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Energetic basis in rational constructions projection

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Abstract. The theory of designing rational load-bearing structures from the standpoint of strength, durability, manufacturability, and material consumption has too much of an energy basis. New variational principles operate at all levels of designing the configuration of load-bearing structures: topology, geometry, parameters of elements with parallel selection of materials. They can also be used for rational distribution of load on the structure. The study examined the foundations of new variational principles of synthesis of supporting structures with the content of an objective criterion of optimality of their practical application. Based on this, a rational energy principle was selected in the design of supporting structures, as well as algorithms for the development of rational systems focused on software design. The obtained dependencies as a result of the study allow to obtain a rational solution in strength, durability, manufacturability, and material consumption, which in turn helps to reduce the cost of construction of buildings and structures, as well as the costs of their reconstruction. Also, the proposed algorithms for the development of rational systems are aimed at software design.

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1. *Introduction*

The object of this study is new variation principles for the synthesis of load-bearing structures with the content of an objective criterion for the optimality of their practical application.

Technical progress is driven by the development of scientific knowledge in advanced industries. The art of construction primarily ensures the load-bearing capacity of structures associated with the rational use of the materials used. On this basis, optimal design of structures was developed [1].

In creating harmony between the environment and human society, an important role is played by the design of technical systems and structures based on the natural principles of structure formation. The design of rational load-bearing structures should be associated with the direct use of the principles that govern the deformation of a solid body. Common to artificial and natural systems is the principle of stationary action [2–4].

The natural constants π, e, Φ can be considered as discrete manifestations of the laws of structure formation arising from the mentioned principle [5].

The presence of round bodies in nature led to the birth of the number π, which expresses the ratio of the circumference to the diameter. The well-known isoperimetric problem of Dido is associated with the shape of a thread of a given length, covering the largest area. The desired line is a circle (in the case of a closed thread) and an arc of a circle (in the case of an open thread).

Equally widespread is the number e – the base of natural logarithms. In technology, a formula is known for the cross-sectional area of beam of equal resistance, stretched by force and its own weight.

The constants π and e are related by the Euler formula:

$$e^{2\pi i} = 1, \tag{1}$$

which testifies to their natural unity.

The golden ratio used in the creations of man and present in the organization of nature has a long history. It corresponds to such a division of an integer into two parts when the ratio of the larger part to the smaller one is equal to the ratio of the whole to the larger part $(\Phi = 1.618033\ldots)$.

In the 13th century, the Italian mathematician L. Fibonacci discovered a sequence of numbers, in which each subsequent component is equal to the sum of the two previous ones. I. Kepler supplemented this discovery with the fact that the ratio of adjacent components of this sequence in the limit tends to the golden ratio.

The golden ratio is an irrational value (like π, e) and symbolizes irrationality in natural proportions, while the Fibonacci numbers emphasize the wholeness in the organization of nature. In general, both patterns reflect the dialectical unity of heterogeneous principles – continual and discrete.

Formula

$$\Phi = 2\cos\frac{\pi}{5}, \tag{2}$$

together with formula (1) testify to the organic unity of the three constants.

Ancient architects, not having a scientific explanation of the properties of the golden ratio, rather applied it intuitively under the influence of the harmony and beauty of nature’s creations. There is a hypothesis of informational resonance: if the shape of the perceived object contains the golden ratio, then the brain is “tuned” to it. The purpose of the analysis of the uncertainty of the state of a technical system is to translate the uncertainty of the initial parameters and assumptions used when the risk assessment into the uncertainty of the results.

Relevance lies in the fact that the ratios obtained during the study allow us to obtain a rational solution from the standpoint of strength, durability, manufacturability, and material consumption, which in turn helps to reduce the cost of constructing buildings and structures, as well as the costs of their reconstruction.

The purpose of the study is to present the foundations of new variation principles for the synthesis of load-bearing structures with the content of an objective criterion for the optimality of their practical application.

The following objectives were addressed within the study:

1. Consideration of new variation principles of structure formation and load arrangement in terms of their practical application;
2. Selection of a rational energy principle in the design of load-bearing structures;
3. Selection of algorithms for the development of rational systems that are focused on software design.

2. Methods

To create a fundamental theory of the structure formation of load-bearing structures, a high level of development of mathematics, in particular, the calculus of variations, was necessary. It works effectively in mechanics. Variational principles have a deep theoretical significance, denoting the energy basis of the organization of matter.

