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Optimization of hybrid I-beams using modified particle swarm method

Оптимизация бистальных балок на основе модификации метода роя частиц

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Ключевые слова: рой частиц; оптимизация; бистальная балка; ребра жесткости; пояса; стенка; метод конечных элементов; пластические деформации; местная устойчивость; общая устойчивость

Abstract. An approach for the optimization of hybrid welded I-beams based on the modification of the particle swarm method is proposed. A solution search is performed on discrete sets of variable parameters, which are taken as the size of sheets of rolled steel and steel grades. Depending on the values of the variables, a design of the support and ordinary stiffeners and their location along the length of the beam is performed. When varying the thickness of the sheets, the change in the design resistance is taken into account. As a mathematical model for calculating the stress-strain state, analytical expressions are used. To save the best solutions, the method of copying particles and their storage strategy in the database are used. This database is generated in accordance with the elitist principle, known in the evolutionary modeling theory. This makes it possible to obtain a high-performance optimization algorithm for structures of this type. The verification of the solution is performed using the finite element analysis.

Аннотация. Предложен подход к оптимизации бистальных сварных балок, базирующийся на модификации метода роя частиц. Поиск решений выполняется на дискретных множествах варьируемых параметров, в качестве которых принимаются размеры листов стального проката и марки стали. В зависимости от значений варьируемых параметров выполняется проектирование опорных и рядовых ребер жесткости, рациональная их расстановка по длине балки. При варьировании толщин листов учитывается изменение расчетного сопротивления. В качестве математической модели для оценки напряженно-деформируемого состояния используются аналитические выражения, что позволяет получить высокопроизводительный алгоритм оптимизации для конструкций такого типа. Для сохранения лучших решений используется прием копирования лучших частиц и стратегия их хранения в базе данных. Эта база формируется в соответствии с известным в теории эволюционного моделирования принципом элитизма. Расчет полученного решения в программном комплексе конечно-элементного анализа NX Nastran показал работоспособность предлагаемой поисковой методики.

1. Introduction

In the process of steel-frame structures construction, welded I-beams made of hot-rolled steel sheets are frequently used. The subject matter of study of such structures, related to the topology and parameter optimization, bears relevance. Thus, special attention is paid to the formation of the web topology [1, 3, 13, 20], search for the rational shape of a cross-section [2, 8] and the adjustment of the section sizes [6, 9, 12, 15]. The tasks of the optimization of compound and inhomogeneous bars were addressed in [7, 9, 10, 11, 23]. When optimizing thin-walled beams the single-purpose approach with regard to the production and transportation costs, expenditures on the painting of beams [5], on the emission of green-house gases into

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the atmosphere [16], as well as multi-purpose approaches [12] were used. To search for solutions, PSO [2, 24], SGA [6], ACO [8] methods, simulated annealing [9], quadratic programming [19], modified genetic algorithms [19, 20, 21, 28], mixed metaheuristic approaches [17, 27, 29] were used. In the research process [14] a thin-walled beam was optimized with regard to the fault stability in the emergency conditions [18, 22]. Along with the optimization algorithms, the complex issues of assessing the stress-strain state of I-beams [4, 15] are being studied, taking into account the contact with a solid body, bending with relation to two central axes of inertia, free and constrained torsion.

One of the effective types of thin-walled I-section structures is a hybrid (consisting of various steels types and grades) beam, which can be used in constructions of a normal level of reliability without permanent human presence. For example, these include beam grillages, girders (Figure 1,a) and supporting structures of auxiliary facilities of treatment plants, meat packing plants, shops specializing in cooling and processing of semi-finished products, etc. With a rational approach to the design of hybrid I-beams, it is possible to significantly reduce the steel consumption, as compared to structures made from homogeneous steel. However, the process of optimal design with regard to the sufficiently wide range of steel grades and sheet sizes is very time-consuming.

The goal of this research is the development of a computational algorithm for obtaining rational design solutions on the basis of a system of numerous steel grades and sheet steel dimensions associated with the characteristics of a particular steel. To achieve the stated goal, the approach based on the modification of the particle swarm method [2] is used.

