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Optimal Design for the Welded Girder of the Crane Runway Beam

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***Abstract*— In this research, multicriteria analysis and optimization of the steel girder of the crane runway were performed. Application of the welded I girder with vertical stiffeners was observed, in comparison with the standard rolled I profile which is most often using for these types of steel structures. The goal was primarily to show savings in the material in applying this design approach. For this reason, the minimization of the mass of the welded girder is set as the objective function. The strength criterion for characteristic points of the girder, local and global stability, the strength criterion for welded joints, as well as the stiffness of the girder, are set as optimization criteria. The optimization procedure was carried out using the Cyclical Parthenogenesis Algorithm (CPA), on the example of one segment of the crane runway track, for one single-beam bridge crane that is in exploitation. In this way, significant savings in the material were achieved, which justifies the presented method of analysis in the design of these types of structures.**

***Keywords*— Buckling, Crane runway, Optimization, Cyclical parthenogenesis algorithm, Welded beam**

I. Introduction

The crane runway beam is a very responsible type of structure and various influences must consider in its design. As the structure of the bridge crane with all its equipment moves along it, due to the failure of this structure, the consequences can be incalculable. For these reasons, it is necessary to particularly pay attention to the selection of the appropriate type of crane runway beam.

When designing these types of structures, to obtain the optimal cross-section of the girder, the welded I-profile is using, as an alternative for the standard types of these profiles.

For the above reasons and importance, analysis, and optimization of these types of structures is the subject of numerous studies. In the paper [1], the type of crane runway beam was analyzed, which web of the I-girder has a sinusoidal shape. The application of FEM in ABAQUS software shows the advantage of these girders in comparison to standard types of I-profiles. The analysis of the crane runway beam failure, which occurred due to fatigue, was performed in the paper [2]. The older procedure of the standard applied for the design of girders is not appropriate for fatigue, whereby the application of Eurocodes was proposed, which better takes into account the load spectrum.

The use of Eurocodes in the analysis of these types of structures is increasing ([2]-[5]). The application of Eurocodes for different types of structures, as well as in crane runway beam structures, was presented in [3]. The analysis of the application of Eurocodes in comparison to national standards for I-girders was presented in papers [4] and [5]. In the paper [6], multicriteria optimization of the welded I-girder of the double-beam bridge crane was performed using GRG2 code and EA code in EXCEL software, taking into account the global stability of the girder. Global stability is of great importance in the analysis of girders with I cross-section ([6]-[10]).

In [7], a multicriteria optimization of the welded I-girder of the single-beam bridge crane was performed, showing the achieved savings in material, in comparison to standard profiles, as well as the justification of this procedure. In researches [8] and [9], the types of girders composed of I and U profiles according to the AISC standard were analyzed, and in [9] experimental tests were performed. In the paper [10], the analysis of the I-profile for the monorail was observed, where the influence of the position of the supports on the global stability of the girder was observed.

Based on the importance of these types of structures, the shown research results, as well as the philosophy of optimal design, this research aims to develop a model for optimizing geometric parameters of the welded I-girder of the crane runway beam, to obtain the smallest possible mass of this type of girder. One metaheuristic method was used for the optimization process, and material savings will be shown, in comparison to existing solutions designed from standard I-profiles.

II. The optimization problem

In this research, the optimization of the crane runway beam is observed, whereby the welded I-profile with vertical stiffeners placed at distance $a=2\cdot h$ was analyzed (Fig. 1). The girder is subject to pressure forces from the wheels of the end carriage of the bridge crane.

The cross-section of the girder shows all required geometric parameters (Fig. 2).

This research aims to minimize the mass of the welded girder of the crane runway beam, where all the necessary conditions must be satisfied.

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

This research treats five geometric variables:

$$\left[x_1\ x_2\ x_3\ x_4\ x_5\right]=\left[b\ h\ d\ s\ a_s\right] \quad (1)$$

where:

b - the flange width (Fig. 2)

h - the web height (Fig. 2)

d - the flange thickness (Fig. 2)

s - the web thickness (Fig. 2)

a_s - the weld thickness (Fig. 2)

The objective function and constraints are presented in the next chapters.

