Design Optimization of the Rectangular Box Section of the Double Beam Bridge Crane Using Matlab Optimization Toolbox

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The paper considers the problem of optimization of the rectangular box section of the double beam bridge crane. Reduction of the girder mass is set as the objective function. The constrained optimization applied in Matlab Optimization Toolbox was used as the methodology for determination of optimal geometrical parameters of the rectangular box section. The criteria of permissible stresses, local buckling of plates, static deflection, permissible period of oscillation, minimum plate thickness and production feasibility were applied as the constraint functions. Verification of the used methodology was carried out through numerical examples and the comparison with some existing solutions of cranes was made. Numerical result shown that the mathematical model of optimization was exact and the algorithm effective.

Keywords: Double beam bridge crane, Eurocodes, Matlab Optimization Toolbox, Optimization, Rectangular box section

1. INTRODUCTION

Double beam bridge cranes are very much present in idustry plants, and all of which are intended for lifting and transportation of large loads and for larger spans. The mass of the girders has the largest share in the total mass of the double beam bridge crane, and that is the reason why it is very important to reduce it in order to obtain a lighter structure, which also reduces the market price of the crane.

There are a large number of papers which deal with the problem of analysis of stresses of main girders of cranes as well as with their optimization. Most papers treat the problem of optimization or stress analysis of the main girder of the bridge crane.

Most authors set permissible stress or permissible stress and permissible deflection as the constraint functions. The criteria of lateral stability, local buckling of plates and permissible period of oscillation have lately been increasingly applied as the constraint functions.

Matlab software is a very effective tool in the optimization procedures, particularly in engineering practice, as is the case with the main girders of the bridge cranes. Application of Matlab software in optimization of the main girder of the single-girder bridge crane is shown in [01]. The single-girder crane is loaded with two loaded trolleys. The performed optimization showed there can be savings in the mass of the main girder, using Matlab Graphical User Interface (GUI). Optimization of geometric parameters of different types of cross-sectional shapes of the main girders of the double beam bridge cranes is shown in [02], using the multi-criteria optimization process in Matlab software. Application of Matlab Optimization Toolbox in optimization of the section of the prestressed steel-concrete composite box girder is shown in [03]. The price of the girder is significantly reduced for a concrete example.

In most cases, the optimization of the girders is performed by FEA. In the paper [04], manual and FEA report for plates buckling is presented to reduce overall weight and cost of the main girder of the bridge cranes. Results obtained from FEM, manual calculations and experimental analysis.

The paper [5] carried out the analysis of local buckling of plates and rigidity of the bridge cranes by using Polish standards, which were later compared with the results of analysis performed according to European standards, using Ms Excel software and FEM. The paper [6] performed topology optimization of the main girder of the double beam crane using by Optistruct solver tool in HyperWorks software, according to the criteria of strength, stiffness and lateral stability. 3D model was made in Pro/E software. The mass of the girder is reduced by 21.16%. Similarly to previous, the paper [07] carried out optimization of the geometrical characteristics (thickness, height and width) of the box girders of the bridge crane using by Patran/Nastran software, and based on these results the secondary optimization is fulfilled with MMA programme (The Method of Moving Asymptotes algorithm).

In [8], optimization of the main girder of the double beam bridge crane using by SolidWorks software, according to the criteria of strength, stiffness and local stability of plates is presented. Similarly to previous, the paper [09] performed optimization of the main girder of the bridge crane using by Ansys software, according to the criteria of strength and stiffness, where the total volume of girder is decreased by about 21.8%.

Besides the above mentioned softwares for FEM, in [10], by using LIAfem software, indicated that the size of the finite element affects the accuracy of the results, where the double beam bridge crane is analyzed.

Application of Abaques software in the analysis of strength and stiffness of the girder of the double beam bridge crane is shown in [11]. The observed example of the crane is modeled in Inventor software. The authors also analyzed the natural frequencies with a modal analysis of the girder with and without load. On the importance of dynamic effects in the analysis and optimization by FEM, show us the following papers. In [12], the analysis was carried out by Ansys software, and the conclusion of the study was that double beam bridge cranes have had less dynamic effects under the same loads as single-girder bridge cranes so they proved to be working faster.

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The paper [13] carried out the analysis of the effects that have inertial forces on the stresses and deflections, by FEM, where the derived certain conclusions for the optimization of these types of girders.

