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OPTIMAL DESIGN OF THE HYBRID I-GIRDER OF THE SINGLE-BEAM BRIDGE CRANE

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Abstract: This paper presents the optimal design of the main girder of the single-beam bridge crane, where the main goal of the research is to reduce the weight, i.e. the cross-sectional area of the main girder. The objective function is the cross-sectional area of the mono-symmetric I-profile. To rationally use materials, plates of different types of structural steel were considered, so S355 grade steel was used for the bottom flange of the main girder and S235 grade steel for the other segments of the main girder. The reason for this is primarily the reduction of the thickness of the bottom flange, as the wheels of the trolley that move on it cause an increase in stress, which is especially pronounced with high load capacities, and taking into account the standard thickness of the plates. This research uses the strength criteria in the characteristic points of the I-profile, the stiffness and dynamic stiffness criteria of the main girder, and the stability criterion of the main girder as constraint functions in this multi-criteria optimization problem. Achieved savings in the main girder weight are between 54.45% and 64.67%, depending on the considered examples, which confirms the justification of the application of the proposed design methodology.

Key words: Bridge crane, GRG2 code, Light-weight design, Optimization, Welded girder

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1 INTRODUCTION

The main task in designing the carrying structure of a single-beam bridge crane is to determine the optimal geometric parameters of the cross-section of the main girder, in this case, I-profile (I-girder).

Thanks to the development of 3D design software, there has been an increase in research involving analysis and optimization using Finite Element Analysis (FEA). CATIA software's Product Engineering Optimization (PEO) was utilized to enhance the I-profile of a single-beam bridge crane, as stated in [1]. Paper [2] showcases the use of FEA for analyzing the local stresses in the bottom flange of I-girder due to trolley wheel movement. The economic approach is relevant when designing an optimal I-girder, [3, 4]. Authors in paper [3] propose a hybrid model of I-girders, where the flanges and web of I-girder are made of different types of steel. In that particular case, savings of up to 50% were achieved, according to Eurocodes. An economic study was carried out in [4], where a new I-profile base was obtained based on Eurocode 3, using the Genetic Algorithm (GA).

The application of various optimization algorithms is very present for carrying structures, [5-7]. The application of algorithms Whale Optimization Algorithm (WOA), Sine Cosine Algorithm (SCA), as well as their hybrid version WOASCA, was performed in [5], on examples of optimization of I-girders of single-beam bridge cranes. On this occasion, enviable savings were achieved. The application of the Generalized Reduced Gradient (GRG2) algorithm in MS Excel software, through Solver module, was performed in paper [6] on the example of the mono-symmetric I-profile of single-beam bridge cranes, and the same algorithm was used in paper [7], on the example of a box cross-section. A detailed description of how Solver module can be applied to various engineering problems is available in [8].

The mentioned researches demonstrate the significance of analyzing and optimizing the main girder of the single-beam bridge cranes and I-girders.

Bearing in mind the mentioned results of the research, as well as the application of the GRG2 algorithm, the goal of this research is to define the optimal geometric parameters of the mono-symmetric I-profile of a single-beam bridge crane that will lead to a reduction in its weight. For this purpose, different types of steel were adopted for the bottom flange of I-girder, on which the trolley wheels move, compared to the other segments of I-girder. The purpose of this is to reduce the optimal thickness of the bottom flange of I-girder, as well as the girder's total weight because the local stresses that occur in the bottom flange increase the total stress in its characteristic points. The possibility of using integer values for plate thickness variables in Solver module's GRG2 algorithm in MS Excel was crucial for the research results and the total weight of I-girder.

This research observed four examples of single-beam bridge cranes that are in operation. The results are being compared with the ones from [6].

2 OPTIMIZATION MODEL

In the optimization problem of reducing the weight of the main girder of a single-beam bridge crane, it is necessary to define the objective function (chapter 2.1) and the optimization variables. Also, it is required to specify all constraint functions (chapter 2.2) for this multi-criteria optimization problem. The analysis procedure of this carrying steel structure is based on models and expressions defined in [9, 10] and research [6].