The input parameters for optimization process are:

$$\left(F_W,\ L,\ L_t,\ \psi,\ \rho_m,\ R_e,\ E,\ \nu,\ K_f,\ t,\ b_s,\ h_s\right) \quad (2)$$

where:

F_W - the vertical load of the end carriage wheel (Fig. 1)

L - the span of the crane runway beam (Fig. 1)

L_t - end carriage wheelbase (Fig. 1)

$\psi = 1,25$ - the dynamic coefficient

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

R_e - the minimum yield stress of the girder material

$E = 21000\,kN/cm^2$ - the elastic modulus of the girder material

$\nu = 0,3$ - Poisson's ratio of the plate

$K_f = 1/750$ - the coefficient who depends on the purpose of the working conditions of the crane

$t = 5\,mm$ - the stiffener thickness (adopted value in this research)

b_s - the rail width

h_s - the rail height

In this research optimization was performed using the Cyclical Parthenogenesis Algorithm (CPA) in MATLAB software. This population-based metaheuristic algorithm is inspired by reproduction and social behavior of aphids, which can reproduce with and without mating, [11]. A detailed description of this method as well as the MATLAB code are shown in [11] and [12].

III. The objective function

The mass of the crane runway beam consists of both the plates of the I-profile and the plates of vertical stiffeners (Fig.1 and Fig. 2). The mass is increased by 5% due to welded joints, (3).

The objective function is defined as follows:

$$M = 1,05\cdot\rho_m\cdot\left(A_p\cdot L + 2\cdot n_v\cdot A_v\cdot t\right) \quad (3)$$

$$A_p = 2\cdot b\cdot d + h\cdot s \quad (4)$$

$$A_v = h\cdot b_v \quad (5)$$

$$b_v = \frac{b-s}{2} \quad (6)$$

where:

A_p - the cross-sectional area of the welded I-profile (Fig. 2)

b_v - the stiffener width (Fig. 2)

A_v - the area of vertical stiffener (Fig. 2)

n_v - the number of vertical stiffeners (Fig. 1)

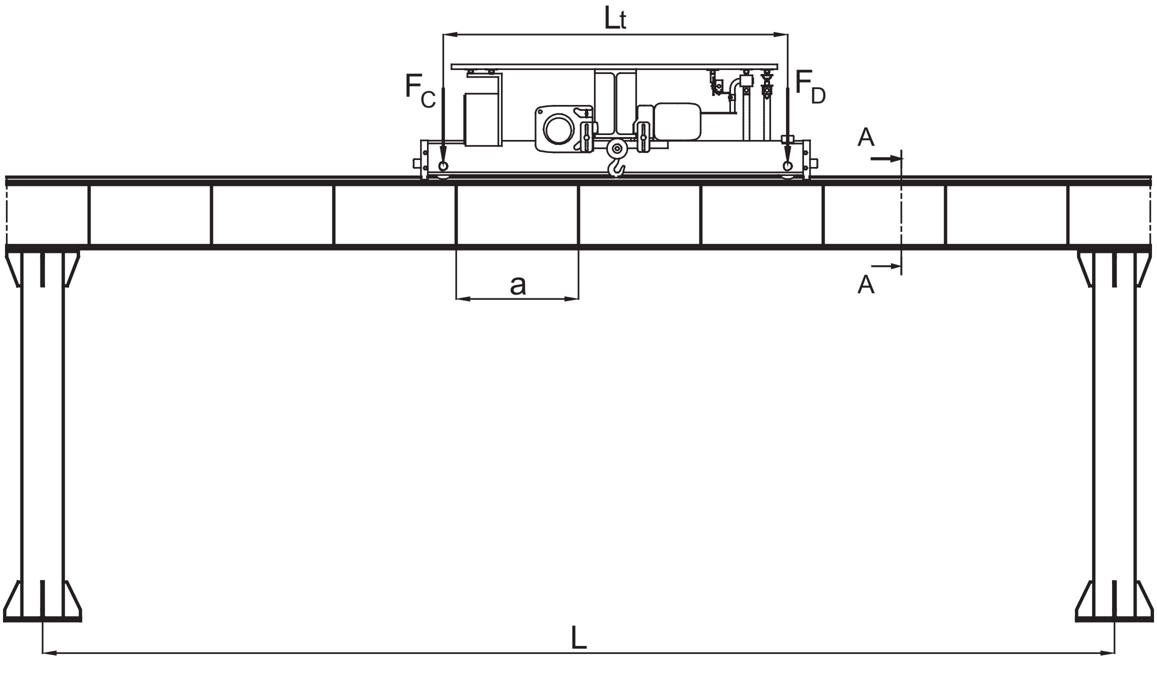

Fig. 1 Disposition of the crane runway beam with the bridge crane

All static parameters necessary for calculations (next chapter) in this optimization problem are (Fig. 1):

