ALGORITHMIZATION OF CAD SYSTEMS FOR OPTIMIZATION OF SHELL STRUCTURES

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***Abstract**. The paper presents the theoretical prerequisites and principles for constructing computer-aided design systems for solving classes of optimization problems for shell structures. Improving the methods for solving optimization problems is supposed to be the algorithmization of optimization models and algorithms for building an automated system for designing shell structures based on a systematic approach and algorithmic methods. On the basis of a systematic approach, questions of the internal organization of such systems, the functions of individual blocks and modules, end-to-end automation of the process of solving optimization problems from setting to obtaining numerical results are investigated. The results of the calculation of the optimization of a cylindrical shell, rectangular in plan, hinged along the entire contour, under a uniformly distributed normal load, are presented.*

***Keywords.** System analysis, algorithmization, optimization, design, construction, shells, plates, model, goal function, minimization, construction weight.*

Introduction. When setting optimization problems in the field of designing shell and plate structures, one can come across a twofold interpretation (understanding) of system analysis (approach): on the one hand, this is an analysis of any real-life system; on the other hand, the formation of system parameters to achieve the set goals. In real conditions, these two sides are inseparable, since it is impossible to create a system that provides the set goals without analyzing the content and determining the real processes that will lead to the desired result. System analysis provides conditions for joint optimization of both the structural parts of the system (its subsystem) and the system as a whole, as well as computer software. The ultimate goal of using systems analysis in design is to actually design the system, its subsystems, and components for optimum efficiency and economy. Despite the fact that there are no strictly defined rules in system analysis, the main features are quite fully disclosed in [5].

Research methods and principles. Taking into account the specifics of the process of designing shell and plate structures and the tasks to be solved, the main features of the system approach can be displayed in the following provisions [6]. Firstly, as an optimized designed shell and plate structure, a certain complex of elements corresponding to the performance of functions, endowed with specified properties and having abstract connections with external conditions and systems, is taken. In this complex, in the process of research, each element can be given the desired properties without taking into account the real characteristics in order to identify the possible contribution of these properties to the processes under study and, therefore, to justify the requirements for the prospective solution of this element. In practical optimization problems, it is assumed that the properties of the elements and their functional and technical characteristics are known, and therefore the functioning processes are considered in the area of admissible (taking into account the accepted restrictions) system solutions. Both in the first and in the second, as well as in the case of software (development of algorithmic complexes), the assessment of the complex under consideration is carried out taking into account the totality of known processes and phenomena and the relationship between them. All this brings to the fore such features of the model of engineering structures and structures being designed, which contribute to the elucidation of the mechanism of functioning of this complex in order to select the least weight or cost. At the same time, it should be noted that in all cases the system includes the concept of a whole, consisting of interconnected, interacting and interdependent parts. At the same time, the properties of these parts depend on the system as a whole, and the properties of the system depend on the properties of its parts.

Secondly, for a particular designed shell and plate structure, a place in the overall structure of other systems must be determined. The system approach requires a reasonable allocation of the system under study in the total composition of systems designed to maintain normalizing parameters, dividing it into subsystems.

Structures or structures are constituent or main elements, which are shells or plates, are considered as an independent object of study and optimization, but taking into account the necessary exchange of information with adjacent and external systems and within it - between subsystems.

The chosen general structure of systems should clearly outline the boundaries of the system under study and contribute to the selection (structuring) of its subsystems that are accessible for research in size and are homogeneous in description. All this ensures the organization of links at each next level of descent from the system to individual elements from top to bottom, followed by the transfer of the received aggregated information to the top (bottom to top). At the same time, both the general structure of compensation systems and the subsystems of structures and structures should be inherent in the properties of integrity: changes that have arisen in any of their parts affect both other parts and their entirety.

Thirdly, the engineering structure or structures are presented as a model. When designing complex systems, such as engineering structures and structures such as plates and shells, knowledge is required about the quantitative and qualitative patterns of behavior of the system and its individual elements, depending on the nature of the change in numerous factors (parameters).

The model should be similar to the original, but also different from it. Its distinctive features are manifested in the fact that it undergoes such transformations in the right direction that are impossible with a direct study of the original. Mathematical modeling allows you to study only those parameters of the original that have a mathematical description that adequately reflects the behavior of the original.

When developing a model, it is very important to get rid of connections and relationships that make it difficult to know the object of research in accordance with the goals set. At the same time, it is important that ideas that are clear in their basis are not overgrown with heavy and cumbersome details.

The choice of the model is the central part of the work on the formation of the research methodology and depends on the main idea that determines the search for the extremum of the goal function.