In addition to FEM application, is increasingly being applied various analytical and numerical methods for optimization process. Multi-criteria optimization was conducted in the paper [14] for the purpose of reducing the crane mass using Ms Excel software, and the solution was verified using Ansys software. The mass of the girder was reduced about 10%.

In the paper [15], problem of reducing the weight of the box girder of the bridge crane, at the same time increasing the productivity and to improve quality of product as required by the Indian standard, is tackled by preparing programme in Visual Basic 6.0. Optimal dimensions of the box girder of the bridge crane are affected by choice of standards, as shown in the paper [16], where the results obtained by Serbian standard and European standard, and compared, on examples of existing solutions of single-girder bridge cranes. GRG2 algorithm in Ms Excel software was used for the optimization process.

Application of the centered differential evolution (CDE) algorithm in the process of optimization of the box girder of the bridge crane is shown in [17], where as opposed to the previously mentioned papers, the cross-section of the box girder is variable along the span. In this way, the mass of the girder is decreased by about 23.50%.

Application of Mathcad software in optimization of the box girder of the bridge crane is shown in [18], where is graphically presented the dependence of the cross-sectional area in relation of capacities of the cranes, for characteristic spans. Similarly to previous, in [19] is graphically presented the dependence of the cross-sectional area in relation of the spans, for characteristic capacities of the cranes. In [20] is also applied Mathcad for multi-criteria optimization and comparison of the results for the welded box girder, for the cases when the objective function is the cross-sectional area and the cost of the girder manufacturing.

The mentioned papers point to the importance of optimization of the main girder of the bridge crane and creation of the model which can allow a more real description of the crane behaviour in operation. As it can be seen in the mentioned papers, there are different constraint functions so that it can be concluded that a better objective function, i.e. smaller girder mass is obtained for a larger number of constraints.

Taking into account the above mentioned results and conclusions, the aim of this paper is to define optimum values of parameters of the geometry of cross-sectional area of the rectangular box girder of the double beam bridge crane that will lead to the reduction of its mass.

2. MATEMATHICAL FORMULATION OF THE OPTIMIZATION PROBLEM

The task of optimization is to define geometrical parameters of the rectangular box section of the girder which result is its minimum mass.

Matlab Optimization Toolbox can be used to solve the problems of linear programming, non-linear programming and multi-target programming.

The optimization algorithm of the parameters of the cross-sectional area of steel rectangular box girder is to utilizing the *fmincon* function in the Optimization Toolbox to realize the minimization of the cross-sectional area of the rectangular box girder, i.e. constrained minimization problem.

The optimization problem can be defined by the following mathematical formulation, [21]:

$$\min f(X) \tag{1}$$

subject to:

$$C(X) \leq 0 \tag{2}$$

$$Ceq(X) = 0 \tag{3}$$

$$A \cdot X \leq b \tag{4}$$

$$Aeq \cdot X = beq \tag{5}$$

$$lb \leq X \leq ub \tag{6}$$

where:

X, b, beq, lb, ub - vectors

A, Aeq - matrices

$C(X)$, $Ceq(X)$ - functions that return to vectors

$f(X)$ - the target function (the objective function)

Functions *f(X)*, *C(X)* and *Ceq(X)* can be nonlinear functions.

In Matlab Optimization Toolbox, the constrained nonlinear optimization problem is realized by *fmincon* fuction. The specific forms are as followings:

$$[X, fval, exitflag, output, lambda, grad, hessian] = fmincon(fun, X0, A, b, Aeq, beq, lb, ub, nonlcon, options) \tag{7}$$

where:

fval - objective function value at solution (returned as a real number)

exitflag - shows reason for stop of *fmincon* function

fun - the target function

fmincon - function which find minimum of constrained nonlinear multi-variable function

output - function which outputs optimization information

nonlcon - function which calculates nonlinear inequality constraint $C(X) \leq 0$ through the accepted vector X and the equality constraint $Ceq(X) = 0$ is used by estimated C and Ceq at the poison of X though the appointed function handle

lambda - the multiplier of Lagrange (it embodies which constraint is valid)

grad - shows the gradient of the target function at X

hessian - shows Hessiab value of the target function at X

$X0$ - the initial value

A and b meet the requirements of the inequality constraint $A \cdot X \leq b$, if there is no such constraint, then $A=[\ ]$ and $b=[\ ]$.