The main input parametrs necessary for optimization process are: Q - the carrying capacity, L - the span, m_t - the mass of the trolley, b_t - the distance between trolley wheels, e_1 - the distance between wheel 1 and the resulting force in the vertical plane, [9], k_a - the dynamic coefficient of crane load in the horizontal plane, [9], d = 1,5 cm - the distance from the edge of the bottom flange to the load, [9], $b_{1,m}$ - minimum value for the bottom flange, γ - the coefficient (depends on the Classification class, [9], γ = 1, for Classification Class I and γ = 1,05, for Classification Class II;), ψ = 1,15 - the dynamic coefficient of the influence of load oscillation in the vertical plane, [9], and A_{pr} - the cross-sectional area of the standard I-profile, [10].

The optimization procedure was carried out based on the GRG2 code, [8].

2.1 The objective function

The objective function presents the cross-sectional area of the mono-symmetric I-profile (Figure 1). The welded structure of the mono-symmetric I-girder consists of the top flange and web made of S235 grade steel and the bottom flange made of S355 grade steel. The objective function A is given by the following relation:

$$A = h \cdot s + b_1 \cdot t_1 + b_2 \cdot t_2 \tag{1}$$

Figure 1 shows the cross-section of the mono-symmetric I-profile (the objective function, A) of the welded structure of a single-beam bridge crane, which have six variables: h, s, b_1, t_1, b_2, and t_2 (Figure 1).

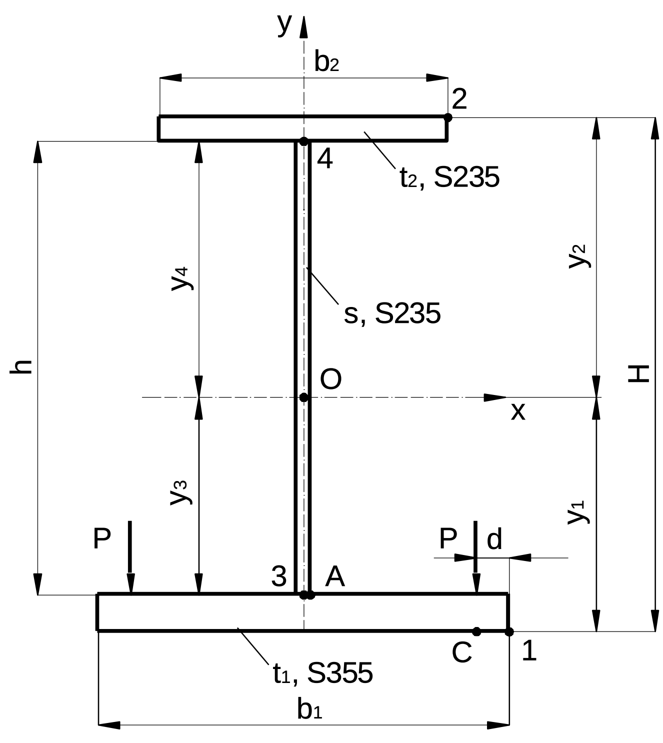

Figure 1. *Mono-symmetric I-profile of a single-beam bridge crane*

2.2 Constraints functions

To solve this optimization problem, specific conditions outlined in references [9, 10] must be satisfied. The criteria that must be met relate to the strength of the girder plates in the characteristic points of I-profile (Figure 1), at the most critical place of a single-beam bridge crane girder [9], the girder stiffness, the dynamic girder stiffness, the global stability of the top flange, as well as geometric limitations.

The static load model of a single-beam bridge crane is shown in [6], with all necessary static parameters. The geometric properties of the mono-symmetric I-profile (Figure 1) are calculated using well-known equations.

