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MASS MINIMIZATION OF BRIDGE CRANES' MAIN GIRDER ACCORDING TO EUROCODE

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Abstract: *Double-beam bridge cranes are the most common in the industry compared to other types of bridge cranes. In addition to box girders, I-profiles are also present as the main girders of double-beam bridge cranes. Since I-profiles have defined dimensions, their geometry is often not optimally utilised for some of the criteria that must be satisfied; therefore, these beams are oversized in such cases. For this purpose, it is necessary to optimize the geometry of the I-profile, which is the topic of this research. This paper addresses the optimal design of a welded double-symmetrical I-girder for a double-beam bridge crane. The minimum mass, i.e. the cross-sectional area of the I-girder, is set as the objective function. The constraint functions include the stresses in the characteristic points of the I-profile at the critical location of the girder, the stress in the welded joint, the deflection at the middle of the girder, the oscillation period of the beam, as well as the global stability of the I-girder. The strength and stability checking are performed according to Eurocode, and the cross-section of the girder is considered for Class 3. The optimization was carried out using a modern algorithm of optimization. Two bridge cranes were used as examples. Finally, the results obtained are compared to the geometrical values of the standard I-profiles in the considered examples of bridge cranes, where conclusions and recommendations for further research are presented.*

Key words*: double-beam bridge crane, optimization, metaheuristic, stress, welded connection, deflection, period of oscillation, buckling, Eurocode*

1. INTRODUCTION

Double-beam bridge cranes are the most common in factories and industrial plants compared to other types of bridge cranes. In addition to box girders, standard types of I-profiles are also present as the main girders of double-beam bridge cranes. Since I-profiles have defined dimensions, their geometry is often not rationally used for some of the design criteria that must be satisfied, so types of standard I-profiles are oversized in that case.

The analysis and optimization of carrying structures and I-girders have been the subject of numerous research publications.

Paper [1] presented the optimization of a mono-symmetric and a double-symmetric I-girder of the double-beam bridge cranes. Paper [2] showed the optimal design of a mono-symmetric I-girder of the single-beam bridge cranes according to Eurocode, using several metaheuristic optimization algorithms. The authors in [3] presented the application of the Moth-Flame Optimization (MFO) algorithm on the example of a reinforced I-girder of single-beam bridge cranes, where the results were verified by applying FEM.

The application of various metaheuristic algorithms is prevalent in engineering practice [4]-[7]. Research [4] showed the optimization procedure for the end carriage of the double-beam bridge cranes, using function *fmincon* in MATLAB [5], while [6] presented the optimization of geometric parameters of standard I-profiles, according to Eurocode 3.

Structural analysis plays a crucial role in the optimal design of carrying structures. Paper [7] presented the application of the Sparrow Search Algorithm (SSA) optimization of the main beam of a bridge crane, where the results were verified by applying FEM in ANSYS software. The same software was also used in [8], where the authors presented the application of two optimization methods: the direct optimization method and the response surface analysis method of Workbench (WB) on a bridge crane girder. The results were compared to those obtained by applying the Genetic Algorithm (GA).

Based on the abovementioned papers, the importance of optimizing the girders of bridge cranes, as well as the application of metaheuristic optimization methods, is evident. The primary objective of this research is to analyze and optimize the mass of a bridge crane girder with a double-symmetric I-profile according to Eurocode. The flange and web of the I-profile are considered in Class 3. The optimization results were compared to those obtained in research [1]. In this research, the Dwarf Mongoose Optimization Algorithm (DMOA) is applied for this optimization problem to reduce the mass of a double-beam bridge crane girder. Paper [9] presents the application of the mentioned algorithm to various engineering examples.

Authors from the Todor Kableshkov University of Transport Sofia, Bulgaria investigate existing structural solutions for overhead cranes [10, 11], analyzing the causes of accidents [12] and examining the load-bearing capacity of the gantry crane girder structure under conditions of dynamic earthquake loading [13].

2. THE OPTIMIZATION PROBLEM

The optimization problem is defined in the following way:

minimize the objective function $f(X)$, subject to the constraint functions $g_i(X) \leq 0$,

$i = 1,...,m$, and $l_j \leq X_j \leq u_j$, $j = 1,..,n$,

where: X is the design vector made of n design variables, l_j, u_j are the lower, i.e. the upper boundary, respectively, and m is the number of constraint functions.

3. THE OBJECTIVE FUNCTION

The objective function is represented by the area of the cross-section of the double-symmetrical I-profile (Fig.1). Also, this figure shows all the necessary geometrical dimensions. Design variables are b, t, h, *and* s *(Fig.* 1).

