condition of stability of the compressed farm elements:

\[ R_y f - N/\varphi A \geq 0 \]

where \( \varphi \) - stability coefficient at compression.

Condition of extreme flexibility:
- for the stretched elements (belts and braces) \( [\lambda = 400] \) (static loading);
for the compressed elements (belts and basic braces) \([\lambda = 180 - 60\alpha]\) and \([\lambda = 210 - 60\alpha]\) 
(other compressed braces). The problem of obtaining the optimal solution can be expressed in the following mathematical view [2]:

It is necessary to minimize function \(f_i(x), x \in R, (i = 1, 2, 3, \ldots, N)\)

Provide that

\[h_j(x) = 0, \quad (j = 1, 2, 3, \ldots, J)\]

\[g_k(x) \leq 0, \quad (k = 1, 2, 3, \ldots, K)\]

where \(h_j(x) = 0, \quad g_k(x) \leq 0\) – restrictions of a task in the form of equalities and inequalities, are function of field of design \(x = (x_1, x_2, \ldots, x_n)\).

The sum of cost of steel and cost of production was accepted in this research as criterion of an optimality so criterion function has the following appearance:

\[C_f = C_m + C_p = C_m + K_1T_1 + C_c\]

\[C_s \rightarrow \min\]

where, \(C_f\) - factory cost; \(C_m\) - cost of materials; \(C_p\) - production cost; \(T_1\) - labor input of production: \(T_1 = f(G, n)\); \(n\) - number of details, welded seams, openings etc.; \(K_1\) - constant coefficient; \(C_c\) - the expenses which are not depending on labor input of production. We will set on the following variable parameters of a design of a truss (tab. 2).

### Table 1. Design parameters

| Target function | Production cost |
|-----------------|----------------|
| Limitations     | 1. Class C245 steel |
|                 | 2. Hinged fixing of a truss with a column |
|                 | 3. Geometrical sizes (span. height, distance between elements). |
|                 | 4. Lattice type |

### Table 2. Variable Truss Design Options

| Variable options | Values |
|------------------|--------|
| Type of section of elements | Hot-rolled angle in accordance with GOST 8509-93 (coupled angle) |
|                   | Seamless hot-rolled pipe in accordance with GOST 8732-78 (round pipe) |
|                   | Closed welded square steel bent Profile in accordance with GOST 30245-2003 (a bent profile) |
| Type of outline of the truss | Parallel belt truss |
|                            | Trapezoidal truss |
|                            | Segment outline truss |

### 4. Numerical experiment

The truss span is 30 m, value of evenly distributed loading (snow + actual) \(q = 3.3\) kN/m.

The optimal solution of a task has to meet the following conditions: the minimal weight of a design with standard restrictions on durability, stability, extreme flexibility, according to norms and the varied values of design parameters.

Process of synthesis of design solutions of the projected design is presented in fig. 1.
Building a settlement system with accepted parameters
Design calculation
Determination of the mass of the structure
Determination of the cost of the construction
One step change of variable parameters
Comparison of objective function values for alternative design solutions
Main value selection

**Figure 1.** Scheme of design

The general view and size of the trusses – see Figure 2.

**Figure 2.** Constructive scheme of trusses: a - general view, b - settlement scheme

For the solution of a task, there were made mathematical models of the studied design on the basis of system of parameters and the accepted restrictions at the chosen options of criterion of optimization. Using specialized settlement programs LIRA there was executed selection of sections of trusses for each design option, their weight and the production cost were also determined [19]. According to the accepted parameters there were considered 9 alternatives of designs.