2. Methods

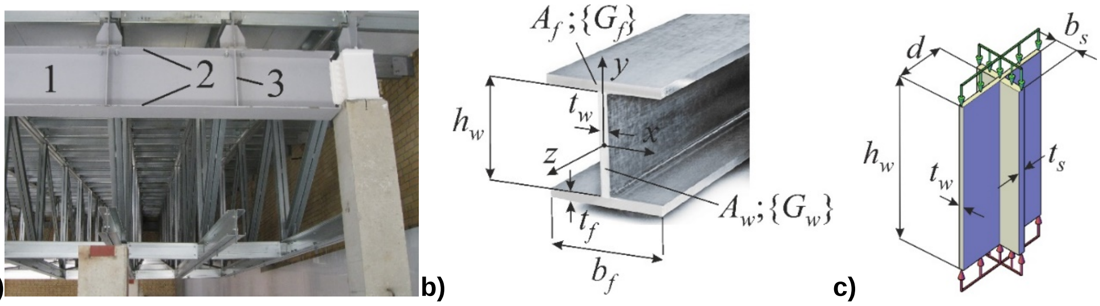
2.1. Formulation of the problem

For a hybrid beam structure of an I-section, the problem of the search for minimum of the objective function on discrete sets $\{V\}$ of variables is formed

$$C(\{V\}_i) + C(D) \to \min,\ i \in [1; in], \qquad (1)$$

where in is the quantity of variables. As independent variables, the width and height of the sheets constituting the I- beam, as well as the steel grades, from which these sheets are made, are taken. Thicknesses of flanges and the web are supposed to be dependent variables determined by values, acceptable for a particular steel grade. The value of the objective function are the costs that are required to manufacture a beam. These costs include both the cost of the flat steel $C(\{V\}_i)$, as well as associated works $C(D)$, where $D = \{D_1, .., D_y\}$, $q \in [1; y]$ y is the number of associated works. The costs of the following works is considered: welding with ultrasonic quality control D_1, end milling D_2, marking and cutting of stiffeners D_3, anti-corrosion treatment D_4, expendable materials D_5. All these costs are calculated in accordance with the formulas of research [5]. The result is:

$$C(D) = \sum_{q=1}^{5} C(D_q). \qquad (2)$$



a) b) c)

Figure 1. For the calculation of stress-strain state of the hybrid I-beam: a – field appearance of one structure variant, 1 – web, 2 – flanges, 3 – stiffeners; b – sectional parameters, A_w, A_f – web and flanges areas, $\{G_f\}$ $\{G_w\}$ – discrete sets of steel grades for flanges and web; c – computational model for the assessment of vertical stiffeners stability

In the course of solving the problem, the volume of rolled steel sheets is directly calculated, the steel grade for webs and flanges of the beam is selected, and the rest of the costs can be approximately assessed based on the data of the manufacturing plants, depending on the volume received. According to commercial proposals of enterprises, it was established that the cost of beams manufacturing $C(D)$ is about 0.3–0.4 of the value $C(\{V\}_i)$.

It is assumed, that the beam bends in the plane of its maximum stiffness. Beam flanges operate under conditions of elastic deformations, and the web operates under limited elastoplastic deformations. These deformations continue, until the stresses in the flanges reach the yield point. In this case, to ensure local stability of the web, it is possible to set vertical stiffeners. These elements are manufactured of the same steel as the web. The load is applied to the upper flange of the beam. To calculate the stress state of the structures under consideration, a mathematical model from regulatory standards [25] is used. For each of the design load cases the following active constraints are taken into account [25]:

1. Structural strength with regard to the development of plastic deformations in the web

$$\frac{\sigma_z}{c_{xr}\beta R_w} \le 1,$$

$$\beta = 1 - \frac{0,2}{(R_f A_f)/(R_w A_w) + 0.25}\left(\frac{\tau_x}{R_{sw}}\right)^4 ; \tau_x = \frac{Q_x}{A_w}; \tag{3}$$

$$c_{xr} = \frac{(R_f A_f)/(R_w A_w) + 0.2 - 0.0833(R_f / R_w)^2}{A_f / A_w + 0.167}.$$

Here, σ_z, τ_x are the maximum axial and shear stresses in the cross-section of the beam with the bending relatively to the x axis (Figure 1, b), Q_x is the maximum shear force, A_f, A_w are the flange and web areas respectively, R_f, R_w are the design resistances to the bend (allowable bending stresses) for the flange and web respectively.

