Optimal solution for the single-beam bridge crane girder using the Moth-Flame algorithm

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https://doi.org/10.5937/vojtehg72-51953

FIELD: mechanical engineering
ARTICLE TYPE: original scientific paper

Abstract:

Introduction/purpose: The paper analyses and optimizes the welded I-girder of the single-beam bridge crane with a U-profile as the top flange. This solution is to provide a lighter carrying structure, so the main goal is to minimize the weight of the main girder, i.e., the cross-sectional area while fulfiling the requirements defined by national standards and geometric constraints.

Methods: The Moth-Flame Optimization (MFO) algorithm was chosen for solving this single-objective multi-criteria optimization task using MATLAB. Also, the results were verified by using the Finite Element Analysis (FEA).

Results: The proposed girder shape is justified in examples of real solutions of single-beam bridge cranes and the previous research results. In this case, significant savings in the material and better results are achieved compared to the examples from the previous research.

ACKNOWLEDGMENT: This work has been supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia, through the Contracts for the scientific research financing in 2024, 451-03-65/2024-03/200108 and 451-03-66/2024-03/200108.

Conclusion: The proposed girder shape, methodology, the optimization algorithm and the achieved savings fully justify this research. Furthermore, this algorithm enables the application of many constraint functions, whereby the optimal values of numerous variables are obtained in a relatively short period. Therefore, it would not be possible to find the solution for that engineering task by applying analytical optimization methods.

Key words: bridge crane, welded girder, FEA, optimization, metaheuristic.

Introduction

Single-beam bridge cranes are used for handling the load in industrial facilities and warehouses as well as in transport, servicing, and maintenance. They are used increasingly in practice, and, in certain cases, their application is more economical than that of double-beam bridge cranes. The main engineering task is a proper choice of equipment and lightweight design of the single-beam bridge crane carrying structure. The welded box-girder or different types of standard rolled I-profiles are most often used as the main girder of single-beam bridge cranes, depending on the span and carrying capacity. However, the applied standard I-profiles are not usually used rationally, so the main crane girder is over-dimensioned. For this reason, a standard I-profile is often combined with the U-profile or L-profiles to increase global stability and achieve a lighter structure.

The analysis and optimization of crane support structures and I-girders have been the research subject in numerous publications. The optimization process can often be performed within the 3D modelling software. For example, Cvijović & Bošnjak (2016) used the 3D Finite Element Analysis (FEA) for local bending effects of the bottom flange of the monorail crane structure. Qin et al. (2015) presented the Solid Isotropic Material with Penalization (SIMP) optimization method on the example of the bridge crane's box girder, and the results were verified by using the FEA. Różyło (2016) used ABAQUS on the example of the I-girder. Finally, Ky et al. (2014) considered the problem of selecting optimal standard profiles of a steel structure by using SAP2000, where these results were compared with a heuristic optimization algorithm.

The application of various optimization algorithms is very present in engineering practice, for both single-objective and multi-objective optimization problems. For example, Qi et al. (2015) presented the Specular Reflection Algorithm application to optimize the box cross-section of the double-beam bridge crane. Wang & Diao (2012) solved a similar optimization problem using the Adaptive Genetic Algorithm.

Metaheuristic algorithms have been widely used in recent years. Pavlović et al. (2024) applied the Water Evaporation Optimization (WEO) algorithm to minimize the weight of the main girder with a non-symmetric box-like cross-section of the double-beam bridge crane. Similar to the previous, Jármai et al. (2021) optimized the cross-sectional area of the main girder of the double-beam bridge crane by applying 15 metaheuristic algorithms. Pavlović & Savković (2022) presented the application of the Moth-Flame Optimization (MFO) algorithm for the optimal design of the main girder of the double-beam bridge crane with an asymmetric box cross-section. It was concluded that the application of that method is justified. Jármai et al. (2003) considered the problem of optimizing the dimensions of the welded I-girder, where three metaheuristic algorithms were applied, as well as Rosenbrock's method.

The I-girder optimization is an actual problem in many previously cited papers. The analysis of global stability is specific to this type of structure. Ellifritt & Lue (1998) analysed the global stability of the I-girder with a channel cap (U-profile), proposing the analytical model for the calculation. The model is experimentally verified. Trahair (2009) studied the I-crane girder concerning lateral distortion buckling according to Australian Standard (AS). The design method proposed is applied to a concrete example. Mela & Heinisuo (2014) optimized the weight and cost of the high-strength steel welded I-girder by the Particle Swarm Optimization (PSO) algorithm. Gąska et al. (2017) analyzed the stresses due to the local bending of the I-girder bottom flange within the single-beam bridge crane using Eurocodes. The obtained analytical results were compared to those from the FEA conducted by ABAQUS. Pavlović et al. (2018) applied the Generalized Reduced Gradient (GRG2) algorithm to the mono-symmetric welded I-girder of the single-beam bridge crane, with significant material savings for the given examples. Sitthipong et al. (2018) considered the complex design of a crane runway beam, composed of an I-section and a U-section, using ASME standards, concerning deflection and stress. In the paper by Schaper et al. (2019), lateral torsional buckling is also considered in various welded I-girder shapes. Besides the usual checking procedure, a simplified verification according to Eurocode was made. Molnár et al. (2022) compared the analytical results to those obtained from the FEA analysis made in ANSYS on the example of the single-beam bridge crane I-girder.

The numerous publications mentioned show a broad application of metaheuristic optimization algorithms. In this paper, the MFO algorithm is applied for a single-objective multi-criteria optimization problem to reduce the weight of the single-beam bridge crane girder. MFO is highly efficient in solving problems in mechanical and structural design, as shown in the paper by Mirjalili (2015) which presented the algorithm. Besides the good mechanical and structural design results compared to some other algorithms, it stands out in complex examples such as a marine propeller analysis. The comparison between the MFO algorithm and other algorithms was also presented in Pavlović et al. (2022), where authors studied the weight reduction of the welded cantilever beam subjected to restrained warping.