Aeq and beq meet the requirements of the equality constraint $Aeq \cdot X = beq$, if there is no such constraint, then $Aeq=[\ ]$ and $beq=[\ ]$.

lb and ub meet the requirements $lb \leq X \leq ub$ if there is no scope, suppose $lb=[\ ]$ and $ub=[\ ]$.

In the process of optimization, *fmincon* function adopts gradient projection method. Gradient projection method is a method to directly deal with the nonlinear programming constraint.

It made a projection matrix according to the initial points and boundary face where the initial points stand. Repeat this procedure frequently so as to obtain the best solution.

3. OBJECTIVE AND CONSTRAINT FUNCTIONS

3.1. Objective function

The objective function is represented by the area of the cross section of the rectangular box girder (Figure 1). The paper treats five optimization parameters (*h*, b_1, t_1, t_2, *y*), where:

h - web height
b_1 - distance between webs
t_1 - flange thickness
t_2 - web thickness
y - value, according to recommendations

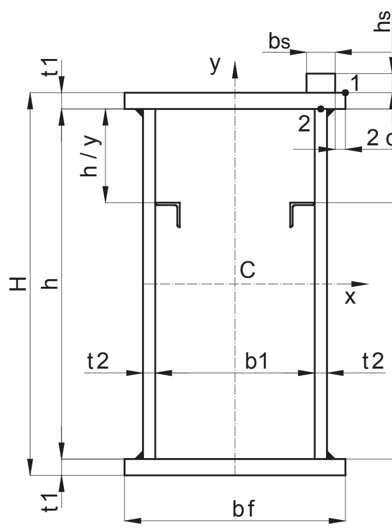

Figure 1: The rectangular box section of the main girder of the bridge crane

The vector of the given parameters is:

$$\vec{x} = \left(Q,\ L, m_k, b_k, k_a,\ f_y,\ b_S, h_S,\ D_t ...\right) \tag{8}$$

where:

Q - the carrying capacity of the crane
L - the span of the crane
m_k - the mass of the trolley
b_k - the distance between the wheels of the trolley
k_a - the dynamic coefficient of crane load in the horizontal plane, [22]
f_y - the minimum yield stress of the plate material
b_S - rail width
h_S - rail height
D_t - the diameter of the trolley wheel

The area of the cross section (Figure 1), i.e. the objective function, is:

$$A_g = 2 \cdot (b_f \cdot t_1 + h \cdot t_2) \tag{9}$$

or

$$A_g = A_g(X) = 2 \cdot \left(x_1 + x_4 + b_S + 4\right) \cdot x_3 + 2 \cdot x_2 \cdot x_4 \ \ cm^2 \tag{10}$$

where:

A_g - the area of the cross section of the rectangular box girder (the objective function)
X - the design vector made of five design variables

$$X = \left[x_1\ x_2\ x_3\ x_4\ x_5\right]^T = \left[b_1\ h\ t_1\ t_2\ y\right]^T \tag{11}$$

Other important relations can be written in the following way:

$$b_f = b_f(X) = b_1 + t_2 + b_S + 4 = x_1 + x_4 + b_S + 4 \ \ cm \tag{12}$$

$$H = H(X) = h + 2 \cdot t_1 = x_2 + 2 \cdot x_3 \tag{13}$$

where:

H - height of the girder
b_f - flange width

The geometrical properties in the specific points of the rectangular box section (Figure 1) shall be determined by well-known expressions (I_x, W_{x1}, W_{y1}, W_{x2}, W_{y2}, S_{x2}).

where:

I_x - moment of inertia about *x* axis
W_{x1}, W_{y1} - section moduli for point 1
W_{x2}, W_{y2} - section moduli for point 2
S_{x2} - static moment of area for point 2

3.2. Constraint functions

3.2.1. The criterion of permissible stresses

The maximum equivalent stresses in specific points of the rectangular box section (Figure 1) have to be lower than permissible stresses.