$$F_C = F_D = \psi\cdot F_W \quad (7)$$

$$R = F_C + F_D \tag{8}$$

$$q = \frac{M}{L} \cdot g \tag{9}$$

$$M_V = \frac{R}{4 \cdot L} \cdot \left(L - \frac{L_t}{2} \right)^2 + \frac{q \cdot L^2}{8} \tag{10}$$

$$F_T = \frac{R}{2 \cdot L} \cdot \left(L - \frac{L_t}{2} \right) + \frac{q \cdot L}{2} \tag{11}$$

where:

F_C, F_D - forces acting upon girder beneath the end carriage wheels

R - resulting force in the vertical plane

q - specific weight per unit of length of the welded girder

F_T - maximum shear force

M_V - maximum bending moment

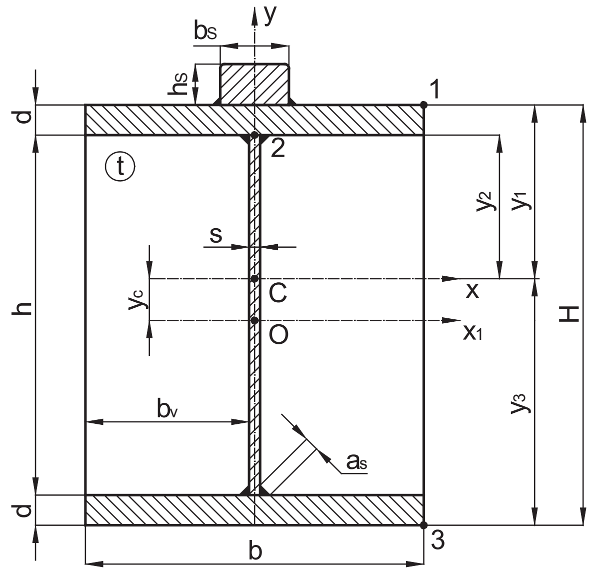

Fig. 2 Cross-section of the crane runway beam (A-A)

The geometric properties in the specific points of I-profile are (Fig. 2):

$$H = h + 2 \cdot d \tag{12}$$

$$A_s = b_s \cdot h_s \tag{13}$$

$$y_c = \frac{A_s \cdot (h + 2 \cdot d + h_s)}{2 \cdot \left(A_p + A_s \right)} \tag{14}$$

$$I_{x1} = \frac{1}{12} \cdot \left(s \cdot h^3 + 2 \cdot b \cdot d^3 + b_s \cdot h_s^{\,3} \right) + \\ + \frac{1}{2} \cdot b \cdot d \cdot (h + d)^2 + A_s \cdot \left(\frac{h + 2 \cdot d + h_s}{2} \right)^2 \tag{15}$$

$$I_x = I_{x1} + y_c^{\,2} \cdot \left(A_p + A_s \right) \tag{16}$$

$$I_{xb} = \frac{1}{12} \cdot \left(s \cdot h^3 + 2 \cdot b \cdot d^3 \right) + \frac{1}{2} \cdot b \cdot d \cdot (h + d)^2 \tag{17}$$

$$I_{yb} = \frac{1}{12} \cdot \left(s^3 \cdot h + 2 \cdot b^3 \cdot d \right) \tag{18}$$

$$y_1 = \frac{h}{2} + d - y_c \tag{19}$$

$$y_b = \frac{h}{2} + d \tag{20}$$

$$y_2 = \frac{h}{2} - y_c \tag{21}$$

$$y_3 = \frac{h}{2} + d + y_c \tag{22}$$

$$W_{x1} = \frac{I_x}{y_1} \tag{23}$$

$$W_{xb} = \frac{I_{xb}}{y_b} \tag{24}$$

$$W_{x2} = \frac{I_x}{y_2} \tag{25}$$

$$W_{x3} = \frac{I_x}{y_3} \tag{26}$$

$$S_{x2} = b \cdot d \cdot \left(\frac{h + d}{2} - y_c \right) + A_s \cdot \frac{h + 2 \cdot d + h_s}{2} \tag{27}$$

$$S_{x2b} = b \cdot d \cdot \frac{h + d}{2} \tag{28}$$

IV. Constraint functions

A. The criterion of stresses

The stress check is conducted at the specific points of the I-profile of the welded girder (Fig. 2). The value of stress σ must be less than the value of permissible stress σ_d.