The research subject in this paper is the analysis and optimization of the welded I-cross-section with a U-profile as the top flange of the main girder of the single-beam bridge crane. A U-profile can be easily manufactured by cold-forming. Due to its geometry, the cold-formed U-profile enables a more rational material use, providing better overall resistance of the girder to the lateral instability, which is the most critical condition for that carrying structure. Furthermore, as the top part of the girder, the U-profile can be formed from a 0.5 cm thick plate, which ensures a lighter type of a carrying structure. This cross-section is simpler than the standard I-profile reinforced with a standard U-profile or a standard I-profile reinforced with two L-profiles. In this way, a light welded structure of the girder is achieved, composed mainly of thin plates (except for the bottom flange), which satisfies all necessary design and work conditions.

The trolley wheels run on the bottom flange and cause its local bending, while the top flange is compressed, so it must be stable in both vertical and horizontal planes. Using standard rolled I-profiles in single-girder bridge cranes is not rational because of the preceding reasons, so these girders are mostly overdesigned.

The objective of the proposed solution in this research is to show that, in this manner, it is possible to gain extra savings in the plate material and thus reduce the total weight of the girder. Since the upper part of the girder is exposed to compression, this solution increases the global stability of the girder and provides the most optimal structure. Finally, the results are compared to the welded girder optimization results obtained by Pavlović et al. (2018) for four examples of single-beam bridge cranes.

Optimization problem

The weight reduction of the welded main girder means to determine the optimal geometric parameters for the proposed type of the cross-section, while all constraint functions must be satisfied.

Figures 1 and 2 present the general view of a single-beam bridge crane with the accompanying equipment and the cross-section of the welded girder with the trolley, respectively.

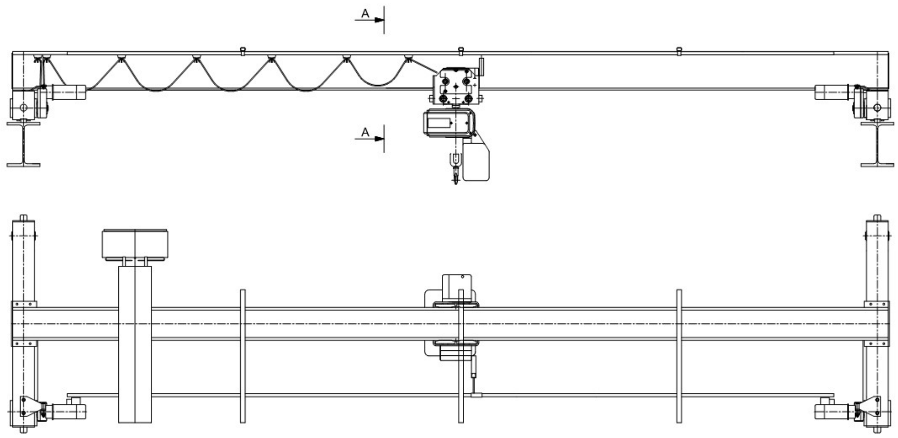

Figure 1 – General view of the structure of the single-girder bridge crane

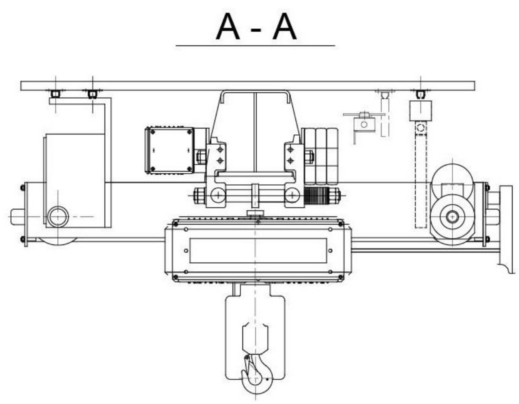

Figure 2 – Cross-section of the welded girder and the trolley (A – A section)

Figure 1 shows the crane-carrying structure which consists of the main girder and the end girders. It also shows an electrical winch with the trolley moving along the main girder.

Figure 2 shows the cross-section of the main girder with the trolley hanging on the bottom flange. This cross-sectional area is the subject of the optimization task.

Mathematical formulation of the optimization problem

This single-objective multi-criteria optimization problem can be defined as:

$$\min\left[f_o\left(X\right)\right] \; subject\ to, \tag{1}$$

$$g_i\left(X\right)=g_{ir}\left(X\right)-g_{id}\left(X\right)\leq 0,\; l_j\leq x_j\leq u_j, \tag{2}$$

where $f_o(X)$ is the objective function, $g_i(X)$ are the constraint functions, $g_{ir}(X)$ is the real value of the criterion, $g_{id}(X)$ is the permissible value of the criterion, i=1,..,m is the number of constraints, j=1,..,n is the number of design variables, and X is the design vector made of n variables.

The variables (x_j) are values that should be defined during the optimization process, and each of them is defined by its lower (l_j) and upper limit (u_j). This paper considers seven geometric variables (Figure 3):

$$X=\left[h\ d\ b\ t\ b_1\ h_1\ a_s\right]^T, \tag{3}$$

where h is the web height, d is the web thickness, b is the bottom flange width, t is the bottom flange thickness, b_1 is the width of the top side of the U-profile, h_1 is the inner width of the lateral side of the U-profile, and a_s is the weld thickness, (Figure 3).

