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OPTIMIZATION OF THE WELDED I-GIRDER OF THE DOUBLE-GIRDER BRIDGE CRANE

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***Key words**: I-section, optimum design, double-girder bridge crane, welded girder*

***Abstract:** The paper presents the optimization of the main girder of the double-girder bridge crane. The main girder is made as welded I-section. Standard rectangular rail for electric trolley running is welded over the top flange. The strength in characteristic points of the main girder section, girder deflection and its dynamic stiffness were analysed. Also, the influence of local bending stresses due to the trolley wheel - rail contact pressure as well as the girder lateral stability due to the ratio between the length and cross-section dimensions of the girder were considered. Thus, the analysis has taken into account the most significant influences for this type of structure. The optimization procedure was conducted by different numerical methods. The results are compared to manufactured cranes with standard rolled I-sections as main girders.*

1. INTRODUCTION

Double-girder bridge cranes are very much present in industrial plants and factories, and all of which are used for grabbing, lifting and transportation of large loads. The mass of the girders has the largest share in the total mass of the structure of the double-girder bridge crane, and that is the reason why it is very important to reduce it, in order to obtain a lighter construction, which also reduces the market price of the whole carrying structure.

The main girders are the most responsible parts of the bridge crane, and therefore the level of reduction of the mass must be strictly observed in order not to jeopardize the reliable operation of the bridge crane.

There are a large number of publications which are dealing with the problem of analysis of stresses and deformations of the main girders of the bridge cranes, as well as their optimization problem.

In the paper [1], numerical simulations of the mechanical phenomena in I-profile of the single-beam gantry crane, using by FEM analysis, was performed, for different force positions and restraint types. Stress analysis is performed in the paper [2], too.

Lateral buckling analysis are presented in [3] and [4], for crane trolley monorails. Similar analysis was carried out in [5], for the main girder of the single-beam bridge-crane.

The problem of local bending, which occurs due to the pressure of the trolley wheels on the bottom flange of the girder, was analysed in the papers [6] and [7].

The study of the bridge cranes from the viewpoint of potential defects in crane structure and possibility to determine the cycle of the crane loading were presented in the paper [8]. Material fatigue is very important for this type of structures, so from this viewpoint, the analysis of the failure of the bridge crane was done in [9].

In addition to analysis and optimization using by FEM, most numerical methods for optimization are present, and all of them was successfully implemented, as shown in [10] and [11], in multi-criteria optimization problems for the double-girder bridge cranes.

Taking into account the above mentioned researches and results, the aim of this paper is to define optimum values of geometric parameters of the cross-sectional area of the welded I-girder of the double-girder bridge crane that will lead to the reduction of its mass in comparison to standard rolled I-profile.

2. MATHEMATICAL FORMULATION OF THE OPTIMIZATION PROBLEM

The optimization problem is defined in following way:

Minimize the objective function: $f(X)$,

subject to the constraint functions: $g_i(X) \leq 0,\ i = 1,...,m$,

and $X_j \geq 0$, $l_j \leq X_j \leq u_j$, $j = 1,...,n$,

where:

$X = [b_1\ b_2\ h\ t_1\ t_2\ t_3]^T$ - the design vector made of *6* design variables

l_j, u_j - lower, i.e. upper boundary

i - number of constraint functions

j - number of design variables

Design variables are the values that should be defined during the optimization procedure. Each design variable is defined by its upper and lower boundaries.

3. THE OBJECTIVE FUNCTION

The objective function is represented by the area of the cross-section of I-girder (Fig.1).

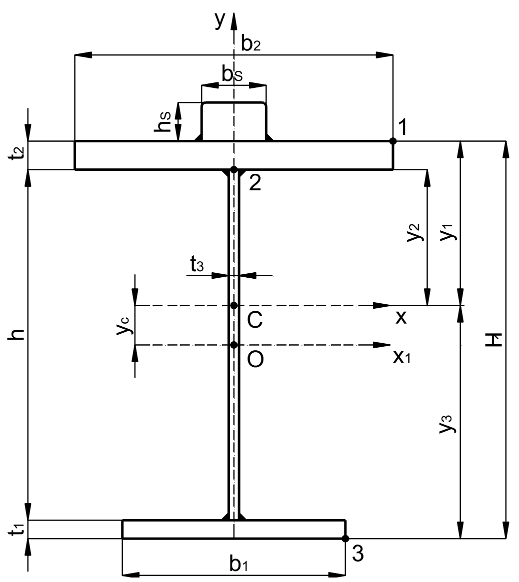

Fig.1 – I-section with rail

The area of the cross-section, i.e. the objective function, is:

$$A = b_1 \cdot t_1 + b_2 \cdot t_2 + h \cdot t_3 \quad (1)$$

The vector of the given parameters is:

$$\vec{x} = (Q,\ L,\ m_t,\ R_e,\ K_f, ...) \quad (2)$$

where:

Q - the carrying capacity of the crane

L - the span of the crane

m_t - the mass of the trolley

R_e - the minimum yield stress of the girder material

K_f - the coefficient which depends on the purpose of the crane and control condition of the crane, [12].