The energy gives a synergistic understanding of the golden ratio. The level of organization of matter is estimated by the ratio of chaos and order in an entropy measure. Harmony function

$$P = \frac{S}{S_{\max} - S}, \tag{3}$$

includes the entropy S, determined by the Boltzmann–Shannon formula, and the maximum entropy of the system $S_{\max}$, corresponding to the equiprobability of all its states (chaos). The function P varies from zero to infinity.

Limitation function

$$R = \frac{S_{\max} - S}{S_{\max}}, \tag{4}$$

decreases from 1 to 0. Harmony corresponds to the intersection of the curves P and R. In this case, the proportion of chaos is 0.382, and the proportion of order is 0.618 (golden proportion).

The unity of the physical forms of the motion of matter reflects the general physical principle, from which particular laws follow. This is the principle of stationary action (according to Hamilton). Differences in the forms of motion of matter reflect the Lagrange functions chosen on the basis of generalization of experimental data. These functions have energy content.

A special case of the principle of stationary action is the principle of possible work, the mathematical expression of which is:

$$\delta U - \delta T = 0, \tag{5}$$

where δT and δU are variations of the functionals of the introduced mechanical energy and potential strain energy. They depend on the increments of a number of parameters: 1) displacements, 2) internal forces, 3) body configuration, 4) material moduli, 5) load. The first two factors are taken into account when formulating the principle of possible displacements (the Lagrange principle) and the principle of possible changes in the stress state (the Castigliano principle). Both are extreme principles and are used to analyze the stress-strain state of structures.

The remaining three factors are aimed at the formulation of variational principles related to the problem of structure formation and the rational distribution of the load assessment into the uncertainty of the results.

3. Results and Discussion

The functional aspect of analyzing the stress-strain state of a structure involves Euler–Lagrange equations and natural boundary conditions derived from established deformation theory equations and boundary conditions. However, for novel problem types, additional equations are introduced into the functional framework to account for variations in system energy concerning changes in configuration, material elastic moduli, and load distribution. Ensuring functional stationarity concerning variable parameters necessitates the incorporation of additional conditions, typically in the form of coupling equations, imposed on the desired functions ψ. These conditions encompass factors, such as stress-strain state functions, configuration, material elastic moduli, and load distribution, thereby facilitating a comprehensive analysis of structural behavior under varying conditions:

$$\varphi\left(\vec{\psi}\right) = 0, \tag{6}$$

$$\int_{\omega} \varphi\left(\vec{\psi}\right) d\omega = c, \tag{7}$$

where ω is the admissible region of integration, c is a given constant.

Conditions (6) and (7) encompass geometric constraints, design specifications, load restrictions, and functional requirements for the structure, expressed through a combination of algebraic, differential, and integral equations. To address a variational problem with these additional conditions, the Lagrange multiplier method is employed to transform it into an equivalent free variational problem.

A variational problem with additional conditions is reduced to a free variational problem by means of the Lagrange multiplier method. In this case, this can be interpreted as a generalization of the principles of Lagrange and Castigliano for cases of expanding the functional space due to configuration, material moduli, and load fields.

If $J_1(J_2)$ is a functional corresponding to the Lagrange (Castigliano) principle, and λ is the Lagrange multiplier, then the functionals of generalized principles have the form:

$$J_1^* = J_1 + \int_V \vec{\lambda}^T \vec{\varphi} dV, \quad (8)$$

$$J_2^* = J_2 + \int_V \vec{\lambda}^T \vec{\varphi} dV, \quad (9)$$

where V is the volume of the body. Under condition (6), the Lagrange multiplier λ is a variable. Under condition (7), the multiplier λ is a constant value (isoperimetric problem).

Following the theory of the calculus of variations, the possible variations of the configuration functions, material moduli, and load are infinitesimal changes in these functions that satisfy the directive requirements for the construction, material, load, and differentiability requirements.

Consequences arising from the stationarity of the functional (J_1) include: 1) equilibrium equations within the body's volume and static boundary conditions; 2) coupling equations (6) or (7); 3) equations governing structure formation or loading systems.

The variational principle of structure formation based on the Lagrange principle has the following formulation: the potential energy of the system in the position of stable equilibrium reaches an absolute minimum in terms of displacements in the functional space, expanded due to the fields of configuration functions and (or) material moduli. This corresponds to the moment when the load-bearing structure acquires maximum rigidity indicators, so that at the stationarity point the functional has a minimax, namely minimum in terms of displacement functions of maxima in terms of the configuration and (or) material moduli function.

