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OPTIMAL DESIGN OF END CARRIAGE STRUCTURES

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Abstract: *Double-girder bridge cranes are widely used in manufacturing and production facilities, especially for large load capacities and spans. In addition to the great attention paid to the design of the main girders, end carriages also have a significant role and responsibility, which ensures the stable movement of the main girders of the double-girder bridge crane. The proper choice for the geometry of the cross-section of this structure is of great importance, primarily in terms of rigidity and the connection of these structures with the main girders. This research presents the analysis and optimization of the cross-section of the end carriage of the double-girder bridge crane, depending on the input design parameters. The presented model is justified and achieved significant savings in the material are shown through the examples of existing solutions of double-girder bridge cranes. The optimization process will be performed in the MATLAB software package, using the fmincon function, which is proven to solve nonlinear engineering problems. Confirmation of the obtained results will be shown using the SAP2000 software package.*

1. INTRODUCTION

End carriages are an integral part of the whole structure of the double-girder bridge crane and represent its very responsible part. In addition to ensuring the movement of the entire structure of the bridge crane along the crane track, it is necessary that they also meet the conditions of strength, rigidity and stability. All loads are transferred from the main girders to the crane track through end carriages. Some of these loads depend on the design of the entire bridge crane structure, the type of trolley, and movement conditions. For these reasons, special attention should be paid when designing tend carriages.

FEM is of great importance in the analysis of bridge crane structures. In the paper [01], the change in stress states was analyzed in both the main girder and end carriages of the single-girder bridge crane, depending on the change in carrying capacity. The influence of skewing and the influence of longitudinal forces that occur during the movement of bridge cranes on the wheels of end carriage are also the subjects of research, which is shown in papers [02] and [03]. For engineering problems, optimization procedures are increasingly carried out using different algorithms. In [04], the optimization of the box cross-section of the end carriage was performed in the MATLAB software package, using a metaheuristic algorithm, whereby significant material savings were achieved. Similar to the previous, in the paper [05], the weight optimization of the welded I-girder of the bridge crane was performed using GRG2 code and EA code in the MS EXCEL software package.

In this paper, the welded box girder of the end carriage will be analyzed and optimized. The obtained results will be verified by applying the FEM analysis, and it will also be shown the saving in the material in that case.

2. MODEL OF OPTIMIZATION PROBLEM

The following figure shows the static scheme of the whole structure of the double-girder bridge crane (Fig.1), the trolley, main girders, and end carriages.

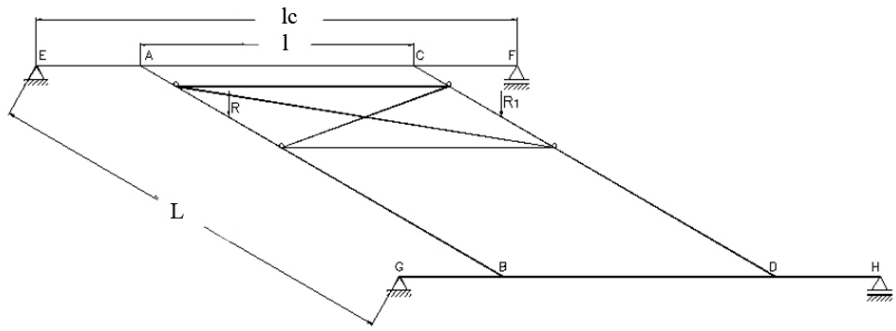

Fig.1 – The static scheme of the double-girder bridge crane

In this paper, analysis and optimal design of the welded structure of the end carriage will be performed using the following static scheme (Fig.2):

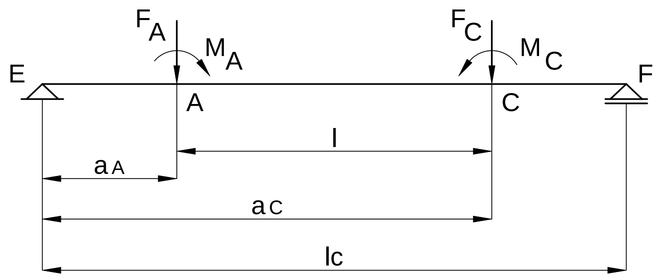

Fig.2 – The static scheme of the end carriage

The subject of optimization is the weight of the end carriage, i.e., the area of the box cross-section, and it is the same as in the paper [04] for the case of the end carriage of the single-girder bridge crane.