2. Overall stability of the I-beam [25]

$$\frac{\sigma_x}{\varphi_b R_f} \le 1, \tag{4}$$

where φ_b is the stability coefficient, determined in accordance with the Supplement in [25].

It should be noted, that the buckling out of the vertical plane of the beam, due to loss of the flat shape bending stability, do not allow in the following ways:

– the I-beam cross-sectional dimensions at varying geometry are assigned so that the values J_x and J_y moments of inertia (Figure 1,b) differ slightly. That is, it is adopted wide-sectional form;

– restriction of the displacements for the beams upper belt out the plane of their bending.

– the following condition for the stability of a flat bend for an I-section is verified [30]:

$$M_{\max} \le M_{cr} = k\frac{\sqrt{EJ_y C}}{l},\ k^2 = \pi^2\left(1 + \pi^2\frac{D_y h^2}{2Cl^2}\right), C = G(J_x + J_y), \tag{5}$$

where M_{cr} is conditional bending moment, corresponding to loss of stability, h, l, C, G, D_y are the section height, beam span, torsional stiffness of the section, shear modulus and shelves stiffness respectively.

3. Local stability of the flange compression [25]:

$$\bar{\lambda} \le \lambda_{ub}, \ \bar{\lambda} = \frac{l_f}{b_f}\sqrt{\frac{R_f}{E}};$$

$$\lambda_{ub} = \delta_x(0.35 + 0.0032\frac{b_f}{t_f} + (0.76 - 0.02\ \frac{b_f}{t_f})\ \times \qquad (6)$$

$$\times\frac{b_f}{h_w}\sqrt{\frac{R_f}{\sigma_z}};\ \ \delta_x = 1 - 0.6(c_{x1} - 1)/(c_{xr} - 1);$$

$$c_{x1} = \max\left\{\sigma_x / R_f;\ \beta c_{xr}\right\}\ .$$

Here l_f is the effective length of the flange between the restraining points from the main loading plane of the beam, E is the elastic modulus of the steel, b_f, t_f, h_w are the dimensions of the section shown in Figure 1, a.

Local stability of stiffeners. The computational model for paired stiffeners is shown in Figure 1, c. The stability condition is presented in the following form [25]:

$$\frac{\sigma}{\varphi_e R} \le 1, \varphi_e = 0.5(\delta - \sqrt{\delta^2 - 39.48\bar{\lambda}^2} / \bar{\lambda}^2; \qquad (7)$$

$$\delta = 9.87(0.96 + 0.09\bar{\lambda}) + \bar{\lambda}^2;\ \bar{\lambda} = (h_w / i)\sqrt{\frac{R_w}{E}}\ .$$

The radius of inertia i is calculated for the conditional section, including the web with the length of $2d$ and the stiffeners adjacent to it in this area (see Figure 1, b). The value d is found as $d = 0.65t_w\sqrt{E / R_w}$

The structural stiffness $\left|\delta_{\max}\right| \le \left[\delta\right]$, where $\left[\delta\right]$ is the allowable value of displacement. The displacements of the system to accelerate calculations are calculated on the basis of formulas obtained using Mohr's integrals. For the final solution, a verifying calculation of the shift is performed on the basis of the finite element method.

The welding condition of sheets of the web and flanges is verified as a passive constraint. The sheet thicknesses obtained in the process of search for the solution are verified according to Table 1 with regard to the condition of $k_f \le 1,2t_{\max}$, k_f is the weld leg, $t_{\max}$ is the maximum thickness of welded elements.