To solve a number of optimization problems, well-known mathematical methods for finding the extremum of functions of several variables can be applied, for example, in classical mathematics this is the solution of a system of linear equations obtained by equating to zero the partial derivatives of the function under study with respect to the parameters being optimized, and the Lagrange method of indefinite multipliers. These methods are valid in the absence of restrictions on the parameters being optimized or under restrictions in the form of equality.

With restrictions in the form of inequality, methods of nonlinear mathematical programming are used, subdivided according to the basis of the organization of the search process according to the method of blind and directed search. The first of these includes the method of continuous enumeration of options with their ordering according to efficiency criteria and the method of statistical tests (Monte Carlo method). The directed search method includes gradient, steepest descent, coordinate descent, etc. There are other non-linear programming methods.

Ultimately, the choice of method is determined taking into account many considerations, not least of which is the convenience of using the algorithm, the duration of the calculation, etc. It is also obvious that problem solving requires informal actions, the ability to intervene in the counting process and obtain intermediate results for the implementation of the dialogue mode.

It is known [5] that the choice of a model largely depends on intuition, experience, skills of informal thinking, on ideas about the essence of the relationship between inputs and outputs for the system itself. In this case, first of all, it is necessary to clarify the tasks, the solution of which should contribute to the model. When setting this problem, the model should provide: a) the possibility of generalizing any initial conditions (factors) into such a form of calculation information that greatly facilitates the targeted choice of competing options for structures and structures, the composition of subsystems and their modes of operation (SAT); b) study of the nature of the relationship between the determining parameters of systems and subsystems, depending on the conditions of the object's functioning; c) representation of the defining parameters in the form of coordinates of the state of the system, the use of which makes it possible to calculate any technical and economic indicators, both of a separate subsystem and of the system as a whole.

The model of construction and structure can be determined by the condition of the relationship of inputs and outputs for the system itself. It is practically impossible to get by with one model; a system of models is needed - a set of interrelated models of individual subsystems. The system of models should create the possibility of independent solution of individual problems without violating their subsequent coordination, taking into account all the links between subsystems.

Fourth, a set of indicators is selected to assess the quality of solutions for the designed structures and facilities. As a rule, the goal of system analysis is to achieve the best (optimal) solution of the designed structures and structures for all possible characteristics of external relations in terms of their design, economic and other indicators. However, optimum and optimality are not absolute concepts; they require a precise definition of optimality criteria, i.e. the main features on the basis of which the comparison of the effectiveness of various solutions is made.

A solution that is best under one set of conditions and according to one criterion may not be the best under other conditions and according to another criterion. Optimization by one criterion (sub-optimization) is most often performed for technical systems at reduced costs and (in this study, the weight of the structure is taken as the objective function).

Fifthly, the results of analysis on models of structures and structures should be transferred to real systems. To transfer solutions to a real object, confidence in the adequacy of the solution is required. Adequacy is assessed by analogy of the properties of the real object and the model according to the main features.

Adequacy is achieved if the model fully reflects the stress-strain state (SSS) of actually existing designed structures and structures such as plates and shells.

The main provisions of the systematic approach listed and accepted for execution characterize only the initial basis of the method, however, the effectiveness of its use depends entirely on the chosen method of their implementation.

To systematize and generalize information about the main features of system analysis, which contribute to the presentation of disparate data in an orderly manner with a smaller number of significant variables, it is necessary to: systematize the relationship between systems designed to maintain normalized parameters; analyze numerous initial conditions, find a form of their generalization; suitable for classifying the defining conditions of the VAT system; identify an appropriate classification of a structure or structure that contributes to the targeted choice of their competing options; to determine the principles of decomposition of systems, based on the analysis of their totality as a whole; formulate the initial basis for constructing a mathematical model of a structure or structure; classify optimization problems arising in the practice of research and design.

Problem statements. Optimization and design of engineering structures is one of the most complex and urgent tasks of mechanics. When optimizing structures, the weight of the structure, cost, vibration frequency, etc. are taken as the objective function. The most widely posed is the task of designing structures of minimum weight, which are widely used in such sectors of the national economy as construction, rocket science, aircraft building, shipbuilding, etc. Solving a number of practically important problems in the calculation and optimization of shell and plate structures allows you to get a significant national economic effect. The results obtained can be successfully applied in the construction of subways in a seismically active zone, as well as in the construction of important surface and underground structures [2].

Weight optimization of engineering structures such as plates and shells provides for minimizing the weight of these structures when exposed to given systems of external forces, while maintaining the necessary strength, stability, and rigidity of structures.

The task in general is written as follows:

$$F(x) = G \to \min; \ \sigma_{max} \leq [\sigma]; \ P_{max} \leq P_{kp}; \qquad (1)$$

where G is the weight of the structure; σ_{max} is the maximum stresses in the structure; [σ] - allowable stresses; P_{max} - maximum compressive force; P_{kr} - critical force; U_{max} - maximum displacements in the structure; [U] - allowable displacements.