The input parameters for the optimization process are, Ostrić & Tošić (2005): the Classification class, Q - the carrying capacity, L - the span, m_k - the mass of the trolley, b_k - the distance between the wheels of the trolley, e_1 - the distance between wheel 1 and the resulting force in the vertical plane (Figure 4), n_k – the number of trolley wheels (4 in all examples), r_k=1.5 cm – the distance from the edge of the bottom flange to the vertical load of the trolley wheel (Figure 3), γ - the coefficient which depends on the Classification class, ψ - the dynamic coefficient of the influence of load oscillation in the vertical plane, k_a - the dynamic coefficient of crane load in the horizontal plane, K_f - the coefficient of stiffness (depending on the Classification class, the purpose of the bridge crane, and the control condition), T_d - the permissible time of the damping of oscillation of the girder (depending on the purpose of the crane), v_1 – the load case 1 factored load coefficient, v_2 – the load case 2 factored load coefficient, E=21000 kN/cm^2 - Young's modulus of the plate material, and R_e - the minimum yield stress of the plate material.

In all considered examples in this research, the crane control is by an operator on the floor, using a pendant system.

Cross-sectional area (the objective function)

The cross-sectional area (Figure 3) f_o of the welded girder is given by the following equation, Eq. (4):

$$f_o = A_p + A_s, \tag{4}$$

where A_p is the area composed of the U-profile (A_U), the web (A_w), and the bottom flange (A_f), and A_s is the area of the welded joints.

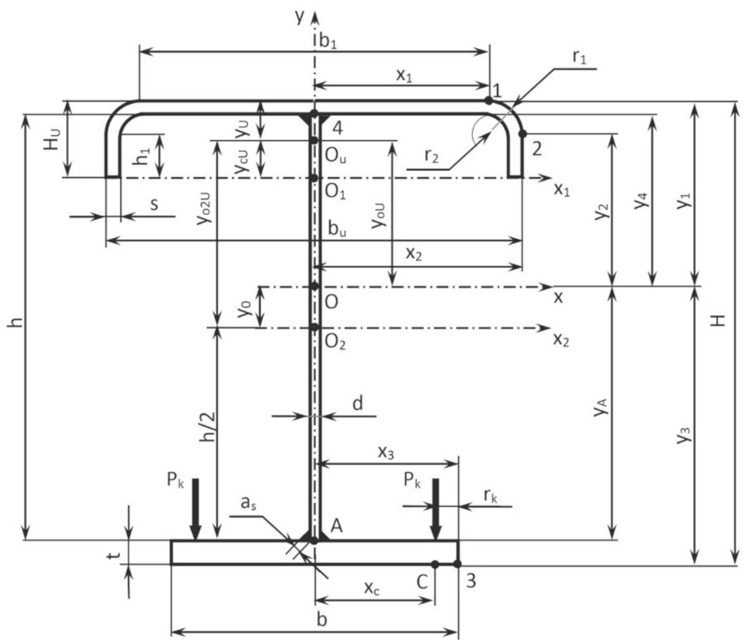

Figure 3 – Cross-section of the main girder of the single-beam bridge crane

$$A_p = A_U + A_w + A_f, \tag{5}$$

$$A_U = s\left(b_1 + 2h_1\right) + \pi\left(r_1^2 - r_2^2\right)/2,\ A_w = d \cdot h,\ A_f = t \cdot b, \tag{6}$$

$$A_s = 4a_s^2, \tag{7}$$

where A_p is the area composed of the U-profile (A_U), the web (A_w), and the bottom flange (A_f), A_s is the area of the welded joints, $r_1=r_2+s$ is the outer radius of the U-profile, r_2 is the inner radius of the U-profile (r_2=0.6 cm), and s is the thickness of the U-profile (s=0.5 cm).

Besides variables, Figure 3 depicts all other necessary geometry parameters used in this analysis.

The principal central axes' position and the geometric properties in the cross-section's characteristic points are calculated by well-known equations.

The geometric constraints for some of the dimensions are given as follows:

$$g_1 = H - H_d = h + t + s - H_d \leq 0, \tag{8}$$

$$g_2 = b_U - b_{Ud} = b_1 + 2 \cdot (r_2 + s) - b_{Ud} \leq 0, \tag{9}$$

$$g_3 = H_U - H_{Ud} = h_1 + r_2 + s - H_{Ud} \leq 0, \tag{10}$$

where H is the profile height, H_d is the permissible value of the profile height, b_U is the width of the U-profile, b_{Ud} is the permissible value of the width of the U-profile, H_U is the height of the U-profile, and H_{Ud} is the permissible value of the height of the U-profile (Figure 3).

Static model of the main girder

The following static scheme shows a model of the main girder in the form of a simple beam with loads in the vertical and horizontal planes (Figure 4). The location of forces on the beam corresponds to maximum bending moments, which are predominant for this type of structure.

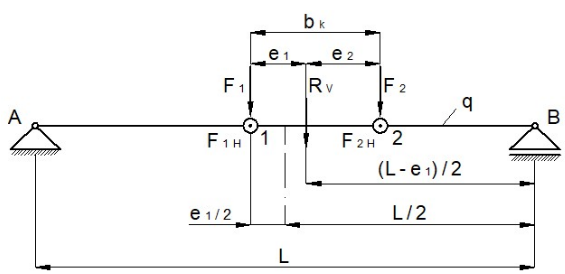

Figure 4 – Static scheme of the main girder of the single-beam bridge crane

where R_V is the resulting force in the vertical plane, F_1, F_2 are the acting forces in the vertical plane, upon the bottom flange, from trolley wheels 1 and 2, respectively, e_2 is the distance between wheel 2 and the resulting force in the vertical plane, F_{1H}, F_{2H} are the acting forces in the horizontal plane, upon the bottom flange, from trolley wheels 1 and 2, respectively, and q is the specific weight per unit of length of the girder.

The quantities necessary for defining the optimization criteria are being calculated by using the well known expressions (Ostrić & Tošić, 2005).