The optimization process will be carried out using the MATLAB function *fmincon*, which is proven to solve nonlinear optimization problems.

The mathematical formulation of the objective function (cross-sectional area) is:

$$f(X) = A(x_1, \dots, x_n) = (b_1, h, t, s) \tag{1}$$

The vector X is the vector of optimization variables (box girder's geometrical parameters). The input parameters for this optimization problem are:

$$Q,\ L,\ l_c,\ l,\ m_t,\ b_t,\ D_w,\ b_w,\ b_{wr},\ b_r,\ \rho,\ f_y,\ \nu_1, \dots \tag{2}$$

where:

$Q,\ L$ - the carrying capacity of the crane and the span of the crane, respectively

$l_c,\ l$ - the end carriage wheelbase and the distance between main girders, respectively

$m_t,\ b_t$ - the trolley weight and trolley wheelbase, respectively

$D_w,\ b_w$ - the diameter and the width of the end carriage wheel, respectively

b_{wr} - the inner width of the end carriage wheel

b_r - the width of the rail

$\rho,\ f_y$ - density and minimum yield stress of the end carriage's material, respectively

ν_1 - the factored load coefficient for load case 1

The box cross-sectional area *A*, i.e., the objective function, is:

$$A = 2 \cdot \left[\left(b_1 + 2 \cdot s \right) \cdot t + h \cdot s \right] \quad (3)$$

The weight of the end carriage m_c (increased by 20% due to other components) is:

$$m_c = 1,2 \cdot A \cdot l_c \cdot \rho \quad (4)$$

All static parameters, bending moments and forces (Fig.1 and Fig.2) in the corresponding planes, are determined in the following way, according to [06]:

$$R = R_1 = F_1 + F_2 = \left(\psi \cdot Q + m_t \right) \cdot g / 2 \quad (5)$$

$$F_1 = F_2 = \left(\psi \cdot Q + m_t \right) \cdot g / 4 \quad (6)$$

$$R_h = F_{1st} + F_{2st} = \left(\psi \cdot Q + m_t \right) \cdot g / 2 \quad (7)$$

$$F_{1st} = F_{2st} = \left(Q + m_t \right) \cdot g / 4 \quad (8)$$

$$M_{t1} = M_{t2} = \gamma \cdot \left(F_1 \cdot x_2 + k_a \cdot F_{1st} \cdot y_2 \right) \quad (9)$$

$$M_A = \left(M_{t1} + M_{t2} \right) \cdot \left(L - b_t / 2 \right) / L \quad (10)$$

$$F_A = F_C = \gamma \cdot \left[R \cdot \left(L - b_t / 2 \right) / L + m_b \cdot g / 2 \right] \quad (11)$$

$$M_C = 2 \cdot \gamma \cdot \left(F_1 \cdot x_2 - k_a \cdot F_{1st} \cdot y_2 \right) \cdot \left(L - b_t / 2 \right) / L \quad (12)$$

$$F_K = R_h \cdot \left(L - b_t / 2 \right) / L + \left(m_c + m_b \right) \cdot g / 2 \quad (13)$$

$$F_Z = \lambda \left(b_{wr} - b_r,\ L / l_c \right) \cdot F_K \quad (14)$$

$$q_c = 1,05 \cdot A \cdot \rho \cdot g \quad (15)$$

$$a_A = b_C = \left(l_c - l \right) / 2,\ a_C = b_A = \left(l_c + l \right) / 2 \quad (16)$$

$$F_E = \left[-M_A + M_C + F_A \cdot a_C + F_C \cdot a_A \right] / l_c + \gamma \cdot q_c \cdot l_c / 2 \quad (17)$$