Verification of constraints (1) is possible only after solving the system of differential equations of equilibrium or motion of the structures under consideration with the corresponding initial or boundary conditions. Let us consider in more detail the methods for solving the direct problem of calculation.

It is known that the equations of equilibrium, vibration and stability of anisotropic plates with respect to moments, respectively, have the form [1]:

Известно, что уравнения равновесия, колебания и устойчивости анизотропных пластин относительно моментов соответственно имеют вид [1]:

$$\frac{\partial^2 M_1}{\partial x^2}+2\frac{\partial^2 M_{12}}{\partial x \partial y}+\frac{\partial^2 M_2}{\partial y^2}=q_1(x,y) \quad , \qquad (2)$$

$$\frac{\partial^2 M_1}{\partial x^2}+2\frac{\partial^2 M_{12}}{\partial x \partial y}+\frac{\partial^2 M_2}{\partial y^2}+h\left(\sigma_x\frac{\partial^2 W}{\partial x^2}+\sigma_y\frac{\partial^2 W}{\partial y^2}+2\sigma_{xy}\frac{\partial^2 W}{\partial x \partial y}\right)=0 \quad , \qquad (3)$$

$$\frac{\partial^2 M_1}{\partial x^2}+2\frac{\partial^2 M_{12}}{\partial x \partial y}+\frac{\partial^2 M_2}{\partial y^2}+m\frac{\partial^2 W}{\partial t^2}=q_2(x,y,t) \quad . \qquad (4)$$

Here W is the deflection of the plate, M_1, M_{12}, M_2 are the bending and torque moments, $m = \gamma\, h/g$, γ is the weight of a unit volume, g is the acceleration of attraction of the plate, h is the thickness.

The relations for M_1, M_{12}, M_2 in cases where the plates are isotropic, orthotropic and anisotropic are given in [1]. Substituting into (2), (3) the relations M_1 , M_{12} , M_2 in the case when the plate is isotropic, orthotropic or in other cases of anisotropy, one can obtain the corresponding equations. These equations are given in many manuals on the theory of elasticity. Therefore, it is not necessary to present their form here.

In this regard, to solve the direct problem of the statistical calculation of arches and axisymmetric conical shells, we used the finite difference method. To calculate an open cylindrical shell, the Ritz method was used, since the finite difference method in this case leads to an overly cumbersome system of algebraic equations, which causes serious difficulties both in solving the direct problem and in optimizing open cylindrical shells [2,3].

Purpose function:

$$F(x)=\int_{\alpha}\int_{\beta} h(\alpha,\beta)\,Rd\alpha d\beta \quad (5)$$

For non-closed shells of the vault type, the following are considered given: a) boundary conditions; b) the length of the overlap - *a*; c) overlap width - *b*; d) shell material: *E* - modulus of elasticity; *ν* - Poisson's ratio; *γ* - specific gravity; *[σ]*- allowable stresses; *[U]* - allowable displacements (if it is required to comply with restrictions on strength and rigidity); e) system of external loads; f) other restrictions (for example: design, technological, etc.), if their satisfaction is required.

Results and discussion. Let us present the results of the calculation of the problem of optimizing a cylindrical shell, rectangular in plan, hinged along the entire contour, under a uniformly distributed normal load of intensity *q*. The shell thickness is constant *h=const*. Physical characteristics of the shell material:

$E = 2\cdot 10^6$ kg/sm^2;

$[\sigma] = 2000$ kg/sm^2;

$\nu = 0{,}5$.

Geometric characteristics of the shell: *a*=150 *sm*; *h*=100 *sm*, load *q*=1 *kg/sm*^{2}. Optimized parameters *h*, β_0. Parameter restrictions:

$$0{,}1\text{см} \le h \le 3\text{см}$$

$$\frac{\pi}{10} \le \beta_0 \le \pi.$$

The function to be minimized is the cross-sectional area

$$S = R \cdot h \cdot \beta_0.$$

There are restrictions on the design:

$\sigma_i \le [\sigma]$,

where σ_i is the stress intensity determined by the (6)

$$\sigma_i = \sqrt{(\sigma_{11}-\sigma_{12})^2+(\sigma_{22}-\sigma_{33})^2+(\sigma_{33}-\sigma_{11})^2+6\tau_{23}^2} \qquad (6)$$

Voltages σ_{11}, σ_{22}, σ_{33}, σ_{23}, σ_{23} are determined after solving equations (6) by the Ritz method. Beam functions are chosen as coordinate functions, which in the case of hinged support of the shell have the form

$$U_{nm} = \cos\frac{n\pi\alpha}{\alpha_0}\sin\frac{m\pi\beta}{\beta_0};$$
$$V_{nm} = \sin\frac{n\pi\alpha}{\alpha_0}\cos\frac{m\pi\beta}{\beta_0};$$
$$W_{nm} = \sin\frac{n\pi\alpha}{\alpha_0}\cos\frac{m\pi\beta}{\beta_0} \qquad (7)$$

Optimization is carried out using the GP-3 algorithm with an accuracy of ε≈2% [4]. The calculation results are given in Table. 1 one.