The next sub-chapters introduce the criteria for analyzing and calculating the single-beam crane main girder. All conditions that have to be fulfilled related to strength, stability, stiffness and oscillation are taken into account according to Ostrić & Tošić (2005) and Serbian Standards: SRPS U.E7.121:1987, SRPS U.E7.081:1987, SRPS U.E7.086:1987, and SRPS U.E7.101:1991 (Petković & Ostrić, 1996).

Strength criterion

In this research, only normal stress components are considered. Tangential stresses are neglected, as the bending moments are predominant for this type of structure.

The maximum stresses at the observed points (Figure 3) must be lower than the permissible ones (σ_{d1} or σ_{d2}). In addition, the local stresses in the *x* and *z* directions must be lower than σ_{d1}, where σ_{d1}, σ_{d2} are the permissible stresses for the load case 1, and the load case 2, rescpectively.

For this criterion, the constraint functions are:

$$g_4 = \sigma_{1z} - \sigma_{d1} = \frac{M_V}{W_{1x}} + \frac{M_H}{W_{1y}} - \sigma_{d1} \le 0, \quad (11)$$

$$g_5 = \sigma_{2z} - \sigma_{d1} = \frac{M_V}{W_{2x}} + \frac{M_H}{W_{2y}} - \sigma_{d1} \le 0, \quad (12)$$

$$g_6 = \sigma_{3z} - \sigma_{d1} = \frac{M_V}{W_{3x}} + \frac{M_H}{W_{3y}} - \sigma_{d1} \le 0, \quad (13)$$

$$g_7 = \sigma_{A,u} - \sigma_{d1} \le 0, \quad (14)$$

$$g_8 = \sigma_{Az} - \sigma_{d1} = \frac{M_V}{W_{Ax}} - \sigma_{d1} \le 0, \quad (15)$$

$$g_9 = \sigma_{Akz} - \sigma_{d1} = K_{Az} \cdot P_k / t^2 - \sigma_{d1} \le 0, \quad (16)$$

$$g_{10} = \sigma_{Akx} - \sigma_{d1} = K_{Ax} \cdot P_k / t^2 - \sigma_{d1} \le 0, \quad (17)$$

$$g_{11} = \sigma_{C,u} - \sigma_{d2} \leq 0, \tag{18}$$

$$g_{12} = \sigma_{Cz} - \sigma_{d1} = \frac{M_V}{W_{Cx}} + \frac{M_H}{W_{Cy}} - \sigma_{d1} \leq 0, \tag{19}$$

$$g_{13} = \sigma_{Ckz} - \sigma_{d1} = K_{Cz} \cdot P_k / t^2 - \sigma_{d1} \leq 0 \tag{20}$$

$$g_{14} = \sigma_{Ckx} - \sigma_{d1} = K_{Cx} \cdot P_k / t^2 - \sigma_{d1} \leq 0, \tag{21}$$

$$\sigma_{A,u} = \sqrt{\left(\sigma_{Az} + \sigma_{Akz}\right)^2 + \sigma_{Akx}{}^2 - \left(\sigma_{Az} + \sigma_{Akz}\right)\sigma_{Akx}}, \tag{22}$$

$$\sigma_{C,u} = \sqrt{\left(\sigma_{Cz} + \sigma_{Ckz}\right)^2 + \sigma_{Ckx}{}^2 - \left(\sigma_{Cz} + \sigma_{Ckz}\right)\sigma_{Ckx}}, \tag{23}$$

$$\sigma_{d1} = R_e / \nu_1,\ \nu_1 = 1.5, \tag{24}$$

$$\sigma_{d2} = R_e / \nu_2,\ \nu_2 = 1.33, \tag{25}$$

where σ_{pz} is the normal stress at the observed point p (p=1, 2, 3, A, C), W_{px}, W_{py} are the section moduli of the area A_p for the point p, σ_{Akz}, σ_{Akx} are the local stresses at the point A, in both directions, respectively, σ_{Ckz}, σ_{Ckx} are the local stresses at the point C, in both directions, respectively, $\sigma_{A,u}$, $\sigma_{C,u}$ are the equivalent stresses at the point A and the point C, respectively, M_V, M_H are the bending moments in the vertical and horizontal planes, respectively, P_k is the maximum pressure of the trolley wheel, K_{Az}, K_{Ax} are the corresponding coefficients for the local stresses at the point A, and K_{Cz}, K_{Cx} are the corresponding coefficients for the local stresses at the point C (Ostrić & Tošić, 2005).

Strength criterion for the welded joints

The maximum stress in the welded connection (σ_s) must be lower than the permissible one (σ_{ds}). The constraint functions for this criterion are:

$$g_{15} = \sigma_s - \sigma_{ds} = \frac{F_T \cdot S_x}{2 \cdot I_x \cdot a_s} - 0.75 \cdot \sigma_{d1} \leq 0, \tag{26}$$

$$g_{16} = a_s - 0.7 \cdot \min\left(s,\ d\right) \leq 0, \tag{27}$$

where F_T is the maximum shear force, S_x is the static moment of the area A_p about the *x*-axis, and I_x is the moment of inertia of the area A_p about the *x*-axis.

Local stability of the web

Checking the local stability of the web is performed according to Standard SRPS U.E7.121:1987 (Petković & Ostrić, 1996). The constraint function is:

$$g_{17} = \nu_1 \cdot M_V / W_{4x} - \min\left(R_e, c_w \cdot \chi_w \cdot R_e\right) \leq 0, \tag{28}$$

where W_{4x} is the section moduli of the area A_p for point 4, χ_w is a reduction factor of the web, SRPS U.E7.121:1987 (Petković & Ostrić, 1996), and c_w is a coefficient, SRPS U.E7.121:1987 (Petković & Ostrić, 1996).