Table 1. Selection of the weld leg, joining the flange with the web

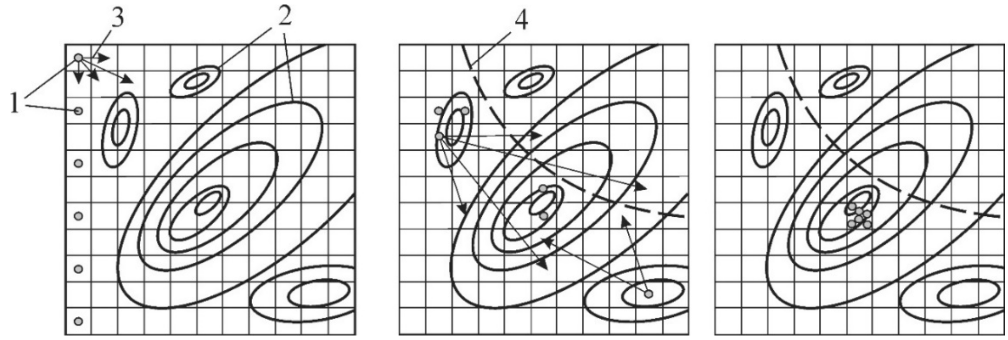
Joint type	Welding type	Steel yield stress, N/mm^2	Minimal weld leg k_f, mm, with the thickness of thicker welded element t, mm						
			4-5	6-10	11-16	17-22	23-32	33-40	41-80
T-joint with double-sided fillet welds	Automatic and machine welding	< 285	3	4	4	5	5	6	6
		285…390	3	4	5	6	7	8	9
		390…590	4	5	6	7	8	9	10

2.2. Method of solving the problem

The principle stages is performed.

1. *Initialization of parameters and ranges of their acceptable values.* Each variant of the structure, formed on the basis of variables, is interpreted as a “particle” (Figure 2). For each variable parameter *i* the range of acceptable values is formed in the type of discrete sets $\{V_k\}_i$, $k \in [1; m]$, m is the quantity of

these values. Elements of these sets should be put in descending order of values. It is assumed that at the maximum values of parameters all the formulated constraints are satisfied. Then the relation for the object cost can be represented as follows: $C(\{V_k\}_i) = f(v_1^{(\max)},...,v_i^{(\max)},...,v_{in}^{(\max)})$. The value $C(\{V_k\}_i)$ should not be more than an order of magnitude greater than the average cost of similar objects introduced on the market.



1. Initialization of parameters and ranges of their acceptable values

2. Identification of the permissible solutions range and particle motion

3. Maintenance of motion. Passing of the local optima

Figure 2. Illustration of the extremum seeking through the example of six particles: 1 – formed particles, 2 – contour lines of values of the function $C(\{V\}_i)$, 3 – directions Pos_i of the particle motion, 4 – boundary between the area of permissible solutions (on the bottom) and the area of infeasible solutions

The decomposition of the parameters by dividing them into independent and dependent variables is performed. The individual particle is presented in the form: $P:\left\{ V_1,...,V_{i_0},V_{i_0+1}(V_j),...,V_{in}(V_j)\right\}$, $j \in [1;i_0]$. Parameters $V_1 - V_i$ for the I-section is the independently variable width of the flange b_f and the height of the web h_w, resistance to bending of flanges R_f and the web R_w, determined by the respective steel grades; i_0 is the number of independent variables. Dependent variables $V_{i_0+1}(V_j) - V_{in}(V_j)$ are thicknesses of flanges $t_f(R_f)$ and of the web $t_w(R_w)$.

The search for the parameters of sheets of flanges and a web for all possible combinations of steel grades of web and flanges is presented. For each of these combinations initial, the sets of particles $P^{(\tilde{c})}$, where $\tilde{c}$ is the number of the combination, is created. For each particle in the set, we a group of positions is formed. The maximum size of such a group is determined by the minimum number m defined in the analysis of all variable parameters. Then the positions of the particles can be represented in the form of the following notation.

$$\begin{array}{c|cccc} Pos_1: & V_{1,1}^{(\max)} & ... & V_{1,in-1}^{(\max)} & V_{1,in}^{(\max)} \\ \hline ... & ... & ... & ... & ... \\ \hline Pos_{n_0}: & V_{m,1}^{(\min)} & ... & V_{m,in-1}^{(\min)} & V_{m,in}^{(\min)} \end{array}. \quad (8)$$