$$F_F = \left[M_A - M_C + F_A \cdot a_A + F_C \cdot a_C \right] / l_c + \gamma \cdot q_c \cdot l_c / 2 \quad (18)$$

$$M_{VA} = F_E \cdot a_A + M_A - \gamma \cdot q_c \cdot a_A^{\ 2} / 2 \quad (19)$$

$$M_{VC} = F_F \cdot a_A + M_C - \gamma \cdot q_c \cdot a_A^{\ 2} / 2 \quad (20)$$

$$M_{V\max} = \max(M_{V1},\ M_{V2}) \quad (21)$$

$$M_H = F_Z \cdot a_A \quad (22)$$

where:

$R,\ R_h$ - resulting forces in the vertical and the horizontal plane, respectively

$\gamma,\ \psi,\ k_a,\ \lambda,\ K_f$ - coefficients, according to [06]

q_c - the specific weight of the end carriage, increased by 5% due to welded connections

$x_2,\ y_2$ - geometrical parameters of the main girder of the double-beam bridge crane

m_b - the weight of the main girder of the double-beam bridge crane

F_A, M_A, F_C, M_C - acting forces and moments at points *A* and *C*, respectively

F_K - the maximum pressure on the end carriage's wheel

F_Z - the transverse horizontal wheel force

F_E, F_F - reacting forces at points *E* and *F*, respectively

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

The above expressions and the calculation scheme are given for the case where the rail is above the web (Example 1), while for the case where the rail is in the middle of the main girder, the direction of the moment at point *C* is different (Example 2).

The value of maximum stress σ_m must be less than the value of the permissible one, σ_d:

$$\sigma_{\mathrm{m}} = M_{V\max} / W_x + M_H / W_y \le \sigma_d = f_y / \left(\nu_1 \cdot \gamma_m\right) \tag{23}$$

where:

γ_m - the coefficient, according to [07]

W_x, W_y - geometrical properties of the box cross-section

Check for local buckling of web plates, and the top flange of the welded girder is done according to [07]:

$$\sigma_w = \nu_1 \cdot \left[M_{V\max} \cdot h / \left(H \cdot W_x\right) + M_H / W_y\right] \le \sigma_{d,w} = \chi_w \cdot f_y / \gamma_m \tag{24}$$

$$\sigma_p = \nu_1 \cdot \left(M_{V\max} / W_x + M_H / W_y\right) \le \sigma_{d,p} = \chi_p \cdot f_y / \gamma_m \tag{25}$$

where:

χ_w, χ_p - coefficients, according to [07]

For the criterion of the maximum deflection, and using the symmetry of the end carriage, the deflection f_{max} must have a value smaller than the permissible one, f_d:

$$f_{\max} = f_1 + f_2 + f_3 + f_q \le f_d = K_f \cdot l_c \tag{26}$$

$$f_1 = 2 \cdot F_A \cdot l_c^3 \cdot \left[b_C / \left(2 \cdot l_c\right)\right] \cdot \left[0{,}75 - \left(b_C / l_c\right)^2\right] / \left(6 \cdot B\right) \tag{27}$$

$$f_2 = -M_A \cdot l_c^2 \cdot \left\{0{,}5 \cdot \left[0{,}75 - 3 \cdot \left(b_A / l_c\right)^2\right] + 3 \cdot \left[\left(l_c / 2 - a_A\right) / l_c\right]^2\right\} / \left(6 \cdot B\right) \tag{28}$$

$$f_3 = M_C \cdot l_c^2 \cdot \left[0{,}75 - 3 \cdot \left(b_C / l_c\right)^2\right] / \left(12 \cdot B\right) \tag{29}$$

$$f_q = 5 \cdot \gamma \cdot q_c \cdot l_c^4 / \left(384 \cdot B\right) \tag{30}$$

3. OBTAINED RESULTS

In this paper, the optimization process was performed in the MATLAB software package, using function *fmincon*. Optimization variables are: X=[b_1; h; t; s].