Global stability of the welded girder

The verification of global stability, in this case, is performed based on Serbian Standards: SRPS U.E7.081:1987, SRPS U.E7.086:1987, and SRPS U.E7.101:1991 (Petković & Ostrić, 1996). The constraint functions for this criterion have the following form:

$$g_{18} = \max\left(\sigma_{1z}, \sigma_{2z}\right) - 1.14 \cdot \chi_p \cdot \sigma_{d1} \leq 0, \tag{29}$$

$$g_{19} = i_p - i_y = \sqrt{\frac{I_{yU}}{A_U}} - \frac{L}{40} \cdot \sqrt{\frac{R_e}{23.5}} \leq 0, \tag{30}$$

where χ_p is a non-dimensional coefficient of the global stability, SRPS U.E7.081:1987 (Petković & Ostrić, 1996), i_p is the radius of gyration of the U-profile about the *y*-axis, i_y is the required value of the radius of gyration, and I_{yU} is the moment of inertia of the U-profile about the *y*-axis.

Criterion of oscillation

With this criterion, the damping time (*T*) of oscillations (relaxation time) of the mass m_1, located in the middle of the main girder, must be checked (Ostrić & Tošić, 2005). The constraint function has the following form:

$$g_{20} = T - T_d = \tau \cdot \ln(20) / \gamma_d - T_d \leq 0, \tag{31}$$

$$m_1 = Q + m_k + 17 \cdot m / 35, \tag{32}$$

$$\tau = \pi \cdot \sqrt{m_1 \cdot L^3 / \left(12 \cdot B_x\right)}, \tag{33}$$

where m is the mass of the girder, m_1 is the mass concentrated at the midspan, $B_x = E \cdot I_x$ is the flexural rigidity of the girder, τ is the period of oscillations, and γ_d is the logarithmic decrement which shows the rate of oscillation damping (depending on the ratio between the height of the welded girder, H and the span, L) (Ostrić & Tošić, 2005).

Criterion of stiffness

This criterion analyses deflection in the vertical plane. In addition to the acting of trolley wheels (f_1), the specific weight of the main girder (f_q) is also observed. The total deflection (f_u) must be lower than the permissible one (f_d):

$$f_u = f_1 + f_q \le f_d = K_f \cdot L, \tag{34}$$

$$f_1 = \frac{F_{1,st} \cdot L^3}{48 \cdot B_x} \cdot \left\{ 1 + \frac{F_{2,st}}{F_{1,st}} \cdot \left[1 - 6 \cdot \left(\frac{b_k}{L} \right)^2 \right] \right\}, \tag{35}$$

$$f_q = \frac{5 \cdot q \cdot L^4}{384 \cdot B_x}, \tag{36}$$

where $F_{1,st}$, $F_{2,st}$ are the static forces in the vertical plane, upon the bottom flange, from trolley wheels 1 and 2, respectively (Ostrić & Tošić, 2005).

The constraint function, based on Eq. (37), is:

$$g_{21} = f_u - f_d = f_u - K_f \cdot L \le 0. \tag{37}$$

Optimization method

The MFO algorithm is a relatively new population nature-inspired metaheuristic algorithm based on the computer simulation of the navigation of moths, introduced by Mirjalili (2015). This algorithm is widely used in science and engineering. Moths use their unique navigation methods at night. They have evolved to fly at night using the moonlight, where a moth flies by maintaining a fixed angle in relation to the moon. Since the moon is so far from a moth, a moth flies in a straight line. Moths fly spirally around the artificial lights because they are tricked by them. When moths see artificial light, they try to maintain an angle to the light source. Since such a light source is extremely close compared to the moon, maintaining the angle to the light source causes a useless or deadly spiral flying path for moths. In this algorithm, it is presumed that the candidate solutions are moths, and variables are the positions of moths in the space. Moths and flames are both solutions. The difference between them is the way how to treat and update them in each iteration. The moths are actual search agents that move around the search space, whereas flames are the best position of moths that have been obtained so far. Therefore, each moth searches around a flame and updates it if it finds a better solution. In this way, a moth never loses its best solution.

The pseudocode for this metaheuristic optimization algorithm is shown in Mirjalili (2015).

Optimization results

The optimization process will be based on the presented MFO method, in the MATLAB software. In addition, the solutions of single-beam bridge cranes, taken from Pavlović et al. (2018), will be considered as examples to compare the results obtained (four examples of single-beam bridge cranes).

Table 1 shows the data of single-beam bridge cranes that are in exploitation. These data also represent the input parameters for the optimization process, where A_{pr} represents the cross-sectional area of the standard rolled profile and b_{min} represents the minimum value for the bottom flange width. All cranes are in Classification class 2.

Other input parameters are: γ=1.05, ψ=1.15, K_f=1/500, and T_d=15 s.

Table 1 – Technical parameters of single-beam cranes

Example	Q (t)	L (m)	m_k (kg)	b_k (mm)	e_1 (mm)	b_{min} (mm)	k_a (-)	Re (kN/cm^2)	A_{pr} (cm^2)
1	5	16.78	350	405	202.5	100	0.1	27.5	260
2	3.2	10.0	340	196	98	82	0.1	23.5	143
3	10	7.75	610	708	354	100	0.05	23.5	239
4	6.3	5.92	380	420	225	100	0.1	23.5	181

The control parameters of the MFO algorithm used for each example in this paper are N_{pop}=200 - population size and *max_it*=300 - maximum number of iterations.

The maximum values (in centrimeters) for the characteristic geometric quantities are: H_d = 100, b_{Ud} = 40, H_{Ud} = 20.

The boundary values (in centrimeters) of the variables for all bridge cranes are: $20 \le h \le 100$, $0.5 \le d \le 2$, $b_{min} \le b \le 30$, $0.6 \le t \le 4$, $10 \le b_1 \le 40$, $3 \le h_1 \le 20$, $0.3 \le a_s \le 0.7$.

After applying the MFO optimization procedure, the following optimal geometric parameters, the value of the objective function and the characteristics of the optimization procedure are obtained (Table 2), where *Std* is the standard deviation of the optimization process.