2. Identification of the permissible solutions range and particle motion. Each particle of the set $P^{(\tilde{c})}$ is tested for the constraint satisfaction. At the same time, an automated design of the stiffeners is performed. To do so, the following steps are implemented:

2.1. For bearing support stiffeners the thickness t_{sr} and width b_{sr} are calculated [25]:

$$b_{sr} = 0.5\left(b_f - t_w\right) - 0.015,\ (m);\ t_{sr} = 1.5\sqrt{R_w / E}. \quad (9)$$

2.2. The need to install stiffeners in the compartments is determined. The compartments are formed by dividing the beam by the boundary stiffeners, which are affixed in a mandatory manner in the places where the concentrated loads are applied. If a uniformly distributed load is applied, the boundary stiffeners are placed on the area of the beam where the bending moment is $M \geq 0.7M_{\max}$. Spacing l_s of stiffeners inside the compartments is determined depending on the value of the specified flexibility of the web $\bar{\lambda}_w = (h_w / t_w)\sqrt{R_{wy} / E}$.

Further the following condition [25] is checked

$$\begin{cases} \bar{\lambda}_w \geq 3.2 \rightarrow l_s = 2h_w \\ \bar{\lambda}_w < 3.2 \rightarrow l_s = 2.5h_w \end{cases}. \tag{10}$$

The thickness of these stiffeners t_s and the width b_s is determined by equations:

$$t_s = \sqrt{R_{wy} / E}\,,\ b_s = 0.1h_w - 0.025,\ (m). \tag{11}$$

2.3. The stability of the transversal stiffeners located under the concentrated forces is verified. The calculation is performed for the most stressed sector of the beam, which is a cross-shaped segment, shown in Figure 1, c.

2.3.1. Material cost calculation. For those particles, that satisfy all constraints, the value $C(\{V\}_i)$ is calculated. If the constraints are satisfied for the initial particle with the minimum values of all variables, then this implies that all solutions are in the permissible range and further reduction of the values of variables is needed. That is, we must return to the stage of the formation of discrete sets. After that we obtain a number of particles for which one or more constraints will be violated. Thus, we separate the range of permissible solutions from the range of infeasible solutions.

2.3.2. Sorting and saving solutions. Particles in the range of permissible solutions are stored in a database, implemented in the form of structured arrays. At this stage, the positions of all the reserved particles are considered to be initial.

2.3.3. Initiation of motion. The modeling of the particle motion is starting. For each of the particles in the initial position, the current set of positions is formed, according to the following principle. In the set only those positions is included, in which the number of the value of one of the variable is reduced by one. Thus, we somewhat imitate the movement of the particle to the optimum, which is assumed by us as a minimum. Further, for each of the particles obtained, constraint satisfaction is verified and the objective function is calculated. If for different positions of the particle the best value of the objective function is the same, then in the next stage all such positions are considered, that is, the particle multiplies.

3. Maintenance of motion. Passing of the local optima. All new particle positions corresponding to the state of variables providing the best value of the objective function when all constraints are satisfied are stored in the database. Further, for these positions the stage of particle motion is performed. That is, the current position is adopted as the initial one and the procedure described above is performed. The process of particle motion continues, until the improvement of the objective function with a change of the position occurs for at least one of the particles.

In order to pass local optima for all particles in their best positions, the formation of possible positions in the range of infeasible solutions is conducted. For these positions, constraints are verified. If constraints are satisfied for any of the positions, this testifies to the fact that the particle falls into the local optimum in its previous position. If the new position of the particle, while satisfying the constraints, exists, then it is memorized and the procedures of motion and motion maintenance are performed for this particle.