The strength criteria in the points of I-profile (Figure 1) *A*, *C*, 1, 2, 3(4) are satisfied if it is fulfilled that the maximum stresses in the specified points are lower than the permitted ones (σ_{d1} or σ_{d2}). Based on this criterion, the following constraint functions are defined:

$$g_1 = \sigma_{1z} - \sigma_{d1} = M_{VI}/W_{1x} + M_{HI}/W_{1y} - \sigma_{d1} \le 0\,, \tag{2}$$

$$g_2 = \sigma_{2z} - \sigma_{d1} = M_{VI}/W_{2x} + M_{HI}/W_{2y} - \sigma_{d1} \le 0\,, \tag{3}$$

$$g_3 = \max\left(\sigma_{3z}, \sigma_{4z}\right) - \sigma_{d1} = \max\left(M_{VI}/W_{3x}, M_{VI}/W_{4x}\right) - \sigma_{d1} \le 0\,, \tag{4}$$

$$g_4 = \sigma_{Au} - \sigma_{d1} \le 0\,, \tag{5}$$

$$g_5 = \sigma_{Az} - \sigma_{d1} = M_{VI}/W_{Ax} - \sigma_{d1} \le 0\,, \tag{6}$$

$$g_6 = \sigma_{Akz} - \sigma_{d1} = K_{Az} \cdot P/t_1^2 - \sigma_{d1} \le 0\,, \tag{7}$$

$$g_7 = \sigma_{Akx} - \sigma_{d1} = K_{Ax} \cdot P/t_1^2 - \sigma_{d1} \le 0\,, \tag{8}$$

$$g_8 = \sigma_{Cu} - \sigma_{d2} \le 0\,, \tag{9}$$

$$g_9 = \sigma_{Cz} - \sigma_{d1} = M_{VI}/W_{Cx} + M_{HI}/W_{Cy} - \sigma_{d1} \le 0\,, \tag{10}$$

$$g_{10} = \sigma_{Ckz} - \sigma_{d1} = K_{Cz} \cdot P/t_1^2 - \sigma_{d1} \le 0\,, \tag{11}$$

$$g_{11} = \sigma_{Ckx} - \sigma_{d1} = K_{Cx} \cdot P/t_1^2 - \sigma_{d1} \le 0\,, \tag{12}$$

where:

$$\sigma_{Au} = \sqrt{\left(\sigma_{Az} + \sigma_{Akz}\right)^2 + \sigma_{Akx}{}^2 - \left(\sigma_{Az} + \sigma_{Akz}\right)\sigma_{Akx}}\,, \tag{13}$$

$$\sigma_{Cu} = \sqrt{\left(\sigma_{Cz} + \sigma_{Ckz}\right)^2 + \sigma_{Ckx}{}^2 - \left(\sigma_{Cz} + \sigma_{Ckz}\right)\sigma_{Ckx}}\,, \tag{14}$$

$$\sigma_{d1} = R_e/\nu_1,\ \nu_1 = 1{,}5\,, \tag{15}$$

$$\sigma_{d2} = R_e/\nu_2,\ \nu_2 = 1{,}33\,, \tag{16}$$

where: σ_{pz} is the normal stress in the observed point p (p = 1, 2, 3, 4, A, C), W_{px}, W_{py} are the section moduli for point p, σ_{Akz}, σ_{Akx} are local stresses in point A, in both directions, respectively, σ_{Ckz}, σ_{Ckx} are local stresses in point C, in both directions, respectively, σ_{Au}, σ_{Cu} are equivalent stresses in point A and point C, respectively, M_{VI}, M_{HI} are bending moments in the vertical and horizontal planes, respectively, P is the maximum pressure of the trolley wheel, K_{Az}, K_{Ax} are corresponding coefficients for local stresses in point A, respectively, [9]. K_{Cz}, K_{Cx} are corresponding coefficients for local stresses in point C, respectively, [9], v_1, v_2 are the load factored coefficient for load cases 1 and 2, respectively, [10], and σ_{d1}, σ_{d2} are permissible stresses for load cases 1 and 2, respectively.