The total stress at point 1 is:

$$\sigma_1 = \frac{M_V}{W_{x1}} \leq \sigma_d \tag{29}$$

$$\sigma_d = \frac{R_e}{\nu_1} \tag{30}$$

where:

$\nu_1 = 1{,}5$ - the factored load coefficient for load case 1, [13]

The components of normal stresses σ_2 and σ_y at point 2 are:

$$\sigma_2 = \frac{M_V}{W_{x2}} \leq \sigma_d \tag{31}$$

$$\sigma_y = \frac{F_C}{s \cdot z_1} \leq \sigma_d \tag{32}$$

$$y_\alpha = \frac{b \cdot d^2 + A_s \cdot (h_s + 2 \cdot d)}{2 \cdot \left(b \cdot d + A_s \right)} \tag{33}$$

$$I_\alpha = \frac{b \cdot d^3}{12} + b \cdot d \cdot \left(y_\alpha - \frac{d}{2} \right)^2 + + \frac{b_s \cdot h_s^3}{12} + A_s \cdot \left(\frac{h_s}{2} + d - y_\alpha \right)^2 \tag{34}$$

$$z_1 = 3,25 \cdot \sqrt[3]{\frac{I_\alpha}{s}} \tag{35}$$

The tangential stress at point 2 is:

$$\tau_2 = \frac{F_T \cdot S_{x2}}{I_x \cdot s} \le \tau_d = \frac{\sigma_d}{\sqrt{3}} \tag{36}$$

Finally, the total stress at point 2 is:

$$\sigma_{2,u} = \sqrt{\sigma_2{}^2 + \sigma_y^2 - \sigma_2 \cdot \sigma_y + 3 \cdot \tau_2{}^2} \le \sigma_d \tag{37}$$

The total stress at point 3 is:

$$\sigma_3 = \frac{M_V}{W_{x3}} \le \sigma_d \tag{38}$$

B. The criterion of local stability of the flange plate of I-profile

For this criterion, the condition from equation (39) must be fulfilled, according to [14]:

$$\sigma_p = \nu_1 \cdot \sigma_1 \le \sigma_{p,d} = \chi_p \cdot R_e \cdot c_p \tag{39}$$

$$\psi_p = 1,\ \alpha_p = \frac{a}{h} \ge 1,\ k_\sigma = 0,43 \tag{40}$$

$$\sigma_E = \frac{\pi^2 \cdot E}{12 \cdot (1 - \mu^2)} \cdot \left(\frac{2 \cdot d}{b} \right)^2 \tag{41}$$

$$\overline{\lambda_p} = \sqrt{\frac{R_e}{k_\sigma \cdot \sigma_E}} \tag{42}$$

$$\chi_p = \frac{0,6}{\sqrt{\overline{\lambda_p}^2 - 0,13}} \le 1 \tag{43}$$

where:
$c_p = 1$ - non-dimensional coefficient, according to [14]

C. The criterion of local stability of the web plate of I-profile

This criterion is satisfied if the condition from equation (44) is fulfilled, according to [13]:

$$\left(\frac{\sigma_I}{\sigma_{kr}} + \frac{\sigma_M}{\sigma_{Mkr}} \right)^2 + \left(\frac{\tau_{sr}}{\tau_{kr}} \right)^2 \le 0.81 \tag{44}$$

$$\sigma_I = \nu_1 \cdot \sigma_2 \tag{45}$$

$$\sigma_M = \nu_1 \cdot \sigma_y \tag{46}$$

$$\sigma_{kr} = K_2 \cdot \left(\frac{d}{h} \right)^2 \cdot 100000,\ \frac{\sigma_M}{\sigma_I} \ge 3,939 \tag{47}$$

$$\sigma_{kr} = 6,3 \cdot \left(\frac{s}{h} \right)^2 \cdot 100000,\ \frac{\sigma_M}{\sigma_I} < 3,939 \tag{48}$$

$$\sigma_{Mkr} = K_{11} \cdot \left(\frac{s}{a} \right) \cdot 100000,\ \frac{\sigma_M}{\sigma_I} \ge 3,939 \tag{49}$$

$$\sigma_{Mkr} = K_{12} \cdot \left(\frac{2 \cdot s}{a} \right) \cdot 100000,\ \frac{\sigma_M}{\sigma_I} < 3,939 \tag{50}$$

$$\tau_{sr} = \frac{\nu_1 \cdot F_T}{s \cdot h} \tag{51}$$

$$\tau_{kr} = \left[125 + 95 \cdot \left(\frac{h}{a} \right)^2 \right] \cdot \left(\frac{s}{h} \right)^2 \cdot 1000 \tag{52}$$

where:
K_2, K_{11}, K_{12} - non-dimensional coefficients, according to [13]