4. *Selection of best particles.* For each of the combinations of steel grades of flanges and the web of the beam, the calculation of the value $C(D)$ is performed, the verification of the passive constraint (welding conditions) is conducted. For the selected solutions, the checking calculation through a finite element analysis is performed. As a result, one best option can be selected, which corresponds to the territorial possibilities of manufacture and minimization of costs

3. Results and Discussion

The main beam with support of secondary structures on the upper flange is considered, the analogue is shown in Figure 1,a. We assume that the secondary structures divide the span of the main beam into 4 compartments equal in length and transmit concentrated forces to its upper flange. The computational model is shown in Figure 3.

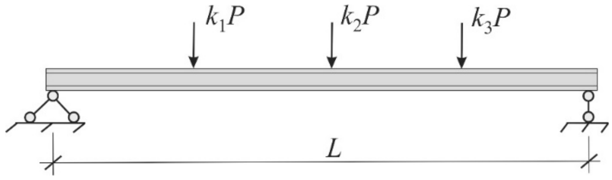


Figure 3. Computational model of main hybrid I-beam

The value $L = 12$ m is set. The following sets of steel grades [26] were accepted for the flanges: $\{G_f\} = \{C345,\ C375,\ C390\}$, for the web, bearing support stiffeners and stiffeners: $\{G_w\} = \{C245,\ C255,\ C285\}$ (Figure 1,b). Concentrated force is $P = 40$ kH. Two loads were taken into account: in the first case $k_1 = k_3 = 1$, $k_2 = 4$ were taken, in the second case $k_1 = 3$, $k_2 = 2$, $k_3 = 1$ were taken. There was a restriction on the movements $[\delta] = 6\ cm$. The limitation of displacements from the plane of the beam bending are assigned to the supports and points of the load application. For each of the possible combinations of steels formed from the sets $\{G_f\}$ $\{G_w\}$, the choice of flat steel thicknesses was allowed in accordance with Table. 2. Independent variables values are presented in Table 3. To account for the difference in the cost of steel grades, cost factors k_c were introduced. The minimum cost has steel C245, for which the factor is $k_c = 1$. The permissible stresses and values k_c for the steel grades under consideration are given in Table 4.

As a result, for these load-bearing and kinematic constraints, 9 solutions were found with a different conditional cost, presented in Table 5.

Table 2. Ranges of thicknesses allowable for the selection

Thickness of sheets t, mm for a steel grade [26]					
C245	C255	C285	C345	C375	C390
6, 7, 8	7, 8, 9, 10, 12, 14, 16, 18 ,20, 22, 24, 26, 28, 30, 32, 34, 36, 40	7, 8, 9, 10, 12, 14, 16, 18, 20	7, 8, 9, 10, 12, 14, 16, 18 ,20, 22, 24, 26, 28, 30, 32, 34, 36, 40, 42, 44, 46 48, 50	7, 8, 9, 10, 12, 14, 16, 18 ,20, 22, 24, 26, 28, 30, 32, 34, 36, 40	7, 8, 9, 10, 12, 14, 16, 18 ,20, 22, 24, 26, 28, 30, 32, 34, 36, 40, 42, 44, 46 48, 50

Table 3 Ranges of plates allowable for the choice of dimensions

Dimensions of beam sheets [26], mm	
h_w	b_f
200, 220, 240, 260, 280, 300, 320, 340, 360, 380, 400, 420, 440, 460, 480, 500 530, 560, 600, 630, 670, 700, 750, 800, 1000, 1200	200, 220, 240, 260, 280, 300, 320, 340, 360, 380, 400, 420, 440, 460, 480, 500 530, 560, 600, 630, 670, 700, 750, 800

Table 4. Ranges of permissible values of design resistances

Yield stress, MPa for steel grades					
C245	C255	C285	C345	C375	C390
225	235 $\forall t \in [7;20)$, 225 $\forall t \in [20;40]$.	260 $\forall t \in [7;12)$, 250 $\forall t \in [12;20]$.	290 $\forall t \in [7;40)$, 270 $\forall t \in [40;50]$.	340 $\forall t \in [7;24)$, 320 $\forall t \in [24;40]$.	370
Coefficients k_c cost of steel grades					
1.0	1.05	1.08	1.11	1.16	1.22