For the criterion of the global stability of the top (compressed) flange of I-girder, the procedure was carried out based on the standards defined in [10]. In this case, two conditions must be met, so the constraint functions are as follows:

$$g_{12} = \sigma_{2z} - 1{,}14 \cdot \chi_{tp} \cdot \sigma_{d1} = M_{VI} / W_{2x} - 1{,}14 \cdot \chi_{tp} \cdot \sigma_{d1} \le 0 \,, \tag{17}$$

$$g_{13} = i_{tp} - i_y = \sqrt{I_{tp} / A_{tp}} - L \cdot \sqrt{R_e / 23{,}5} / 40 \le 0 \,, \tag{18}$$

where χ_{tp} is a non-dimensional coefficient of the global stability, i_{tp} is the radius of gyration of the top flange about y-axis, i_y is the required value of the radius of gyration, A_{tp} is the area of the top flange, and I_{tp} is the moment of inertia of top flange about y-axis, [10].

The stiffness criterion of the girder is fulfilled when the maximum deflection of the girder f_{max} is less than the permissible one f_d, [9]. The constraint function is:

$$g_{14} = f_{\max} - f_d = f_{\max} - K_f \cdot L \le 0 \,, \tag{19}$$

where:

$$f_{\max} = \frac{F_{1st} \cdot L^3}{48 \cdot I_x \cdot E} \cdot \left\{ 1 + \frac{F_{2st}}{F_{1st}} \cdot \left[1 - 6 \left(\frac{b_t}{L} \right)^2 \right] \right\} + \frac{5 \cdot q \cdot L^4}{384 \cdot I_x \cdot E} \,, \tag{20}$$

where K_f is the stiffness coefficient of the girder (depends on Classification Class), [9], F_{1st}, F_{2st} are static forces in the vertical plane, [9], q is the specific weight of the girder, I_x is the moment of inertia about x-asis, and E = 21000 kN/cm^2 is Young's modulus of the plate material.

For the criteria of oscillation of the concentrated mass (the reduced mass of the girder, the carrying capacity, and the trolley mass) in the middle of the girder, the relaxation period T must be less than the permissible one T_d, [9]. The constraint function is:

$$g_{15} = T - T_d = \tau \cdot \ln(20) / \gamma_d - T_d \le 0 \,, \tag{21}$$

where τ is the period of oscillation and γ_d is the logarithmic decrement which shows the rate of damping of oscillation, [9].

3 OPTIMIZATION RESULTS

The GRG2 code (in MS Excel, [8]) was used to optimize the cross-sectional area of the mono-symmetric I-profile of the bridge cranes. The following limit conditions apply to some of the variables are: $s \geq 5$ mm, $b_{1,m} \leq b_1 \leq 300$ mm, t_1, $t_2 \geq 6$ mm, $b_2 \leq$ 300 mm.

The objective function is defined by equation (1) and constrained functions are defined by equations: (2)-(12), (17)-(19), and (21).

The optimization problem's proposed model was implemented on four operational bridge cranes (Table 1). The main girders in all examples are standard I-profiles made of S235 grade steel.

Table 1. *Characteristics of single-beam bridge cranes*

Example	**Q (t)**	**L (m)**	**Cl. Class**	**m_t (kg)**	**b_t (mm)**	**e_1 (mm)**	**k_a (-)**	**$b_{1,m}$ (mm)**	**A_{pr} (cm^2)**
1	2	4,81	I	180	116	58	0,05	55	62,6
2	3,2	10	II	340	196	98	0,1	82	143
3	10	7,75	II	610	708	354	0,05	100	239
4	6,3	5,92	II	380	420	225	0,1	100	181

In addition to the data in Table 1, the following parameters are taken as input data: T_d = 22 s for Classification Class I and T_d = 15 s for Classification Class II, [9]; K_f = 1/400 for Classification Class I and K_f = 1/500 for Classification Class II, [9]; R_e = 23,5 kN/cm^2 for S235 and R_e = 35,5 kN/cm^2 for S355, [10]. Also, standard plate thicknesses (integer values) were observed in the optimization procedure.

Table 2 shows the optimization results: optimal geometric parameters, the optimal areas, and the material savings for four bridge crane examples.