The values of the bending moments in the corresponding planes and the value of the transverse force are calculated in the following way (Figure 2):

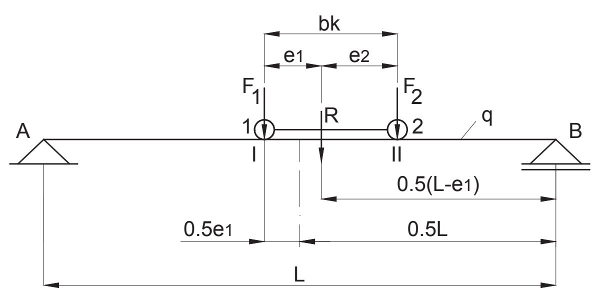

Figure 2: Model of the main girder of the bridge crane

$$M_{VI} = \frac{R}{4 \cdot L} \cdot (L - e_1)^2 + \gamma \cdot \frac{q \cdot L^2}{8} \tag{14}$$

$$e_1 = \frac{b_k}{2} \tag{15}$$

$$q = 1.1 \cdot \rho \cdot g \cdot A \tag{16}$$

$$M_{HI} = \gamma \cdot \left[\frac{R_h}{4 \cdot L} \cdot (L - e_1)^2 + \frac{q \cdot L^2}{8} \cdot k_a \right] \tag{17}$$

$$F_t = \frac{R}{2 \cdot L} \cdot (L - e_1) + \frac{\gamma \cdot q \cdot L}{2} \tag{18}$$

while the values of the corresponding forces are:

$$F_1 = F_2 = \gamma \cdot \frac{\psi \cdot Q + m_k}{4} \cdot g \tag{19}$$

$$R = F_1 + F_2 \tag{20}$$

$$F_{1,st} = F_{2,st} = \frac{Q + m_k}{4} \cdot g = F_{st} \tag{21}$$

$$F_{1,h} = F_{2,h} = F_{st} \cdot k_a \quad (22)$$

$$R_h = F_{1,h} + F_{2,h} \quad (23)$$

where:

γ - the coefficient which depends on the classification class, [22]

ψ - the dynamic coefficient of the influence of load oscillation in the vertical plane, [22]

F_1, F_2 - forces acting upon girder beneath the trolley wheel 1 and trolley wheel 2, respectively

R - resulting force in the vertical plane

$\rho = 7850\ \dfrac{kg}{m^3}$ - densiny of material of the girder

q - specifically weight per unit of length of the girder (increased by the weight of the diaphragms and the longitudinal stiffeners)

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

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

R_h - resulting force in the horizontal plane

F_t - maximum shear force

The value of the equivalent stress at point 1:

$$\sigma_{1,u} = \sigma_{zV1} + \sigma_{zH1} = \frac{M_{VI}}{W_{x1}} + \frac{M_{HI}}{W_{y1}} \leq f_{d,1} \quad (24)$$

$$f_{d,1} = \frac{f_y}{\gamma_m \cdot \nu_1} \quad (25)$$

where:

$\sigma_{1,u}$ - maximum equivalent stress at point 1

$f_{d,1}$ - permissible stress

$\gamma_m = 1.1$ - general resistance factor, [23]

$\nu_1 = 1.5$ - the factored load coefficient for load case 1

The value of the normal stress in the x direction at point 2:

$$\sigma_{z2} = \sigma_{zV2} + \sigma_{zH2} = \frac{M_{VI}}{W_{x2}} + \frac{M_{HI}}{W_{y2}} \leq f_{d,1} \quad (26)$$

The value of the normal stress in the y direction due to the action of wheel pressure on the web plate (Figure 3):

$$\sigma_y = \frac{F_1}{t_2 \cdot l_r} \leq f_{d,1} \quad (27)$$

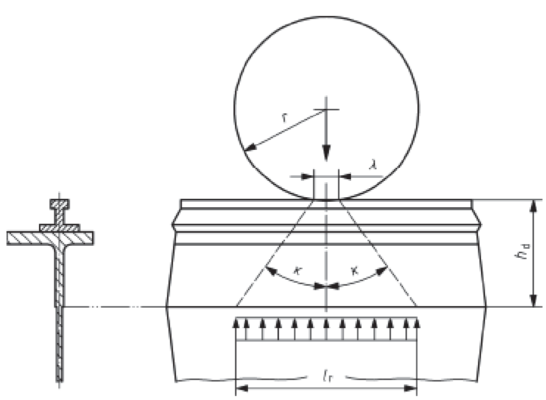

Figure 3: Effective distribution length under concentrated load

where:

σ_{z2}, σ_y - the normal stresses in the x and y directions at point 2, respectively

l_r - the effective distribution length (given in Annex C.4, [23])

$$l_r = l_{1r} = 2 \cdot h_d \cdot tg\kappa + 0.2 \cdot r = 2 \cdot h_{d1} \cdot tg\kappa + 0.1 \cdot D_t \quad (28)$$

$$h_d = h_{d1} = h_S + t_1 \quad (29)$$

where:

h_d - the distance between the section under consideration and contact level of acting load (Figure 3)