The geometrical properties in the specific points of I-girder (Fig.1) shall be determined by well-known expressions (I_x, I_y, W_{x1}, W_{y1}, $W_{x1,b}$, W_{x2}, S_{x2}, W_{x3}, W_{y3}).

4. THE CONSTRAINT FUNCTIONS

4.1 The criterion of maximum stresses

Total stress in point 1:

$$\sigma_{1,u} = \sigma_{zV1} + \sigma_{zH1} = M_V / W_{x1} + M_H / W_{y1} \le \sigma_d \quad (3)$$

$$\sigma_d = R_e / \nu_1 \quad (4)$$

where:

M_V, M_H - the bending moments in the vertical and horizontal planes, respectively

σ_d - the permissible stress

$\nu_1 = 1{,}5$ - the factored load coefficient for load case 1

Total stress in point 2:

$$\sigma_{2,u} = \sqrt{\sigma_{zV2}^{\ 2} + \sigma_y^2 - \sigma_{zV2} \cdot \sigma_y + 3 \cdot \tau_2^{\ 2}} \le \sigma_d \quad (5)$$

$$\sigma_{zV2} = M_V / W_{x2} \quad (6)$$

$$\sigma_y = F_1 / (t_3 \cdot z_1) \quad (7)$$

$$\tau_2 = F_T \cdot S_{x2} / (I_x \cdot t_3) \le \tau_d = \sigma_d / \sqrt{3} \quad (8)$$

where:

F_1 - the acting force upon I-girder beneath the trolley wheel

F_T - the transversal force

z_1 - the length of impact zone of longitudinal weld connections, [12]

Total stress in point 3:

$$\sigma_{3,u} = \sigma_{zV3} + \sigma_{zH3} = M_V / W_{x3} + M_H / W_{y3} \le \sigma_d \quad (9)$$

4.2 The criterion of lateral stability of the girder

Safety check for lateral stability of I-girder is done in compliance with [13], where the I-girder was analysed without rail. So, it has to be fulfilled:

$$\sigma_{zV1,b} \le \sigma_{b,d} = \alpha_p \cdot \chi_M \cdot R_e / \nu_1 \quad (10)$$

$$\sigma_{zV1,b} = M_V / W_{x1,b} \quad (11)$$

where:

α_p, χ_M - the coefficients, according to [13]

4.3 The criterion of maximum stress in welded connections

In order to satisfy this criterion, it is necessary that maximum stress in welded connections has the value smaller than limit design weld stress:

$$\sigma_{s,\max} \leq \sigma_{s,d} = 0,75 \cdot \sigma_d \qquad (12)$$

$$\sigma_{s,\max} = \sqrt{V_n^{\ 2} + V_p^{\ 2}} \qquad (13)$$

$$V_n = \frac{F_1}{2 \cdot a_s \cdot z_1} \qquad (14)$$

$$V_p = \frac{F_{T,\max} \cdot S_{x2}}{I_x \cdot 2 \cdot a_s} \qquad (15)$$

where:

a_s - the weld thickness

$F_{T,\max}$ - the maximum transversal force

$\sigma_{s,d}$ - the permissible stress for welded connection (limit design weld stress)

V_n, V_p - stresses in welded connection in normal and longitudinal direction, respectively

4.4 The criterion of permissible static deflection

In order to satisfy this criterion, it is necessary that the static deflection in the vertical plane f_{max} have the value smaller than the permissible value:

$$f_{\max} = F_{1,st} \cdot L^3 \cdot \left[1 + \alpha \cdot (1 - 6 \cdot \beta^2)\right] / \left(48 \cdot B\right) + 5 \cdot q \cdot L^4 / \left(384 \cdot B\right) \leq f_{dop} = K_f \cdot L \qquad (16)$$

where:

$F_{1,st}$ - static force upon girder beneath the trolley wheel

q - specific weight per unit of length of the girder

$B = E \cdot I_x$ - the flexural rigidity of the girder

$E = 21000\ kNcm^2$ - the elastic modulus of material

α, β - the coefficients, according to [12]

f_{dop} - the permissible deflection in vertical plane

4.5 The criterion of permissible period of oscillation

To determine the time of damping of oscillation *T*, it is necessary to analyse the vertical oscillation of the main girder with the payload:

$$T = \pi / \left(2 \cdot \gamma_d\right) \cdot \sqrt{3 \cdot m_1 \cdot L^3 / B} \leq T_d \qquad (17)$$

$$m_1 = \left(Q + m_t\right) / 2 + 35 \cdot m_g / 72 \qquad (18)$$

$$m_g = 1,05 \cdot \rho \cdot L \cdot A \qquad (19)$$

where:

$\rho = 7850\ kg / m^3$ - material density of the girder

m_g - the mass of the I-girder (increased 5 % for welded connections)

γ_d - the logarithmic decrement which shows the rate of damping of oscillation, [12]

T_d - the permissible time of damping of oscillation, which depends on the purpose of the bridge crane, [12]