D. The criterion of global stability of the girder

The global stability (buckling) of the girder is checking in compliance with [15]. The following condition must be fulfilled:

$$\frac{h}{s} \le 3 \cdot \sqrt{\frac{E}{R_e}} \tag{53}$$

This criterion is satisfied if the condition from equation (54) applies:

$$\sigma_b = \nu_1 \cdot \frac{M_V}{W_{xb}} \le \min\left(\sigma_{b,d}, R_e \right) \tag{54}$$

$$I_D = \frac{1}{3} \cdot \left(2 \cdot d^3 \cdot b + s^3 \cdot h \right) \tag{55}$$

$$K = 1 + 0,156 \cdot \left(\frac{L}{H} \right)^2 \cdot \frac{I_D}{I_{yb}} \tag{56}$$

$$\phi = \frac{\sqrt{K + \rho^2} - \rho}{\sqrt{K + \rho^2}} \tag{57}$$

$$I_{p1} = \frac{b^3 \cdot d}{12} + \frac{s^3 \cdot h}{72} \tag{58}$$

$$A_{p1} = b \cdot d + \frac{h \cdot s}{6} \tag{59}$$

$$i_p = \sqrt{\frac{I_{p1}}{A_{p1}}} \tag{60}$$

$$\lambda_y = \frac{L}{i_p \cdot \sqrt{\eta}} \tag{61}$$

$$\sigma_{wd} = \frac{\pi^2 \cdot E}{\lambda_y{}^2} \tag{62}$$

$$\sigma_{vd} = \frac{\eta \cdot \pi}{L \cdot W_{xb}} \cdot \sqrt{G \cdot E \cdot I_D \cdot I_{yb}} \tag{63}$$

$$G = \frac{E}{2 \cdot (1+\nu)} \tag{64}$$

$$\sigma_{crd} = \phi \cdot \sqrt{\sigma_{wd}^2 + \sigma_{vd}^2} \tag{65}$$

$$\overline{\lambda_D} = \sqrt{\frac{2 \cdot S_{x2b}}{W_{xb}} \cdot \frac{R_e}{\sigma_{crd}}} \tag{66}$$

$$\chi_M = \left(\frac{1}{1+\overline{\lambda_D}^{2 \cdot n}} \right)^{1/n}, \quad \overline{\lambda_D} \geq 0,4 \tag{67}$$

$$\chi_M = 1, \quad \overline{\lambda_D} < 0,4 \tag{68}$$

$$\sigma_{b,d} = \alpha_b \cdot \chi_M \cdot R_e \tag{69}$$

where:

$\eta = 1,35$, $\rho = 0,55$ - coefficients, according to [15]

$n = 1,5$ - non-dimensional coefficient, according to [15]

E. The criterion of stresses in the welded connection

The value of stress σ_s in the welded connection (Fig. 2) must be less than the value of permissible stress $\sigma_{s,d}$.

$$\sigma_s \leq \sigma_{s,d} = 0,75 \cdot \sigma_d \tag{70}$$

$$\sigma_s = \sqrt{V_n^2 + V_p^2} \tag{71}$$

$$V_n = \frac{F_C}{2 \cdot a_s \cdot z_1} \tag{72}$$

$$V_p = \frac{F_T \cdot S_{x2}}{I_x \cdot 2 \cdot a_s} \tag{73}$$

$$a_s \leq 0,7 \cdot \min(s, d) \tag{74}$$

where:

V_n, V_p - stresses in the welded connection

F. The criterion of deflection of the girder

To satisfy this criterion, the total deflection f_u in the vertical plane must have the value smaller or equal to the permissible value f_d:

$$f_u = f_F + f_q \leq f_d = K_f \cdot L \tag{75}$$

$$f_F = \frac{F_C \cdot L^3}{48 \cdot E \cdot I_x} \cdot \left\{ 1 + \frac{F_D}{F_C} \cdot \left[1 - 6 \cdot \left(\frac{L_t}{L} \right)^2 \right] \right\} \tag{76}$$

$$f_q = \frac{5 \cdot q \cdot L^4}{384 \cdot E \cdot I_x} \tag{77}$$

V. The obtained results of optimization

The optimization process was done in MATLAB software using CPA code [12], without any modifications.