In addition to the above criteria, geometric constraints (lower and upper limits) should be considered: L_b=[b_w; D_w; 0.6; 0.5]; U_b=[15; 50; 3; 2].

Two double-girder bridge cranes in exploitation (Example 1 and Example 2) will be considered examples. The input data for the optimization process can be found in Table 1 and Table 2. Table 1 shows the characteristics of bridge cranes, while Table 2 shows the data related to end carriages.

Table 1

Ex.	Q (t)	L (m)	m_b (kg)	m_t (kg)	b_t (cm)	b_r (cm)	x_2 (cm)	y_2 (cm)
1.	15	20,69	4214	780	100	5	15,8	53
2.	3,2	15,2	1706	250	80	5	-	20,5

Table 2

Ex.	l_c (cm)	l (cm)	A_c (cm^2)	H_2=H_4(cm)	a_1 (cm)	a_2 (cm)	D_w (cm)	b_w (cm)	b_{wr} (cm)

1.	315	170	109,36	1,5	3	3	25	12	6,9
2.	250	120	59,24	1,5	1,5	3	11	11,1	6,2

Both cranes are in classification class 2, while end carriages are made of S355 material. For these bridge cranes other necessary input data are taken according to [06] and [07]: f_y = 35,5 kN/cm^2, γ_m = 1,1, ν_1 = 1,5, σ_d = 21,52 kN/cm^2, ρ = 7850 kg/m^3, γ = 1,05, ψ= 1,15, k_a = 0,1, K_f = 1/1000.

Table 3

Ex.	b_1 (cm)	h (cm)	t (cm)	s (cm)	A_{op} (cm^2)	Saving (%)	σ_m (kN/cm^2)	f (cm) $\leq f_d$ (cm)
1.	18,0	41,884	0,6	0,5	64,684	40,85	15,50	0,315 $\leq$ 0,315
2.	14,1	19,822	0,6	0,5	37,942	35,95	9,17	0,250 $\leq$ 0,250

Ex.	$\sigma_{d,w}$ (kN/cm^2)	σ_w (kN/cm^2)	$\sigma_{d,p}$ (kN/cm^2)	σ_p (kN/cm^2)
1.	32,27	22,71	32,27	23,25
2.	32,27	13,09	32,27	13,76

Table 4

Ex.	$F_A = F_C$ (kN)	M_A (kNcm)	M_C (kNcm)	F_E (kN)	F_F (kN)	F_Z (kN)	M_{VA} (kNcm)	M_{VC} (kNcm)	M_H (kNcm)
1.	112,318	1852,04	1852,04	110,514	115,852	15,951	9849,90	9396,21	1156,47
2.	28,494	35,47	35,47	28,613	29,181	3.843	1888,51	1889,93	249,80

Table 3 shows optimal geometrical values, maximum stresses, deflections, and savings in material for two examples of the double-girder bridge cranes, where A_{op} is the optimal value of the box cross-sectional area. Table 4 shows important static parameters.