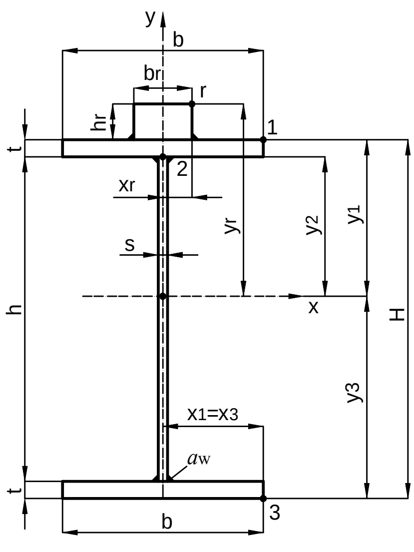


Fig. 1. The cross-sectional area of the welded I-girder

The area of the I-profile (A_g), i.e. the objective function, is:

(1) $$A_g = 2 \cdot \left(b \cdot t + a_w^{\,2}\right) + h \cdot s$$

where: $a_w = 0{,}7 \cdot \min(t, s)$ is the throat thickness, Fig.1.

The following input quantities are present in this optimization problem: Classification class, Q, L, m_t, k_a, f_y, f_u, f_{yr}, K, b_r, h_r, A_p,
where Q is the carrying capacity of the crane, L is the span of the bridge crane, m_t is the trolley mass, k_a is the dynamic coefficient for the horizontal plane load, [14], f_y is the yield strength for I-girder, f_u is the ultimate strength for I-girder, f_{yr} is the yield strength for the rail, K is the coefficient (depends on the purpose of the crane and control condition), [14], b_r, h_r are the rail dimensions (Fig.1), and A_p is the value of the cross-sectional area of standard I-profile.

The static quantities (F_{1st}, M_V, M_H, F_T, F_{max}) necessary for the analysis shall be determined according to the formulas shown in [14]. The geometrical properties for the I-girder (Fig.1) shall be determined by well-known expressions (I_{1x}, I_{1y}, I_x, I_y, S_{x2}, I_t, I_w).

4. THE CONSTRAINT FUNCTIONS

The following relationships are valid for the flange and web of the I-profile (Fig.1), for Class 3 and [15], respectively:

(2) $c/t \le 14 \cdot \varepsilon = \sqrt{23{,}5/f_y}$

(3) $d/s \le 124 \cdot \varepsilon = \sqrt{23{,}5/f_y}$

where ε is a yield strain.

4.1 The criterion of stresses at the specific points of the girder

Total stress in the rail (σ_r), Fig.1:

(4) $\sigma_r = \frac{M_V}{I_x} \cdot y_r + \frac{M_H}{I_y} \cdot x_r \le \sigma_{rp} = \frac{f_{yr}}{\upsilon_1 \cdot \gamma_{M0}}$

Total stress at point 1 (σ_1), Fig.1:

(5) $\sigma_1 = \frac{M_V}{I_x} \cdot y_1 + \frac{M_H}{I_y} \cdot x_1 \le \sigma_p = \frac{f_y}{\upsilon_1 \cdot \gamma_{M0}}$

Total stress at point 2 (σ_2), Fig.1:

(6) $\sigma_2 = \sqrt{\left|\sigma_{V2}{}^2 + \sigma_y^2 - \sigma_{V2} \cdot \sigma_y + 3 \cdot \tau_2{}^2\right|} \le \sigma_p$

(7) $\sigma_{V2} = \frac{M_V}{I_x} \cdot y_2 \le \sigma_p$

(8) $\sigma_y = \sigma_{y1} + \sigma_{y2} = \frac{F_{\max}}{s \cdot l_{eff}} + \left|\frac{3 \cdot F_{\max}}{s \cdot L} \cdot \eta \cdot th(\eta)\right| \le \sigma_p$

(9) $\tau_2 = \tau_{12} + \tau_{22} = \frac{F_T \cdot S_{x2}}{I_x \cdot s} + 0{,}2 \cdot \sigma_{y1} \le \tau_p = \sigma_p / \sqrt{3}$

Total stress at point 3 (σ_3), Fig.1:

(10) $\sigma_3 = \frac{M_V}{I_x} \cdot y_3 + \frac{M_H}{I_y} \cdot x_3 \le \sigma_p$

where $x_r = b_r/2$ (Fig.1), $x_2 = x_3 = b/2$ (Fig.1), M_V, M_H are the bending moments in the vertical and horizontal planes, respectively, I_x, I_y are principal moments of inertia for the I-profile with the rail, S_{x2} is the static moment of inertia for point 2, σ_{rp}, σ_p are permissible stresses for the rail and the I-profile, respectively, $\gamma_{M0}=1$ is the particular partial factor, [15], $\upsilon_1=1{,}5$ is the factored load coefficient for load case 1, [14], σ_{V2} is the normal stress at point 2, σ_y is the longitudinal stress at point 2, τ_2 is the tangential stress at point 2, τ_p is the permissible tangential stress, F_{max} is the acting force upon the I-girder beneath the trolley wheel, F_T is the transversal force, l_{eff} - the effective loaded length, [16], and η is the relation from [16].

4.2 The criterion of buckling of the girder

A safety check for buckling of the I-girder is performed in compliance with [15], where the I-girder is analyzed without the rail. So, it has to be fulfilled:

$$(11)\ M_{cr} = \frac{C_1 \cdot \pi^2 \cdot E \cdot I_{1y}}{L^2} \cdot \sqrt{\frac{I_\omega}{I_{1y}} + \left(\frac{L}{\pi}\right)^2 \cdot \frac{G \cdot I_t}{E \cdot I_{1y}} + \left(C_2 \cdot z_G\right)^2} - C_2 \cdot z_G \le M_p$$

$$(12)\ M_p = \chi \cdot \frac{2 \cdot I_{1x}}{H} \cdot \sigma_p$$

where M_{cr} is the moment design value, M_P is the design buckling resistance moment, C_1=1,348, C_2=0,63, [15], I_{1x}, I_{1y} are principal moments of inertia for the I-profile, respectively, I_ω is the sectorial moment of inertia for the I-profile, I_t is the torsional moment of inertia for the I-profile, $Z_G = H/2$, E is the elastic modulus, G is the shear modulus, and χ is the lateral-torsional buckling reduction factor, [15].

4.3 The criterion of stress in welded connection

To satisfy this criterion, the maximum stress in the welded connection (σw) must have a value smaller than the limit design weld stress (σ_{wp}):

$$(13)\ \sigma_w = \sigma_{w1} + \sigma_{w2} \le \sigma_{wp} = \frac{f_u}{\sqrt{3} \cdot \beta_w \cdot \gamma_{M2}}$$

$$(14)\ \sigma_{w1} = \frac{F_{\max}}{2 \cdot a_w \cdot l_{eff}}$$

$$(15)\ \sigma_{w2} = \frac{F_T \cdot S_{x2}}{2 \cdot a_w \cdot I_x}$$

where β_w=0,8 is the appropriate correlation factor, [17], γ_{M2}=1,25 is the partial safety factor for welds, [13], and σ_{w1}, σ_{w2} are stresses in the welded connection in normal and longitudinal direction, respectively.

4.4 The criterion of deflection in the middle of the girder

To satisfy this criterion, it is necessary that the static deflection in the vertical plane (f_{max}) has a value smaller than the permissible one (f_p):

$$(16)\ f_{\max} = \frac{F_{1st} \cdot L^3}{48 \cdot E \cdot I_x} \cdot \left[1 + \alpha \cdot (1 - 6 \cdot \beta^2)\right] + \frac{5 \cdot q \cdot L^4}{384 \cdot E \cdot I_x} \le f_p = K \cdot L$$

where F_{1st} is the static force upon girder beneath the trolley wheel, [14], $q = \rho \cdot g \cdot A$ is the specific weight per unit of length of the girder, $A = A_g + b_r \cdot h_r$, Fig.1, and α, β are the coefficients, [14].

4.5 The criterion of permissible period of oscillation

To satisfy this criterion, it is necessary that the time of damping of oscillation (T) has a value smaller than the permissible one (T_p, [14]):

$$(17)\ T = \frac{\pi}{2 \cdot \gamma_d} \cdot \sqrt{\frac{3 \cdot m_1 \cdot L^3}{E \cdot I_x}} \le T_p$$

$$(18)\ m_1 = \left(Q + m_t\right)/2 + 35 \cdot \rho \cdot L \cdot A / 72$$

where ρ is the material density of the girder, m_1 is the lumped mass at the midspan, [14], and γ_d is the logarithmic decrement, [14].

5. RESULTS OF THE OPTIMIZATION

The optimization was done using the DMOA code [5], in MATLAB software. A detailed description of this algorithm can be found in [9]. For the DMOA, control parameters are: the population size is 100, and the number of iterations is 800.