Table 5. Results of beam costs calculation

Cost of materials $C(\{V\}_i)$ for the solution number:								
1	2	3	4	5	6	7	8	9
98152	89046	87801	75606	90592	98950	95361	92020	72345
Manufacturing costs $C(D)$								
29445.6	28494.72	31608.36	26462.1	29895.36	29685	28608.3	28526.2	24597.3
Total costs $C(\{V\}_i)+C(D)$								
127597.6	117540.7	119409.4	102068.1	120487.4	128635	123969.3	120546.2	100559.6

The presented algorithm was implemented within the I-BEAM software developed by the authors of this article. The user interface is presented in Figure 4. Table 5 summarizes the obtained solutions for nine parallel running threads in an iterative process. Each thread corresponds to a combination of steel grades for the wall and shelves, all combinations are given in Table 6. The data on the convergence of these iterative processes are shown in Figure 5,a. Parameters of the nine best solutions are represented in Table 6. Spacing of stiffeners in all options equals to 1 m.

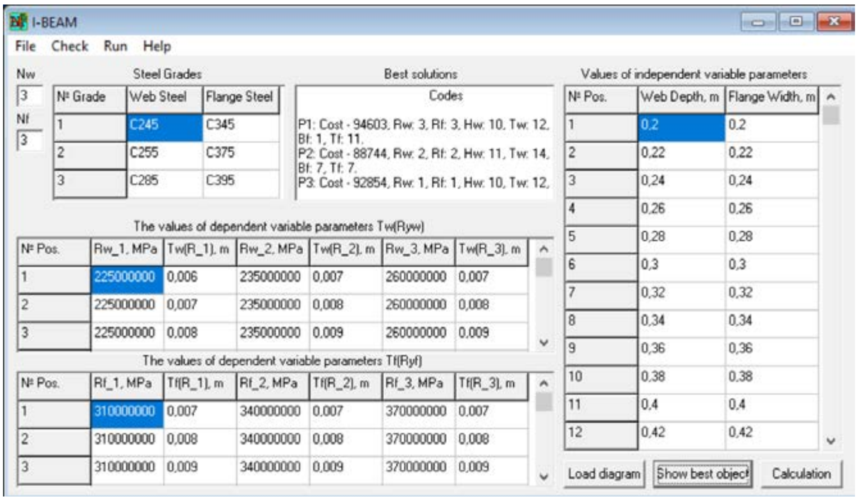


Figure 4. Initial data and calculation results in the I-BEAM software

Table 6. Parameters of a beam, obtained in the result of the problem solution

No.	Steel grade of a web	Steel grade of a flange	h_w, cm	t_w, mm	b_f, cm	t_f, mm	b_{sr}, mm	t_{sr}, mm	b_s, mm	t_s, mm
1	C285	C390	38	7	42	24	191	22	63	15
2	C255	C375	40	16	48	16	217	24	65	16
3	C245	C345	38	6	42	24	192	21	63	14
4	C285	C375	42	7	48	16	221	26	67	17
5	C285	C345	38	7	42	24	191	22	63	15
6	C255	C390	38	12	42	22	189	21	63	14
7	C245	C390	38	6	42	24	192	21	63	14
8	C255	C345	38	12	42	22	189	21	63	14
9	C245	C375	42	6	48	16	222	24	67	16

Table 6 shows that the best solution number 9 on the condition of a minimum of total costs was found. This girder structure is better, if the manufacturer has available steel grades C245 and C375 to produce. If, for example, steel grades C255 and C375 are available for production, then the best solution is beam number 2. For the purpose of verification of the obtained solution, a finite element analysis of beam number 9 was performed. This beam is divided in accordance with clauses 2.1, 2.2 of the proposed algorithm into four compartments I-IV (Figure 5, b). The boundaries of these compartments are determined by the location of the bearing support stiffeners s_1 and stiffeners under load s_2. Ordinary stiffeners s_3 are installed inside the compartments, which provide local stability of the flanges and the web of the beam.