The results of calculations are presented in tab. 3, and charts in fig. 3 and 4.
Table 3. Design cost

| No | Type of truss outline | Section type | Weight t | Surface, sq. m | Development of metal detailing structures | Production cost | Corrosion protection | Cost of metal | TOTAL |
|----|-----------------------|--------------|----------|----------------|------------------------------------------|----------------|---------------------|--------------|-------|
| 1  | Polygonal form        | Coupled corner | 3.85     | 112.3         | 5 500                                    | 91 500         | 9 600               | 226 372     | 332 972|
| 2  | Polygonal form        | Steel bent profile | 3.01 | 63.0 | 3 380 | 80 600 | 5 450 | 159 407 (52 959 rub / t) | 226 372 | 332 972|
| 3  | Polygonal form        | Seamless hot-rolled pipe | 2.99 | 54.6 | 3 148 | 125 700 | 4 830 | 291 840 (97 507 rub / t) | 248 837 | 425 518|
| 4  | Trapezoidal form      | Coupled corner | 3.92     | 105.7         | 5 200                                    | 97 300         | 9 140               | 232 344     | 343 984|
| 5  | Trapezoidal form      | Steel bent profile | 3.28 | 67.3 | 3 650 | 83 220 | 5 800 | 177 620 (54 168 rub / t) | 232 344 | 343 984|
| 6  | Trapezoidal form      | Seamless hot-rolled pipe | 3.08 | 53.1 | 3 140 | 130 670 | 4 670 | 294 650 (95 790 rub / t) | 232 344 | 343 984|
| 7  | Form with parallel belts | Coupled corner | 4.00     | 101.4         | 4 890                                    | 95 000         | 8 700               | 251 670     | 360 260|
| 8  | Form with parallel belts | Steel bent profile | 3.55 | 70.0 | 3 880 | 90 000 | 6 040 | 199 763 (56 287 rub / t) | 251 670 | 360 260|
| 9  | Form with parallel belts | Seamless hot-rolled pipe | 3.27 | 55.2 | 3 295 | 137 960 | 4 860 | 311 433 (95 356 rub / t) | 251 670 | 360 260|
Figure 3. Changes of mass in parameters of trusses

Figure 4. Change of total cost in parameters of trusses
The analysis of the charts received on the basis of use of computer technologies and specialized computing programs allows to make the following conclusion. By criterion of metal consumption the most effective are all types of trusses with a round pipe section, with an optimal variant at a polygonal type of an outline of belts. As expected, the trusses with the coupled angled section are the heaviest. Sections with a pipe section and steel bent profiles are equivalent for a case of polygonal trusses. Also, the chart shows that within each type of an outline there is decrease in weight in the following direction "coupled angle" - "steel bent profiles" - "pipe".

However, the fuller criterion (factory cost) demonstrates that the trusses with steel bent profile section are the most economic, on the second place there are sections of the coupled angle and the trusses with round pipe sections are the most expensive.

The form of coupled angled section shows that the difference in total cost between a polygonal truss and a truss with the parallel belts is 8.2%, and the difference between a trapezoidal truss and a truss with parallel belts is 4.7%.

The form of steel bent profile section shows that the difference in total cost between a polygonal truss and a truss with parallel belts is 20.4%, and the difference between a trapezoidal truss and a truss with parallel belts is 10.9%.

The form of pipe section shows that the difference in total cost between a polygonal truss and a truss with parallel belts is 7.5%, and the difference between a trapezoidal truss and a truss with parallel belts is 5.6%.

5. Conclusion

Problems of search of constructive solutions for building constructions with the minimum cost are still urgent [20,21]. Use of computer technologies and mathematical modeling while working with the optimizing tasks allows to accelerate design process and reduce labor input of works.

So, as a result of the conducted research it was determined that the variation of different types of outlines of belts leads to a difference in production cost up to 20%. The most effective design option for metal consumption, i.e. the minimum metal consumption, becomes the most expensive one by criterion of cost of production. That is, the optimality of versions of design decisions depends on completeness and complexity of criterion of optimization. Seeking for receiving a global minimum it is expedient to consider the combined indicators in criterion.

The further development of this methodology is automation of search process [14,17] that will allow to analyse a bigger quantity of versions of design decisions while having small expenses of resources and time.

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