Table 1

Optimization Calculation Results

In lok. min.	*S, sm*^{3}	*h, sm*	β_0*, radian*	σ_i *,kg/sm*^{2}	Steps
1	125,0179	0,956369	2,467197	1990	52
2	126,6418	1,125607	1,662033	1977	28
3	114,072	0,8343	2,6613	1989	39
4	165,1633	1,53425	1,320312	1993	42

Fig. 1 shows the curves σ_i *(α,β)* corresponding to the obtained minima.

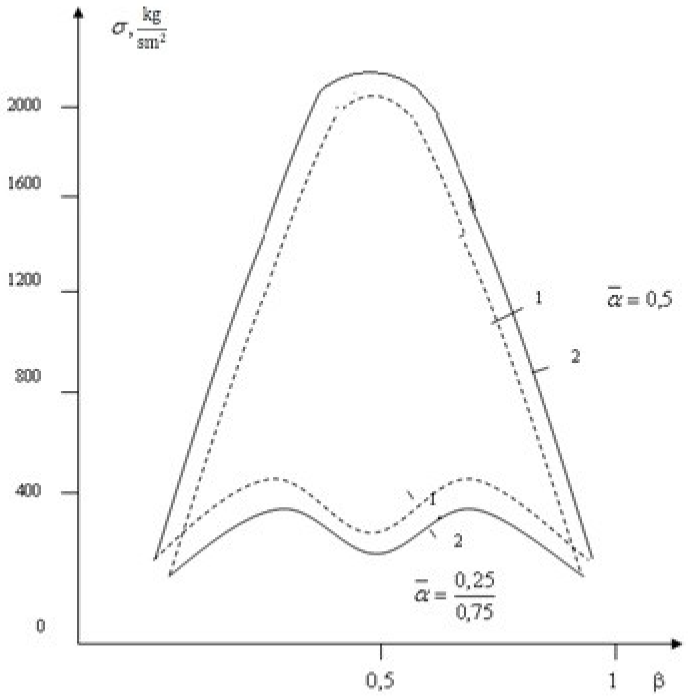

Fig. 1. Curves σ_i *(α,β)* corresponding to the obtained minima

Based on the results of solving the problem, it can be seen that the use of cylindrical shells of variable thickness makes it possible to reduce the weight of the structure by about 14%, hence the conclusion that there is weight optimization, i.e. significant reduction in the weight of the structure. The need to optimize designs is clearly seen in the results of solving the above problems. While in all found minima the structures under consideration were on the borderline of strength or stability, the values of their weights differed significantly, both structures, having the same margin of safety, differ in weight by almost 20%. For example, the application for shells of variable thickness (in the form of different laws h(β) - for cylindrical shells made it possible in some cases to reduce the weight of the structure by ~14% (for cylindrical shells) compared to shells of constant thickness, which indicates optimization - the feasibility of using the variable thickness, formulation and solution of optimization problems in the design of special shells of minimum weight [7].

Conclusion. The problems of optimization of engineering structures such as plates and shells are complex. It is especially difficult to take into account the limitations due to their diversity. Here are the simplest restrictions on parameters, such as $Q_i \leq x_i \leq b_i$, and functional ones (in terms of strength, stability, rigidity). Moreover, in most cases, to calculate a single number G_{max}, it is necessary to solve a system of partial differential equations with appropriate boundary conditions, which presents certain difficulties. Optimized parameters can vary both continuously and discretely. The objective function can also be used implicitly.

In the case of weight optimization of structures, the time required to check constraints is mainly several orders of magnitude longer than to calculate the objective function - the weight of the structure, which predetermines the need for a differentiated approach to these calculations in order to minimize the number of constraint checks while maintaining the necessary reliability and accuracy of finding optimum. The multi-extremality of design optimization problems, as stated by a number of scientists, is once again confirmed by the results obtained: when solving problems, several minima were found.

The work was carried out in accordance with the priority areas for the development of science and technology: SSTP -17 - "Development of modern information systems, intelligent controls and training, scientific and technical databases and software products that ensure the widespread development and implementation of information and telecommunication technologies."

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