The formulation of new variational principles for the synthesis of load-bearing structures and the formation of the load in the presented form was carried out by A.G. Yuriev in 1982 [6]. The special cases that took place included the formulation of isoperimetric problems of determining the geometric parameters of structures [7].

The new approach to solving design problems excludes the adoption of any criterion a priori. Its role is played by the equation of structure formation (location of the load), which, as mentioned above, is a consequence of the stationarity of the functional of the variational problem under consideration.

Thus, the criterion of minimum volume (mass, cost) in the established optimal design loses its force. With it, there is no guarantee that the goal functional will achieve a global extremum due to the possible absence of the convexity property.

A sufficient condition for achieving this objective can only be attained through integrating an energy based approach into the optimal design process, aligning with the duality inherent in constrained extremum problems with integral constraints [8–10]. Consequently, formulating the volume minimization problem aligns precisely with the overarching physical principle of stationary action, albeit under restricted circumstances. The new variational principles ensure a global minimum in the volume (or cost) of homogeneous material. In specific instances, the structure can exhibit uniform stress distribution throughout its entirety. As per Vasyutinskii's theorem [11], applicable to linearly elastic bodies, the structure possesses a minimum potential energy of deformation. Given this energy is directly proportional to the body's volume, minimizing volume serves as a rational criterion in this context.

The need to put into circulation a new method of structure formation is confirmed by comparison using another, the ordinary criterion [12–14].

Example 1. The console, having a length of I = 2 m, is loaded at the end with a moment M = 50 kN·m. The cross section of the beam is presupposed in the form of an I-beam with the given: wall thickness 2.2 cm (= $2t_1$) and shelf height t_2 = 1 cm. The relative deflection of the console end is set f_0 / l = 0.006. The modulus of elasticity of the material E = 2·105 MPa. It is required to determine the height of the section h and the width of the shelf b.

It is known that the deflection at the end of the console is:

$$f_0 = \frac{MI^2}{2EI}, \quad (10)$$

where I is the moment of inertia of the section. The absolute value of stresses in the extreme longitudinal fibers is equal to:

$$\sigma_0 = \frac{M}{I}\frac{h}{2}. \quad (11)$$

Consequently,

$$\frac{f_0}{l} = \frac{\sigma_0 l}{Eh}, \quad (12)$$

$$\sigma_0 = \frac{f_0}{l} Eh \frac{1}{l} = 60h. \quad (13)$$

Substituting expression (13) into the formula

$$\sigma_0 = \frac{M}{W}, \quad (14)$$

where W is the moment of resistance of the cross-section during bending, we find the expression b, and then the area of the cross-section (taking into account formula (13)):

$$A = 2t_1 h + \left[0.1Mt_2 - 2t_1 t_2 \left(h - 2t_2\right)^3\right]\left(3h^2 t_2 - 6ht_2^2 + 4t_2^3\right)^{-1} - 4t_1 t_2. \quad (15)$$

From the condition of minimum cross-sectional area (15) for given values of M, t_1, t_2 follows the equation:

$$h^4 - 4h^3 + 6h^2 - 22730h + 22730 = 0, \quad (16)$$

whence h = 29.32 cm. In this case, b = 1.07 cm, A = 62.24 cm^2.

The same values of b and h will be obtained by solving the isoperimetric problem for A = 62.24 cm^2. Let us determine the value b = 33.32 – 1.1h and substitute it into the expression for the moment of inertia I, which we will introduce into the energy functional:

$$J_2 = \frac{M^2 l}{2EI}. \quad (17)$$

From the condition $\partial J_2 / \partial h = 0$ follows the equation:

$$h^2 - 30.29h + 28.95 = 0,$$

whence h = 29.32 cm. In this case, b = 1.07 cm (the confluence of I -beam).

In this case, the direct use of the J_2 – functional turned out to be acceptable. Therefore, there was no need to use the method of Lagrange multipliers.

Example 2. In the condition of example 1, instead of the given value f_0 / l, we introduce the admissible stress σ_{adm} = 160 MPa.