Table 2 – Optimization results

Example	h (cm)	d (cm)	b (cm)	t (cm)	b_1 (cm)	h_1 (cm)	f_o (cm^2)	Std (-)
1	81.52	0.5	10.00	1.88	37.80	15.24	95.44	16.54
2	46.48	0.5	8.20	1.74	33.80	3.00	59.14	5.97
3	68.95	0.5	10.00	2.69	37.42	3.00	84.73	6.41
4	44.14	0.5	10.00	2.20	32.49	3.00	64.98	3.63

The optimal value for the variable a_s is 0.3 cm in all examples.

The following figures show the convergence graphs for all examples (Figures 5–8).

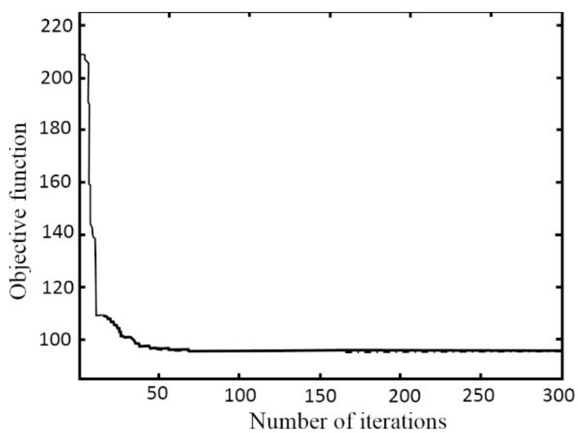

Figure 5 – Convergence graph for Example 1

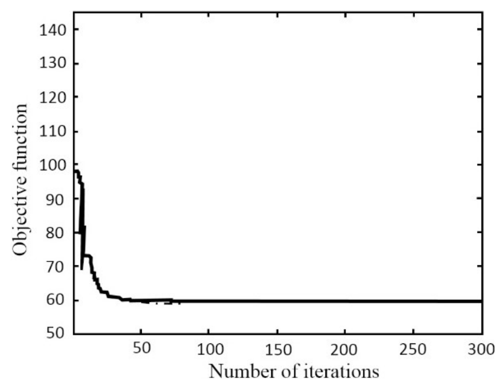

Figure 6 – Convergence graph for Example 2

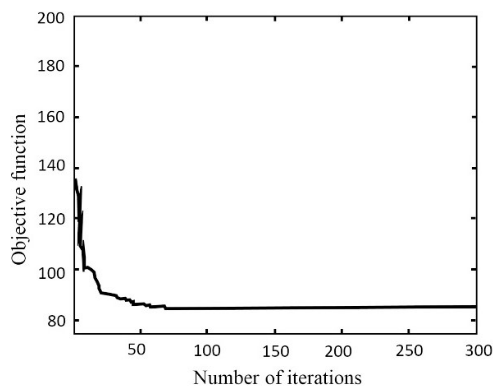

Figure 7 – Convergence graph for Example 3

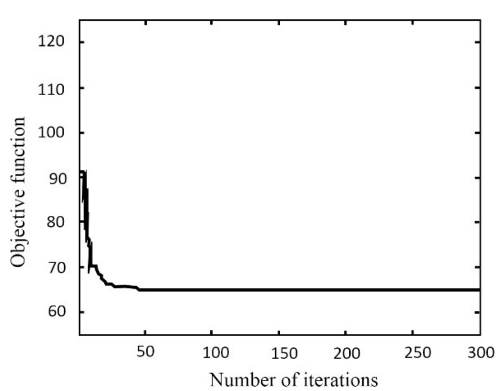

Figure 8 – Convergence graph for Example 4

Table 3 shows the rounded values of the optimal geometric parameters, the optimal areas A_{op}, and the material savings.

Table 3 – Rounded values of the optimal geometric parameters and the material savings

Example	h (cm)	d (cm)	b (cm)	t (cm)	b_1 (cm)	h_1 (cm)	A_{op} (cm^2)	Saving (%)
1	81.5	0.5	10.0	1.9	37.8	15.3	95.29	63.35
2	46.5	0.5	8.2	1.8	33.8	3.0	59.25	58.57
3	69.0	0.5	10.0	2.7	37.5	3.0	84.59	64.61
4	44.1	0.5	10.0	2.2	32.5	3.0	64.64	64.29

To determine which criteria are the most critical, Table 4 shows the values of the optimization criteria (for the obtained optimal geometric parameters, Table 2) g_{ir} and the boundary (permissible) values for two characteristic examples of optimization g_{id}. In addition, Example 1 with the largest bridge span and Example 3 with the largest carrying capacity were analysed.

For all values of i=1,..,m, m=21, g_{ir} is less than or equal to g_{id}, which means that the boundary conditions were not exceeded. Then, comparing two examples of bridge cranes, where the first one has a twice greater span than the second one, and the second one has a twice greater carrying capacity than the first one, it is determined which criteria are the most critical for both cases.

Table 4 – Calculated and permissible values of all criteria for Example 1 and Example 3

i	Example 1		Example 3	
	g_{ir}	g_{id}	g_{ir}	g_{id}
1 (cm)	83.90	100	72.13	100
2 (cm)	40	40	39.62	40
3 (cm)	16.34	20	4.10	20
4 (kN/cm^2)	15.25	18.33	15.67	15.67
5 (kN/cm^2)	15.26	18.33	15.61	15.67
6 (kN/cm^2)	14.81	18.33	11.77	15.67
7 (kN/cm^2)	14.14	18.33	11.80	15.67
8 (kN/cm^2)	12.86	18.33	9.74	15.67
9 (kN/cm^2)	3.21	18.33	3.14	15.67
10 (kN/cm^2)	10.51	18.33	10.27	15.67
11 (kN/cm^2)	20.68	20.68	17.67	17.67
12 (kN/cm^2)	14.38	18.33	11.40	15.67
13 (kN/cm^2)	8.72	18.33	8.52	15.67

i	Example 1		Example 3	
	g_{ir}	g_{id}	g_{ir}	g_{id}
14 (kN/cm^2)	6.31	18.33	6.17	15.67
15 (kN/cm^2)	1.25	13.75	2.27	11.75
16 (cm)	0.3	0.35	0.3	0.35
17 (kN/cm^2)	14.57	14.58	16.42	19.06
18 (kN/cm^2)	15.26	15.26	15.67	16.41
19 (cm)	15.66	45.38	12.89	19.38
20 (s)	14.03	15	4.05	15
21 (cm)	2.74	3.36	0.64	1.55