$\kappa \leq 45^\circ$ - the dispersion angle, [23]

r - the radius of the trolley wheel ($D_t / 2$)

The value of the tangential stress at point 2:

$$\tau_2 = \frac{F_t \cdot S_{x2}}{2 \cdot t_2 \cdot I_x} \leq \frac{f_{d,1}}{\sqrt{3}} \quad (30)$$

The value of the equivalent stress at point 2 (maximum equivalent stress at point 2):

$$\sigma_{2,u} = \sqrt{\sigma_{z2}^{\ 2} + \sigma_y^{\ 2} - \sigma_{z2} \cdot \sigma_y + 3 \cdot \tau_2^{\ 2}} \leq f_{d,1} \quad (31)$$

3.2.2. The criterion of local buckling of plates

Testing of the box girder stability was carried out in accordance with the European standard, [23]. According to this standard, it is necessary to check the buckling of the flange plate with the width b_1 and the thickness t_1 (Figure 4 and Figure 5), the buckling of the web plate above the longitudinal stiffener (length a, height h_1 and thickness t_2 – Figure 4 and Figure 6) as well as the buckling of the web plate under the longitudinal stiffener (length a, height h_2 and thickness t_2 – Figure 4 and Figure 6). Length a is distance bitween the diaphragms (Figure 4).

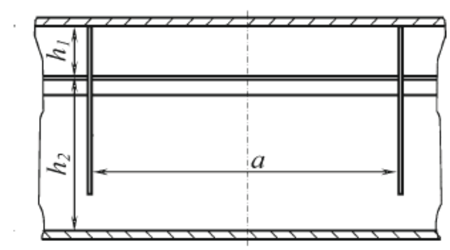

Figure 4: Stiffeners of the box girder

The criterion of local buckling of top flange plate of the box girder

Testing of the stability of the flange plate segment (Figure 5) subjected to the action of normal compressive stress in the x direction was carried out in compliance with [23].This criterion is fulfilled if the following condition is satisfied:

$$|\sigma_{Sx}| = \nu_1 \cdot (\sigma_{zV1} + \sigma_{zH2}) \leq f_{b,Rx} \quad (32)$$

$$f_{b,Rx} = \kappa_x \cdot f_d \quad (33)$$

$$f_d = \frac{f_y}{\gamma_m} \quad (34)$$

where:

$|\sigma_{Sx}|$ - design value of the compressive stress in the x direction

$f_{b,Rx}$ - critical stress

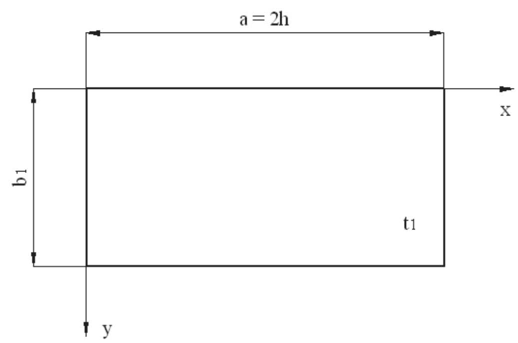

Figure 5: Top flange

κ_x - a reduction factor, [23]

$$\kappa_x = c_e \cdot \left(\frac{1}{\lambda_x} - \frac{0.22}{\lambda_x^{\ 2}} \right) \le 1 \quad for \quad \lambda_x > 0.673 \qquad (35)$$

or

$$\kappa_x = 1 \quad for \quad \lambda_x \le 0.673 \qquad (36)$$

where:

λ_x - non-dimensional plate slenderness, [23]

$$\lambda_x = \sqrt{\frac{f_y}{K\sigma \cdot \sigma_e}} \qquad (37)$$

$$c_e = 1.25 - 0.12 \cdot \psi_e, \; c_e \le 1.25 \qquad (38)$$

where:

$K\sigma$ - a buckling factor (given in Table 15, [23])

σ_e - a reference stress, [23]

ψ_e - the edge stress ratio of the plate, relative to the maximum compressive stress

$$K\sigma = \frac{8.2}{\psi_e + 1.05} \qquad (39)$$

$$\psi_e = \frac{\sigma_2}{\sigma_1} = \frac{\sigma_{zV1} - \sigma_{zH2}}{\sigma_{zV1} + \sigma_{zH2}} \qquad (40)$$

$$\sigma_e = \frac{\pi^2 \cdot E}{12 \cdot (1 - \nu^2)} \cdot \left(\frac{t_1}{b_1} \right)^2 \qquad (41)$$

where:

$\nu = 0.3$ - the Poisson's ratio of the plate

$E = 21000 \dfrac{kN}{cm^2}$ - the elastic modulus of the plate

The criterion of local buckling of web plate of the box girder

Testing of the stability of the web plate segment (Figure 6) subjected to the action of normal stresses in the *x* and *y* directions was carried out in compliance with [23].