From the strength condition, the expression b can be derived, so that the cross-sectional area is equal to

$$A = 2t_1 h + \left[\frac{6Mt_2 h}{\sigma_{adm}} - 2t_1 t_2 \left(h - 2t_2\right)^3\right]\left(3h^2 t_2 - 6ht_2^2 + 4t_2^3\right)^{-1} - 4t_1 t_2. \quad (18)$$

The condition $\partial A / \partial h = 0$ implies an equation that, for given values of M, t_1, t_2, σ_{adm} takes the form:

$$h^4 - 4h^3 - 420.13h^2 - 6h + 568.18 = 0, \tag{19}$$

whence h = 22.6 cm In this case, b = 8.26 cm, A = 61.84 cm^2, moment of inertia I = 3530.9 cm^4.

Let us now solve the isoperimetric problem for A = 61.84 cm^2. Having determined the value b = = 33.32 – 1.1h, let us substitute it into the expression for the moment of inertia I, which we introduce into the functional (17).

From the condition $\partial J_2 / \partial h = 0$ follows the equation:

$$h^2 - 30.11h + 28.77 = 0, \tag{20}$$

whence h = 29.13 cm. In this case, b = 1.08 cm, = 4088.7 cm^4, σ_{adm} = 178.1 MPa.

The solutions do not coincide, since in the case of minimizing the cross-sectional area, the condition σ_{adm} = 160 MPa has no energy meaning, which eliminates the duality of the problem statement. The problem statement in example 1 is deprived of this deficiency.

Yuriev's variational principles and the theory of structure formation of load-bearing structures based on them changed the nature of design. The subjective design criteria, which are speculative in nature, have been replaced by the laws of structure formation arising from the general physical principle of stationary action.

Designing a structure configuration within the specified requirements includes determining its topology, geometry, and element parameters [15, 16].

The topology of rod systems provides for the mutual arrangement of nodes and the way they are connected to each other to form a geometrically unchanging structure. The variational principles of structure formation make it possible to reveal a rational construction from the allowed variants by studying the corresponding energy functionals.

In the case of a linear-elastic formulation of the problem, the values of the potential strain energy are compared for directive geometric parameters. The problem statement can be extended by varying some geometric parameters within each topology variant.

In rod systems, it is possible to change the sign of longitudinal forces in some rods by varying the geometric parameters. When a stretched rod passes into a compressed one, in addition to strength, it is necessary to ensure the stability of its equilibrium.

In the case of an isoperimetric problem for a truss under the generalized variational Castigliano principle, the functional has the form [17–20]:

$$J_2^* = \sum_{i=1}^{n} \frac{N_i^2 l_i}{2E\varphi_i^2 A_i} + \lambda \sum_{i=1}^{n} A_i l_i, \tag{21}$$

where n is the number of rods of length l_i, having a cross-sectional area A_i and longitudinal forces N_i, φ_i is the coefficient of reduction of the design resistance.

This problem is solved in an iterative way. The coefficient φ is assigned in accordance with the regulatory requirements for ensuring of the stability of the belt and lattice rods.

Based on Yuriev's variational principles [6], the problem of structure formation of dispersely and discretely reinforced material was solved [21–26]. In the case of dispersed reinforcement, the desired is the modulus of longitudinal elasticity of the composite material, which corresponds to a certain nature of fiber reinforcement [27–30].

In the case of discrete (bar) reinforcement, the generalized functional J_1^* contains the term $\frac{1}{2}\sum_i S_i q_i$, where S_i is the internal force in the reinforcing bar, q is the corresponding displacement. The generalized functional J_2^* contains the term $\sum_i \frac{S_i^2 l_i}{2B_i}$, where l_i is the length of the reinforcing bar, B_i is the stiffness of its cross-section, which has a specific expression depending on the type of deformation (in tension $B_i = EA_i$, where E is the modulus of longitudinal elasticity of the reinforcing material, A_i is the cross-sectional area of the rod) [31–34].

4. Conclusion

Based on the conducted research, the following has been established:

1. The considered new variational principles of structure formation and load location have a strict physical basis – the principle of stationary action. The solution of practical problems based on them does not require the introduction of any criterion, which is typical for pre-existing design methods. First of all, this concerns the formulation of design tasks with an especially economic criterion (minimum volume, mass, cost).
2. The proposed energy principle in the design of load-bearing structures makes it possible to obtain a rational solution from the standpoint of strength, durability, manufacturability, and material consumption and helps to reduce the cost of constructing buildings and structures, as well as the costs of their reconstruction. In turn, this contributes to the implementation of an ecological approach to the habitat with the effective use of building materials, energy, space, and the entire ecological system.
3. Rational systems development algorithms aimed at software design are considered.

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