Algorithm parameters taken in all examples for this optimization process are: $N_a = 60$ - population size (number of aphids), $N_c = 4$ - number of colonies, $F_r = 0,4$ - parameter to determine the ratio of aphids of each colony to be considered as female, $\alpha_1 = 1$, $\alpha_2 = 2$ - search step size parameters, $\max N = 3000$ - maximum number of objective function evaluations.

Bound values of variables for all example are:

$100 \leq x_1 \leq 300$, $300 \leq x_2 \leq 800$, $6 \leq x_3 \leq 40$, $5 \leq x_4 \leq 20$, $3 \leq x_5 \leq 7$

TABLE I The values of input parameters

	F_W (kN)	L (m)	L_t (m)	M_p (kg)
1	32,5	12	2	1871
2	28,5	5	2,5	290
3	54	7	2,5	1085

Input parameters are taken from project documentations of three existing solutions of crane runway beams (Table I). In all examples, dimensions for the rail are b_s x h_s = 30 x 50 *mm*; the material of crane runway beams is S235. For this material, mechanical properties are: R_e = 23,5 kN/cm^2, σ_d = 15,67 kN/cm^2, and $\sigma_{s,d}$ = 11,75 kN/cm^2.

For the problem of the crane runway beam analysis defined in this way, coefficients for the criterion of local stability of the web plate are: K_2 = 17,79, K_{11} = 17,57, and K_{12} = 4,81, [13].

Table II shows the results of the optimization (optimal values of the geometric parameters and convergence characteristics) for all examples of the girders of the crane runway beams. Table III shows the rounded values of optimal geometrical parameters, optimal mass, and savings in material. Table IV shows the values of all constraint functions, for the rounded optimal values.

where:

M_p - the value of the mass of I-girder (Table I)

M_o - the value of the optimal mass of the welded I-girder (Table III)

TABLE II The values of optimal geometric parameters and convergence characteristics of the CPA method

	b (mm)	h (mm)	d (mm)	s (mm)	a_s (mm)	n_v	Best (kg)	Worst (kg)	Mean (kg)	Std	time (s)
1	142,89	459,55	40,0	5,12	3,00	13	1397,5	1898,7	1413,3	59,82	4,38
2	227,45	351,07	6,00	5,00	3,39	8	207,4	283,9	208,0	4,52	4,13
3	299,99	494,95	10,71	5,52	3,58	7	570,3	741,7	573,5	15,35	4,15

TABLE III The rounded values of optimal geometric parameters, optimal mass and Savings in material

	b (mm)	h (mm)	d (mm)	s (mm)	a_s (mm)	M_o (kg)	Saving (%)
1	143	460	40	6	3	1438,3	23,13
2	228	351	6	5	4	210,9	27,28
3	300	495	11	6	4	594,1	45,24

TABLE IV THE VALUES OF CONSTRAINT FUNCTIONS

	σ_1	σ_2	σ_y	τ_2	$\sigma_{2,u}$	σ_3	σ_p	$\sigma_{p,d}$	$\leq 0{,}81$	σ_b	$\sigma_{b,d}$	σ_s	f_u	f_d
1	6,10	5,10	2,86	1,40	5,05	7,47	9,16	23,50	0,014	11,96	11,96	3,18	1,59	1,60
2	3,83	3,65	5,33	1,47	5,36	6,67	5,74	14,79	0,008	13,30	13,35	3,45	0,13	0,67
3	5,97	5,67	7,55	1,79	7,48	7,96	8,95	22,14	0,027	13,20	13,61	5,82	0,48	0,93

VI. CONCLUSIONS

In this study, the mass of the welded girder of the crane runway beam was optimized. The mass of the girder was optimized using Cyclical Parthenogenesis Algorithm (CPA) in MATLAB software. The results were compared with the existing solutions of the crane runway beams. The results show that the method used is reliable, convenient, and rapid (Table II).