Variable parameters for optimization are: b, t, h, s (Fig.1). Limit values (in centimeters) for variables are: $10 \le b \le 50$, $0{,}6 \le t \le 4$, $20 \le h \le 100$, $05 \le s \le 3$.

The input parameters for optimization procedure were taken according to basic characteristics for examples of the double-beam bridge cranes (Table 1) and according to [14], depending on the Classification class (Cl. class, Table 1).

Table 1

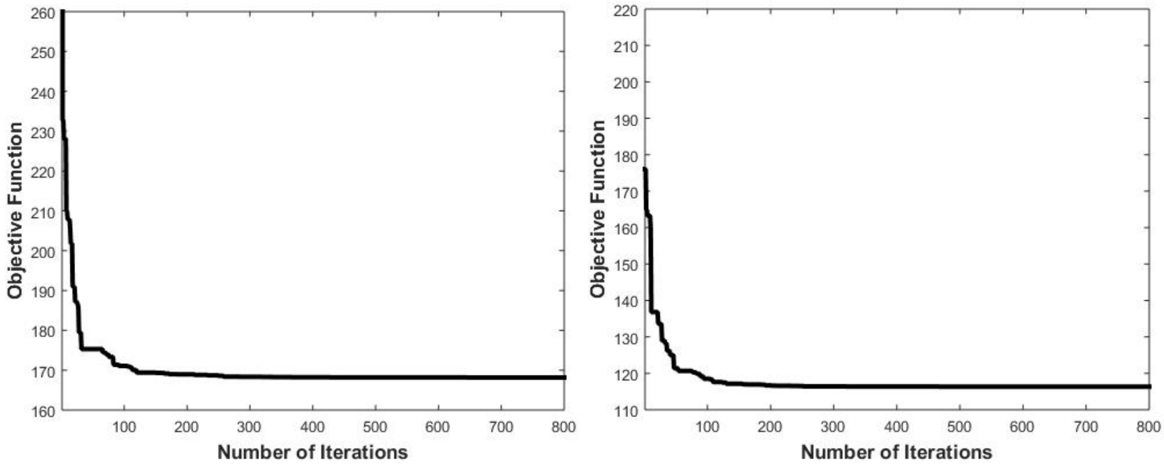
	Q (t)	L (m)	m_t (kg)	k_a (-)	Cl. class	A_p (cm^2)	b (cm)	t (cm)	h (cm)	s (cm)	A_{opt} (cm^2)	Saving (%)
1	10	14,005	690	0,1	II	212	40,28	1,386	83,86	0,700	168,174	20,67
2	3,2	15,200	250	0,05	I	143	33,48	1,154	69,73	0,558	116,348	18,64

The material of the I-girder for both bridge crane examples is S235 (f_y=23,5 kN/cm^2, f_u=36 kN/cm^2), and the material of the rail is S355 (f_{yr}=35,5 kN/cm^2).

The rail dimensions are b_r x h_r = 5 x 3 cm.

Table 1 shows input parameters for bridge cranes and the results of the optimization (optimal geometrical values for the I-profile and savings in the material) for both examples of double-beam bridge cranes (A_{opt} is the optimal value of the cross-sectional area of the I-profile).

The following figure (Fig.2) presents convergence diagrams for both examples of double-beam bridge cranes (Fig.2a – example 1 and Fig.2b – example 2).



(a) **(b)**

Fig. 2. Convergence diagrams

6. CONCLUSIONS

This research presents the optimization of geometrical parameters of the I-girder of the double-beam bridge crane using the Dwarf Mongoose Optimization Algorithm (DMOA). The criteria for the stresses in the characteristic points of the I-profile at the critical location of the girder, the stress in the welded joint, the deflection at the middle of the girder, the oscillation period of the girder, as well as the buckling of the girder, were applied as constraint functions. The objective function is to minimise the cross-sectional area of the I-profile, while satisfying the given constraint conditions.

As can be seen from Table 1 and based on Table 3 from [1], the material savings are significantly lower here. The reason is the analysis of the flange and web of the I-profile only for Class 3. Due to the minimization of the cross-sectional area and the reduction of plate thickness, it is necessary to include Class 4 in future research.

Also, the obtained results show that the optimal web height of I-profiles is higher compared to standard I-profiles, which is a consequence of observing only Class 3.

Ultimately, it can be observed that the application of the DMOA algorithm was successful in addressing the considered engineering problem, allowing for the inclusion of a larger number of variables and constraint functions in the analysis.

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