Table 2. *Optimization results*

Example	**h_o (mm)**	**s_o (mm)**	**b_{1o} (mm)**	**t_{1o} (mm)**	**b_{2o} (mm)**	**t_{2o} (mm)**	**A_o (cm^2)**	**Savings (%)**
1	23,43	5	55	9	180,3	6	27,48	56,10
2	50,60	5	82	12	300	10	65,14	54,45
3	61,49	5	100	20	296,0	12	86,26	63,91
4	47,90	5	100	16	300	8	63,95	64,67

4 CONCLUSION

This research presents the problem of the weight optimization for the mono-symmetric I-girder of the single-beam bridge cranes using the GRG2 code in Solver module (MS Excel). I-girder is the welded structure consisting of the top flange and web made of S235 grade steel and the bottom flange made of S355 grade steel. The objective function is the cross-sectional area of I-girder. The optimization variables are the dimensions of the I-girder plates. The criteria of permissible stresses in the characteristic points of the cross-section (Figure 1), the global stability of the top flange, the deflection of the girder, the period of oscillation of the concentrated mass in the middle of the girder, and geometric limits were applied as the constraint functions. Significant savings in material were achieved (from 54.45% to 64.67%, Table 2). These savings are greater than those from [6], except in one case, where the difference is in the first decimal place (Table 2, Example 2). Also, the thickness of the bottom flange of I-girder is significantly smaller, which was one of the goals of this research. The web thickness and the width of the bottom flange of I-girder have the minimum set values in all cases. The optimal web heights of I-profiles are similar to those from [6], except in one case where a significantly lower web height was obtained (Table 2, Example 3). Based on this, the justification of the application of the presented approach of analysis and optimization of the weight of the welded structure of the single-beam bridge cranes, as well as the applied optimization method, which is simple and practical to use, has been proven.

For further research, it is necessary to introduce additional constraint functions into the optimization process, which relate to the type of material of the girder plates, material fatigue, and technology influence, introducing the economic and green approach to design and production.

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NOMENCLATURE

A the area, cm^2

b the flange width of I-profile, mm

b_t distance between the wheels of the trolley, mm

d the distance from the edge of the bottom flange to the vertical load of the trolley wheel, [9], cm

E Young's modulus of the plate material, kN/cm^2

e_1 the distance between wheel 1 and the resulting force in the vertical plane, [9], cm

F_{1st}, F_{2st} static forces in the vertical plane, respectively, kN

f deflection, cm

g constraint function

H, h the web and I-profile height, respectively, mm

I, i the moment of inertia and the radius of gyration, respectively, cm^4, cm

k_a the dynamic coefficient of crane load in the horizontal plane, [9]

K_{Ax}, K_{Az} corresponding coefficients for local stresses at point A, respectively, [9]

K_{Cx}, K_{Cz} corresponding coefficients for local stresses at point C, respectively, [9]

L the span, m

m_t the trolley mass, t

M_{VI}, M_{HI} bending moments in the vertical and horizontal planes, respectively, kNcm

P the maximum pressure of the trolley wheel, kN

q the specific weight of the girder, kN/cm

Q the carrying capacity, t

R_e the minimum value for the yield stress, kN/cm^2

s the web thickness, mm

t the flange thickness, mm

T the relaxation period of oscillation, s

W_{px}, W_{py} the section moduli at the observed point *p* of I-profile, cm^3

γ the coefficient which depends on the Classification class, [9]

γ_g the logarithmic decrement which shows the rate of damping of oscillation, [9]

ν_1, ν_2 the load factored coefficient for load cases 1 and 2, respectively, [10]

σ_{pz} the normal stress at the observed point *p* of I-profile, kN/cm^2

σ_{d1}, σ_{d2} permissible stresses for load cases 1 and 2, respectively, kN/cm^2

τ the period of oscillation, [9], s

χ_{tp} a non-dimensional coefficient of the global stability, [10]

ψ the dynamic coefficient of the influence of load oscillation in the vertical plane, [9]

o optimal value

p opserved point at I-profile (A,C,1,2,3,4)

pr profile

tp top plate

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