Justification of the application of the proposed procedure and method resulted in significant savings in material, within the range of 23,13 ÷ 45,24% (Table III), with none of the constraint functions is not exceeded. (Table IV). The adopted optimization algorithm was used for the reason that it has proven to give good results in different types of engineering problems, [11].

Table IV shows the criterion of global stability is the most critical, which was to be expected, as it is a girder with the I-cross section. In the first example, the deflection criterion is also critical, since it is a large value of the girder span. Also, the criterion of local stability of the web plate could be ignored for the observed examples.

The presented procedure is very useful for designers and researchers and can be applying for similar optimization problems. In further analysis should include the FEM, to verify the results of optimization.

The procedure should be further improved, which includes in the analysis of other important criteria, such as the position of stiffeners (vertical and horizontal), the fatigue of materials, types of materials, manufacturability, etc.

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REFERENCES

[1] M. Maali, A.C. Aydin, and M. Sagiroglu, “Investigation of innovative steel runway beam in industrial building”, *Sadhana*, Vol. 40, pp. 2239–2251, 2015.

[2] F. Pelayo, C. Rodríguez and A.F. Canteli, “Failure and repair analysis of a runway beam: Influence of the standard applied to lifetime prediction”, *Engineering Failure Analysis*, Vol. 56, pp. 89–97, 2015.

[3] D. Beg, U. Kuhlmann, L. Davaine and B. Braun, *Design of Plated Structures - Eurocode 3: Design of Steel Structures Part 1-5 – Design of Plated Structures*, ECCS – European Convention for Constructional Steelwork, Belgium, 2010.

[4] P. Bieranowski, “The Modernisation of Steel Construction Beam Gantry for the Work of Transport Suspended – Using the Example of Track Length Expansion by a Short Bracket”, *Czasopismo Techniczne*, Vol. 2-B, pp. 3-16, 2016.

[5] M. Gašić, M. Savković, N. Zdravković, G. Marković and H. Hot, “Stress determination in reinforced I-section bottom flange of single girder crane”, *The Fifth International Conference On Transport And Logistics til 2014*, Serbia, pp. 123-128, 5–6 June, 2014.

[6] G. Pavlović, M. Savković, N. Zdravković, G. Marković and M. Gašić, “Optimization of the Welded I-Girder of the Double-Girder Bridge Crane”, *MTC AJ,* Vol. 16, Issue 3/3, article No. 1667, 2018.

[7] G. Pavlović, M. Savković, N. Zdravković, R. Bulatović and G. Marković, “Analysis and Optimization Design of Welded I-Girder of the Single-Beam Bridge Crane”, *IV International Conference "Mechanical Engineering in the 21st Century – MASING 2018"*, Serbia, pp. 145-150, 19–20 April, 2018.

[8] W.T. Hsu, D.M. Lue and Y.F. Chen, “Design Aid for Moment Strength of Built-up Crane Runway Girders”, *International Journal of Steel Structures*, Vol. 12(3), pp. 403-417, 2012.

[9] D.S. Ellifritt and D. Lue, “Design of Crane Runway Beam with Channel Cap”, *Engineering Journal,* Second Quarter, pp. 41-49, 1998.

[10] N.S. Trahair, “Lateral buckling of monorail beams”, *Engineering Structures*, Vol. 30, pp. 3213-3218, 2008.

[11] A. Kaveh and A. Zolghadr, “Cyclical Parthenogenesis Algorithm: A New Meta-Heuristic Algorithm”, *Asian Journal of Civil Engineering (Building and Housing)*, Vol. 18(5), pp. 673-701, 2017.

[12] A. Kaveh and T. Bakhshpoori, *Metaheuristics: Outlines, MATLAB Codes and Examples*, Springer Nature Switzerland AG, Switzerland, 2019

[13] Z. Petković and D. Ostrić, *Metalne konstrukcije u masinogradnji 1*, Institute for Mechanization of the Faculty of Mechanical Engineering of the University in Belgrade, Serbia, 1996.

[14] SRPS U.E7.121:1986, *Provera stabilnosti nosećih čeličnih konstrukcija - Proračun izbočavanja limova*, Jugoslovenski zavod za standardizaciju, Beograd, 1986

[15] SRPS U.E7.101:1991, *Provera stabilnosti nosećih čeličnih konstrukcija - Bočno izvijanje nosača*, Jugoslovenski zavod za standardizaciju, Beograd, 1991.