The FEA for Examples 1 and 3 were carried out in Autodesk Inventor Nastran software to check the optimization results for the stress and the stiffness (deflection) criteria. The 3D CAD models of the main girders were made in Autodesk Inventor software using the data from Tables 1 and 3. They were the basis for creating the finite element models using the shell elements. The analyses were conducted for the critical trolley position depicted in Figure 4.

Figures 9 and 10 depict the equivalent stress and the deflection for Example 1, respectively.

Figure 9 – Equivalent stress for Example 1

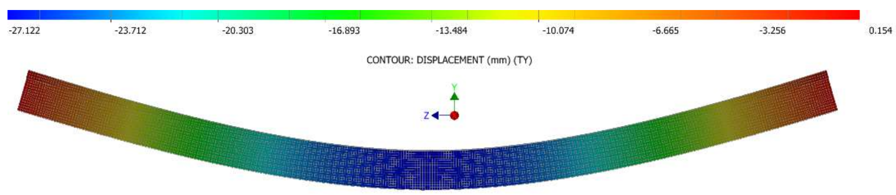

Figure 10 – Deflection for Example 1

Figures 11 and 12 depict the equivalent stress and the deflection for Example 3, respectively.

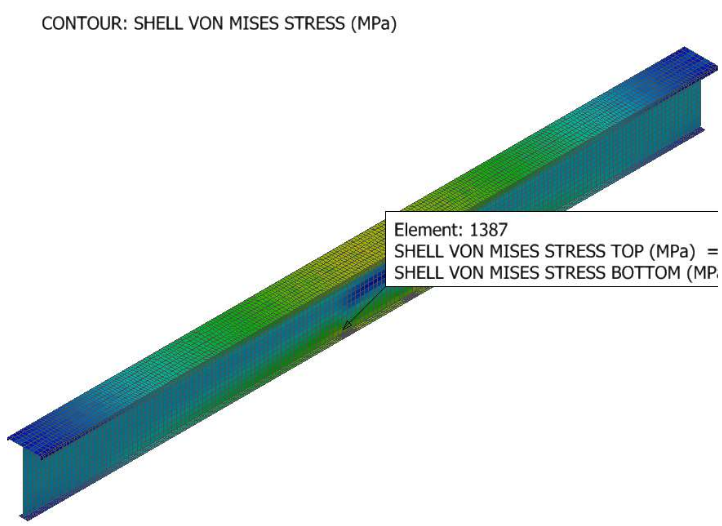

Figure 11 – Equivalent stress for Example 3

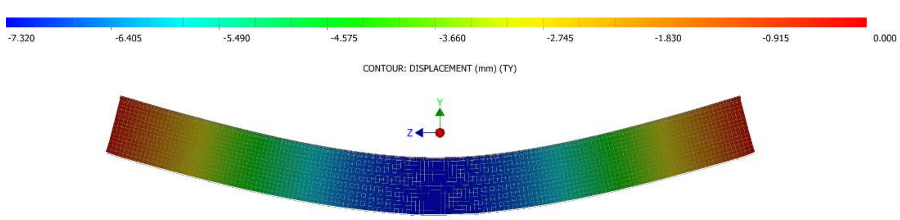

Figure 12 – Deflection for Example 3

Conclusion

This research presents the analysis and the optimization procedure for a welded I-profile with a U-profile as the top flange (the main girder) of the single-beam bridge crane, according to national standards, using the MFO optimization method. The criteria of permissible stresses in the characteristic points of the cross-section, the stress in the weld joints, the local stability of the web, the global stability of the girder, the deflection of the girder, the damping time of oscillations, and the geometric limits were applied as constraint functions. The objective function is the cross-sectional area.

The results justify the application of the presented model of the welded I-girder with a U-profile as the top flange and the applied nature-inspired optimization algorithm. This is concluded by comparing the results from Table 3 to the results in Pavlović et al. (2018).

Significant material savings within 58.57-64.61% are achieved compared to the considered examples of single-beam bridge cranes (made of standard I-profiles, Table 1). These results are better than those in Pavlović et al. (2018) (which are within 47.36-61.98%).

It should be noted that the global stability of the welded girder is of primary importance (except for the last two examples where there are smaller spans and higher carrying capacities). It is to be expected, so when designing these types of structures, one should pay attention to this condition. The local stability of the web is also essential in the analysis and optimization of these types of girders, which is specific for the examples where spans are larger than 10 m (Example 1, Table 4). Considering the strength criterion, in all examples, the stress at the point *C* achieved its boundary value, while in the cases of higher carrying capacities, it occurred in points 1 and 2. The stiffness criterion was not dominant in these examples. Also, the oscillation damping period did not have values close to the limit, except in the case with a larger span (Example 1). The stress in the welded joints was far lower than the limit values in all examples.

Regarding the applied metaheuristic optimization algorithm, the MFO method proved to be very efficient, which can be seen from the convergence graphs (Figures 5-8), i.e. the standard deviation (*Std*, Table 2). Furthermore, the graphs show that the minimum value of the objective function is achieved in fewer than 100 iterations, in one example in fewer than 50 iterations (Figure 8).