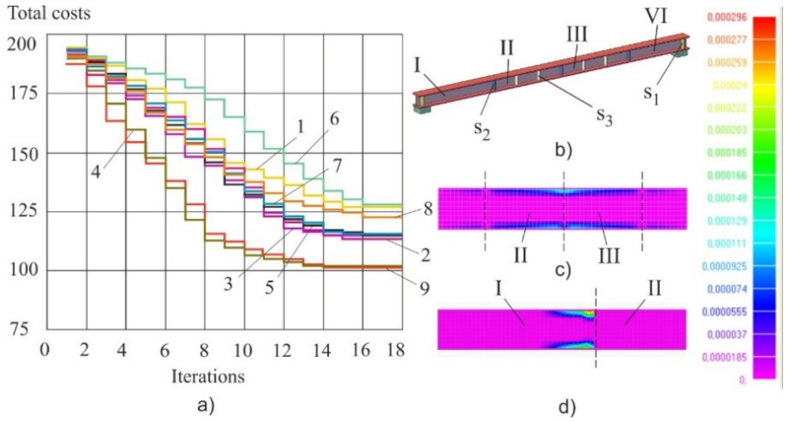


Figure 5. Data on the results of solving the problem: a – convergence graph of iterative processes, 1-9 number of solution on Table 6; b – I-beam stiffeners design topology; c, d – plastic strains on top fiber of the web for load cases 1 and 2 respectively

The FE-analysis of the overall stability of structure No. 9 from Table 5 in the NX Nastran software package (buckling mode) was performed. A shell model with “Plate” type of finite elements was used. As a result, a safety factor of 1.3257 was obtained. Local stability of the I-beam walls and shelves is also provided. Also an analysis under a static loading considering physical nonlinearity (nonlinear static mode) for this object has been performed. In the process the ideal elastoplastic Prandtl model was used to describe the material behavior. This calculation showed, that plastic deformations are present in the wall of the beam. This circumstance confirms the optimality of the obtained solution. The result is shown in Table 7 and Figure 5, c-d.

As a result of the calculation of the beam according to the method [25], the following values of the maximum deflections were obtained. The deflections, determined using the Mohr integrals, from the action of load case 1 and load case 2 were 5.81 mm and 5.94 mm, respectively. From Table 7 it can be seen that the allowable stresses correspond to the set limits. There are differences in displacement by 16.4% and 19.4%. These discrepancies are due to the physical nonlinearity in the finite element analysis.

The presented algorithm can be used effectively for statically definable beams and beam structures. When there is a large number of combinations of steel grades of a web and flanges, as well as when repeatedly statically indeterminate systems for the particle motion modelling are considered, it seems reasonable to introduce genetic algorithms with the finite element method to calculate the displacements [6, 20, 21].

According to the results of calculations for the specified hybrid beams, the displacement values, calculated on the basis of the control finite element analysis under a static loading considering physical nonlinearity, can surpass the deflection calculated on the basis of Mohr's integrals. If such excesses are impermissible according to manufacturing process or aesthetic requirements, the allowable movements should be reduced by 10-25% and the optimal search should be repeated.

Table 7. Components of the stress-strain state of the best solution (No. 9 in Table 5)

Load case	Compartment	Maximum equivalent stresses in the upper flange, MPa	Maximum equivalent stresses in the web, MPa	Maximum plastic strain in the web	Maximum deflection, cm
1	I	157	134	0.0	
	II	164	143	0.0	6.95
	III	182	225	0.00000	
	IV	332	225	0.00007	
2	I	313	225	0.00024	
	II	218	146	0.0	7.37
	III	229	154	0.0	
	IV	307	225	0.00007	

4. Conclusion

A method of search for rational solutions for hybrid I-beams on the basis of the particle swarm method modification was developed. It allows to design a hybrid I-beams, the web and flanges of which are made of different steels. The search is performed on discrete sets of the web and flanges dimensions’ values, as well as on the steel grades from which they are made. Optimization efficiency is achieved by parallel reproduction of the calculation procedure for each of the possible combinations of steel grades for flanges and web. In this case, the analytical dependencies used take into account the strength, stiffness, local and overall stability of the structure. The considered method has high convergence and allows to search for several solutions, based on the possibility of manufacturing the structure. The presented approach can be adapted to optimize other bearing structures, such as trusses and arches.

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