5. NUMERICAL REPRESENTATION OF THE OBTAINED RESULTS

The optimization procedure was done using by generalized reduced gradient algorithm (GRG2) and Evolutionary algorithm (EA), with Solver Tool in Analysis module, in Ms EXCEL software package. Variable parameters for optimization are width of bottom flange, width of top flange, web height and plate thicknesses. Minimum thickness of the web plate was adopted to be 5 *mm* and minimum thickness of the bottom and top flange was adopted to be 6 *mm*, which are also the constraint functions (additional constraints). Another additional criterion was taken that the maximum values of the width of the bottom and top flange is less than 300 mm, which corresponds to the maximum values of flanges for standard I-profiles. Minimum value of width of flanges was adopted to be 100 mm. For the weld thickness, as input parameter of optimization process, the thickness of 4 mm was taken. Input parameters for optimization procedure was taken according to basic characteristics for existing solutions of the double-girder bridge cranes (Table 1) and according to [12].

Table 1

	Location	Q (t)	L (m)	m_t (kg)	Cl. class	Profile	Material	A_p (cm^2)
1	MPE Balkan-Kula	10	14,005	690	II	HEA-550	S235	212
2	Drina Plastika – Nova Pazova	3,2	15,200	250	I	HEA-360	S235	143

Table 2 and Table 3 show the results of the optimization (optimal geometrical values and savings) for two solutions of the double-girder bridge cranes made of standard I-profiles, for non-symmetric (Table 2) and symmetric I-section (Table 3), respectively.

Table 2

	Q (t)	L (m)	Method	b_1 (mm)	t_1 (mm)	h (mm)	t_3 (mm)	b_2 (mm)	t_2 (mm)	A_{opt} (cm^2)	Saving %
1	10	14,005	GRG2	100,0	6	816,9	5	300,0	18	100,84	52,43
			EA	100,0	6	861,9	5	293,3	18	101,90	51,94
2	3,2	15,200	GRG2	100,0	6	480,9	5	300,0	13	69,05	51,72
			EA	100,0	6	440,8	5	297,9	14	69,75	51,23

Table 3

	Q (t)	L (m)	Method	b_1=b_2 (mm)	t_1= t_2 (mm)	h (mm)	t_3 (mm)	A_{opt} (cm^2)	Saving %
1	10	14,005	GRG2	205,2	30	504,3	5	148,33	30,03
			EA	248,8	25	508,0	5	149,82	29,33
2	3,2	15,200	GRG2	299,9	14	315,8	5	99,77	30,23
			EA	169,9	24	303,5	5	96,72	32,36

where:

A_p – value of the cross-sectional area of standard I-profile

A_{opt} – optimal value of the cross-sectional area of welded I-girder

6. CONCLUSIONS

This research presents optimization procedure for geometrical parameters of I-section of the mean girder of the double-girder bridge crane, using by GRG2 and EA method. The criteria of maximum stresses in the characteristic points of I-section, lateral stability of the girder, maximum stress in welded connections, permissible static deflection of the girder, permissible period of oscillation of the girder, minimum plate thicknesses and other geometric limits were applied as the constraint functions. The objective function is minimum cross-sectional area, whereby given constraint conditions are satisfied.

Both optimization procedures (GRG2 and EA) gave similar values for the optimal cross-sectional areas of I-profile. The application of these methods resulted in significant savings in the material, within the range from 51,23% to 52,43% for non-symmetric I-section, and from 29,33% to 32,36 % for symmetric I-section. Based on results from Table 2, it can be seen that, for all cases, optimum value sets were obtained for minimum values of the width of bottom flange. Based on results from Table 2 and Table 3, optimal cross-sectional areas (Table 3) are significantly larger for the case when the bottom and top flanges are equal (symmetric I-section) in comparison to non-symmetric I-section (Table 2).

Taking into account the possibilities offered by presented procedure, the imposing conclusion is that further research should include additional constraint functions, such as: types of material, material fatigue, conditions of crane control and operation, the cost of materials, as well as the production of the welded girder.

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ОПТИМИЗИРАНЕ НА ЗАВАРЕНИ I-ГРЕДИ НА ДВУГРЕДОВ МОСТОВИ КРАН

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***Ключови думи**: I-секция, оптимален дизайн, двугредов мостови кран, заварен трегер*

***Резюме:** В статията е представена оптимизацията на основната греда на мостовия кран с двойни греди. Основната греда е направена като заварена I-секция. Стандартната правоъгълна релса за задвижване на електрически колички се заварява над горния фланец. Анализирана е якостта в характерни точки на основната част на гредата, деформацията на гредата и нейната динамична коравина. Също така се изследва влиянието на локалното напрежение на огъване, дължащо се на контактното налягане на колелото и релсата, както и страничната стабилност на гредата, дължаща се на съотношението между дължината и размерите на напречното сечение на гредата. По този начин в анализа са предвидени най-съществените влияния за този тип структура. Процедурата за оптимизация е проведена чрез приложението на различни числови методи. Резултатите се сравняват с произведени кранове със стандартни валцувани I-секции като основни греди.*