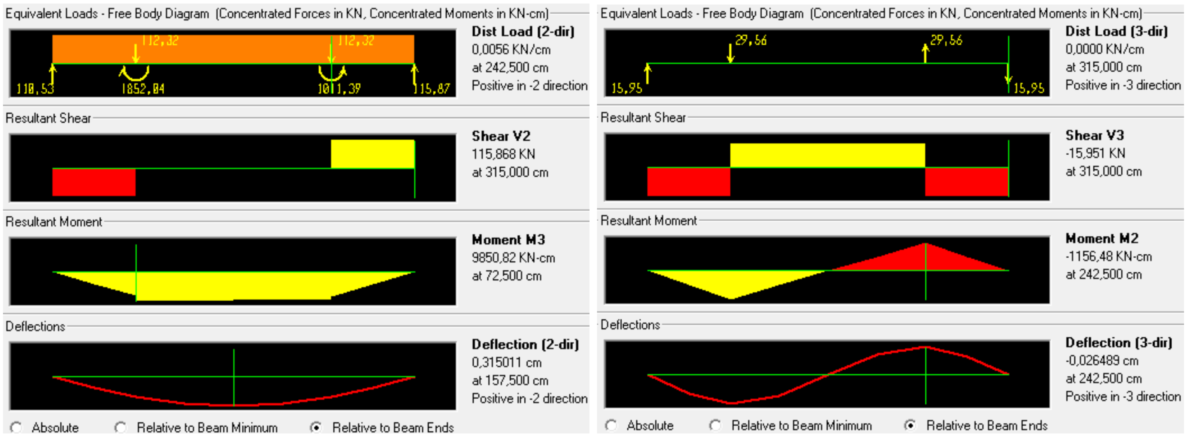

Fig.3 – Static diagrams from SAP2000 for Example 1

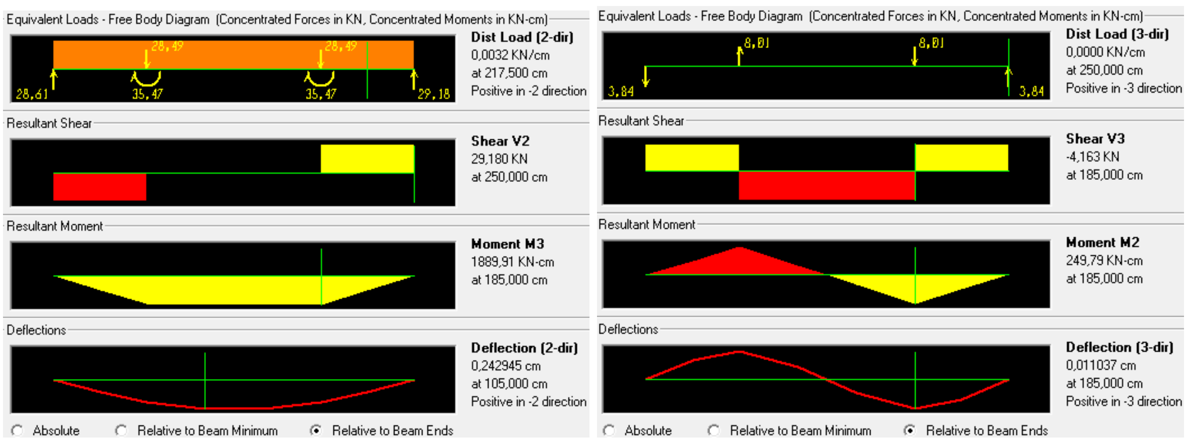

Fig.4 – Static diagrams from SAP2000 for Example 2

Fig.3 and Fig.4 show static diagrams from the SAP2000 software package for both examples, respectively, for the optimal calculated values of the box cross-section. It is noticed that static quantities from Table 4 are almost identical with those from the static diagrams so that maximum stresses are also identical. From Table 3 and Fig.3, the deflection values are the same (Example 1), while for Example 2, there is a difference between the deflection values, which is less than 3% (Tables 3 and Fig.4).

6. CONCLUSION

This research presents analysis, optimization and the FEM verification of the welded box-girder of an end carriage structure, using MATLAB and SAP2000 software packages. The criteria of stress, local buckling of plates and deflection were taken as the constraint functions for optimization. The minimization of the weight of the welded end carriage was the goal in this study.

For these observed examples and input data, in both cases, the most critical condition is the criterion of the maximum deflection. Table 3 shows that the presented optimization model and used optimization function *fmincon* achieve significant material savings within the range from 35,95 to 40,85% compared to standard end carriages. Confirmation of this model is the verification performed in the SAP2000 software package, where a high concordance of results was achieved (Table 3 and Table 4).

This approach to analysis and optimization, using the MATLAB software package, can be successfully applied to similar load-bearing structures, where optimal results are obtained quickly and successfully, regardless of the number of variables and constraint functions. Also, the SAP2000 software package enables fast model preparation, calculation and analysis.

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