The FEA for Examples 1 and 3 (Figures 9-12) showed good compliance with the optimization results (Table 4). The relative deviation for the Example 1 maximum equivalent stress was 3.7% (the optimization result was 20.68 kN/cm^2 while the FEA yielded 19.93 kN/cm^2), and the relative deviation for the Example 1 deflection was 1.1% (the optimization result was 2.74 cm while the FEA yielded 2.71 cm). In addition, the relative deviation for the Example 3 maximum equivalent stress was 5.5% (the optimization result was 17.67 kN/cm^2 while the FEA yielded 18.69 kN/cm^2), and the relative deviation for the Example 3 deflection was 12.5% (the optimization result was 0.64 cm while the FEA yielded 0.73 cm).

As a large number of constraint functions can be used in the presented procedure, this analysis can be further expanded. Additional conditions may be included in future research, such as manufacturability, green design, material fatigue, economic aspects, etc.

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Solución óptima para la viga puente de grúa monoviga mediante el algoritmo Moth-Flame

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CAMPO: ingeniería mecánica
TIPO DE ARTÍCULO: artículo científico original

Resumen:

Introducción/objetivo: El artículo analiza y optimiza la viga I- soldada del puente grúa monoviga con perfil en U como ala superior. Esta solución tiene como objetivo proporcionar una estructura de transporte más ligera, por lo que el objetivo principal es minimizar el peso de la viga principal, es decir, el área de la sección transversal, al tiempo que se cumplen los requisitos definidos por las normas nacionales y las limitaciones geométricas.

Métodos: Se eligió el algoritmo Moth-Flame Optimization (MFO) para resolver esta tarea de optimización multicriterio de un solo objetivo utilizando MATLAB. Además, los resultados se verificaron utilizando el análisis de elementos finitos (FEA).

Resultados: La forma de viga propuesta se justifica en ejemplos de soluciones reales de puentes grúa monoviga y en los resultados de investigaciones anteriores. En este caso, se consiguen ahorros significativos en el material y mejores resultados en comparación con los ejemplos de la investigación anterior.

Conclusión: La forma de viga propuesta, la metodología, el algoritmo de optimización y los ahorros conseguidos justifican plenamente esta investigación. Además, este algoritmo permite la aplicación de muchas funciones de restricción, con lo que se obtienen los valores óptimos de numerosas variables en un periodo relativamente corto. Por tanto, no sería posible encontrar la solución para esa tarea de ingeniería aplicando métodos de optimización analítica.

Palabras claves: puente grúa, viga soldada, FEA, optimización, metaheurística.

Оптимальное решение для однобалочной подкрановой балки моста с использованием алгоритма Moth-Flame

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РУБРИКА ГРНТИ: 55.51.31 Краны и крановое оборудование
ВИД СТАТЬИ: оригинальная научная статья

Резюме:

Введение/цель: В данной статье анализируется и оптимизируется сварная двутавровая балка однобалочного мостового крана с U-образным профилем в качестве верхней ламели. Это решение облегчает несущую конструкцию, так как основной целью является минимизация веса основной балки, то есть площади поперечного сечения при соблюдении требований, определенных государственными стандартами и геометрическими ограничениями.

Методы: Для решения одноцелевой задачи многокритериальной оптимизации с использованием MATLAB был выбран алгоритм оптимизации по принципу "Пламя мотылька" (MFO). Помимо того, результаты были проверены с помощью метода конечных элементов (FEA).

Результаты: Предложенная форма балки обоснована примерами реальных решений однобалочных мостовых кранов и результатами предыдущих исследований. В этом случае достигаются значительная экономия материалов и лучшие результаты по сравнению с примерами предыдущих исследований.

Выводы: Предложенная форма балки, методология, алгоритм оптимизации и достигнутая экономия полностью оправдывают данное исследование. Помимо того, этот алгоритм позволяет применять множество ограничивающих функций, благодаря чему оптимальные значения множества переменных выводятся за относительно короткий промежуток времени. Следовательно, решить эту инженерную задачу, применяя аналитические методы оптимизации, было бы невозможно.

Ключевые слова: мостовой кран, сварная балка, МКЭ, оптимизация, метаэвристика.

Оптимално решење носача једногредне мосне дизалице применом алгоритма Мољца

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ОБЛАСТ: машинство
КАТЕГОРИЈА (ТИП) ЧЛАНКА: оригинални научни рад

Сажетак:

Увод/циљ: У раду се анализира и оптимизира заварени I-носач једногредне мосне дизалице са U-профилом као горњом ламелом. Ово решење обезбеђује лакшу носећу конструкцију, тако да је главни циљ минимизирање тежине главног носача, односно површине попречног пресека, уз испуњавање услова дефинисаних националним стандардима и геометријским ограничењима.

Методе: Алгоритам Мољца (MFO) изабран је за решавање овог једноциљног вишекритеријумског задатка оптимизације применом MATLAB-а. Такође, резултати су верификовани коришћењем методе коначних елемената (МКЕ).

Резултати: Предложени облик носача је оправдан на примерима реалних решења једногредних мосних дизалица. У овом случају постижу се значајне уштеде у материјалу и бољи резултати у односу на примере из претходног истраживања.

Закључак: Предложени облик носача, методологија, алгоритам оптимизације и остварене уштеде у потпуности оправдавају ово истраживање. Поред тога, овај алгоритам омогућава примену многих функција ограничења, при чему се у релативно кратком периоду добијају оптималне вредности бројних варијабли. Због тога, применом метода аналитичке оптимизације не би било могуће наћи решење за такав инжењерски задатак.

Кључне речи: мосна дизалица, заварени носач, МКЕ, оптимизација, метахеуристика.

Paper received on: 03.02.2024.
Manuscript corrections submitted on: 25.09.2024.
Paper accepted for publishing on: 26.09.2024.