The case when, in addition to vertical stiffeners at midspan, a row of horizontal stiffeners is also placed, the horizontal stiffeners being placed at the distance of *h/y* was considered (Figure 1).

The criterion of stability of the web plate in zone 1 is fulfilled if the following condition is satisfied:

$$\left(\frac{|\sigma_{S1x}|}{f_{b,R1x}} \right)^{e_{1x}} + \left(\frac{|\sigma_{S1y}|}{f_{b,R1y}} \right)^{e_{1y}} - \left(\kappa_{1x} \kappa_{1y} \right)^6 \left(\frac{|\sigma_{S1x} \sigma_{S1y}|}{f_{b,R1x} f_{b,R1y}} \right) \le 1 \qquad (42)$$

$$|\sigma_{S1x}| = \nu_1 \cdot \left(\sigma_{zV2} + \sigma_{zH2} \right) \qquad (43)$$

$$|\sigma_{S1y}| = \frac{\nu_1 \cdot F_1}{t_2 \cdot l_{1r}} \qquad (44)$$

$$f_{b,R1x} = \kappa_{1x} \cdot f_d \qquad (45)$$

$$f_{b,R1y} = \kappa_{1y} \cdot f_d \qquad (46)$$

$$e_{1x} = 1 + \kappa_{1x}^4, \; e_{1y} = 1 + \kappa_{1y}^4 \qquad (47)$$

$$h_1 = \frac{h}{y} \qquad (48)$$

where:

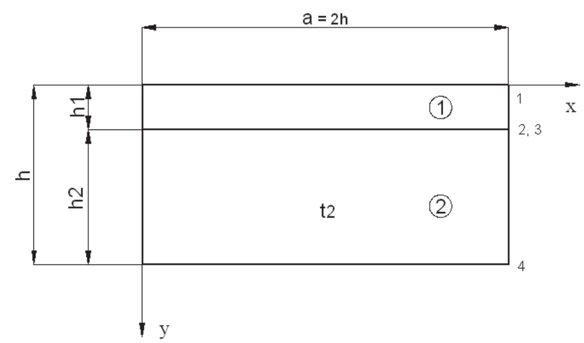

Figure 6: Web plate

$|\sigma_{S1x}|$, $|\sigma_{S1y}|$ - design values of the compressive stresses in zone 1 in the *x* and *y* directions, respectively

$f_{b,R1x}$, $f_{b,R1y}$ - critical stresses

κ_{1x}, κ_{1y} - reduction factors for zone 1 in the *x* and *y* directions, respectively, [23]

$$\kappa_{1x} = c_{1e} \cdot \left(\frac{1}{\lambda_{1x}} - \frac{0.22}{\lambda_{1x}^{\ 2}} \right) \le 1 \quad for \quad \lambda_{1x} > 0.673 \qquad (49)$$

or

$$\kappa_{1x} = 1 \quad for \quad \lambda_{1x} \le 0.673 \qquad (50)$$

where:

λ_{1x} - non-dimensional plate slenderness, [23]

$$\lambda_{1x} = \sqrt{\frac{f_y}{K\sigma_1 \cdot \sigma_{1e}}} \qquad (51)$$

$$c_{1e} = 1.25 - 0.12 \cdot \psi_{1e}, \; c_{1e} \le 1.25 \qquad (52)$$

$$K\sigma_1 = \frac{8.2}{\psi_{1e} + 1.05} \qquad (53)$$

$$\psi_{1e} = \frac{(y-2) \cdot \sigma_{zV1} + y \cdot \sigma_{zH2}}{y \cdot \left(\sigma_{zV1} + \sigma_{zH2} \right)} \qquad (54)$$

$$\sigma_{1e} = \frac{\pi^2 \cdot E}{12 \cdot (1 - \nu^2)} \cdot \left(\frac{t_2}{h_1} \right)^2 \qquad (55)$$

$$\kappa_{1y} = 1.13 \cdot \left(\frac{1}{\lambda_{1y}} - \frac{0.22}{\lambda_{1y}^{\ 2}} \right) \le 1 \quad for \quad \lambda_{1y} > 0.831 \qquad (56)$$

or

$$\kappa_{1y} = 1 \quad for \quad \lambda_{1y} \le 0.831 \qquad (57)$$

where:

λ_{1y} - non-dimensional plate slenderness, [23]

$$\lambda_{1y} = \sqrt{\frac{f_y}{K\sigma_{1y} \cdot \sigma_{1e} \cdot \dfrac{a}{c_{1r}}}} \qquad (58)$$

where:

$K\sigma_{1y}$ - a buckling factor for zone 1 (determined using Figure 11, [23])
c_{1r} - the width over which the transverse load is distributed (equivalent to l_{1r})

The criterion of stability of the web plate in zone 2 is fulfilled if the following condition is satisfied:

$$\left(\frac{|\sigma_{S2x}|}{f_{b,R2x}}\right)^{e_{2x}} + \left(\frac{|\sigma_{S2y}|}{f_{b,R2y}}\right)^{e_{2y}} - \left(\kappa_{2x}\kappa_{2y}\right)^6 \left(\frac{|\sigma_{S2x}\sigma_{S2y}|}{f_{b,R2x} f_{b,R2y}}\right) \le 1 \quad (59)$$

$$|\sigma_{S2x}| = \nu_1 \cdot \left(\sigma_{zV1} \cdot \frac{h/2 - h_2}{h/2} + \sigma_{zH2}\right) \quad (60)$$

$$|\sigma_{S2y}| = \frac{\nu_1 \cdot F_1}{t_2 \cdot l_{2r}} \quad (61)$$

$$l_{2r} = 2 \cdot h_{d2} \cdot tg\kappa + 0.2 \cdot r = 2 \cdot h_{d2} \cdot tg\kappa + 0.1 \cdot D_t \quad (62)$$

$$h_{d2} = h_S + t_1 + h_1 \quad (63)$$

$$f_{b,R2x} = \kappa_{2x} \cdot f_d \quad (64)$$

$$f_{b,R2y} = \kappa_{2y} \cdot f_d \quad (65)$$

$$e_{2x} = 1 + \kappa_{2x}^4, \quad e_{2y} = 1 + \kappa_{2y}^4 \quad (66)$$

$$h_2 = \frac{h \cdot (y-1)}{y} \quad (67)$$

where:
$|\sigma_{S2x}|$, $|\sigma_{S2y}|$ - design values of the compressive stresses in zone 2 in the *x* and *y* directions, respectively
$f_{b,R2x}$, $f_{b,R2y}$ - critical stresses
κ_{2x}, κ_{2y} - reduction factors for zone 2 in the *x* and *y* directions, respectively, [23]

$$\kappa_{2x} = c_{2e} \cdot \left(\frac{1}{\lambda_{2x}} - \frac{0.22}{\lambda_{2x}^2}\right) \le 1 \quad for \quad \lambda_{2x} > 0.673 \quad (68)$$

or

$$\kappa_{2x} = 1 \quad for \quad \lambda_{2x} \le 0.673 \quad (69)$$

where:
λ_{2x} - non-dimensional plate slenderness, [23]

$$\lambda_{2x} = \sqrt{\frac{f_y}{K\sigma_2 \cdot \sigma_{2e}}} \quad (70)$$

$$c_{2e} = 1.25 - 0.12 \cdot \psi_{2e}, \quad c_{2e} \le 1.25 \quad (71)$$

$$K\sigma_2 = 7.81 + 6.29 \cdot \psi_{2e} + 9.78 \cdot \psi_{2e}^2 \quad (72)$$

$$\psi_{2e} = \frac{(y-2) \cdot \sigma_{zV1} + y \cdot \sigma_{zH2}}{y \cdot (\sigma_{zH2} - \sigma_{zV1})} \quad (73)$$

$$\sigma_{2e} = \frac{\pi^2 \cdot E}{12 \cdot (1-\nu^2)} \cdot \left(\frac{t_2}{h_2}\right)^2 \quad (74)$$

$$\kappa_{2y} = 1.13 \cdot \left(\frac{1}{\lambda_{2y}} - \frac{0.22}{\lambda_{2y}^2}\right) \le 1 \quad for \quad \lambda_{2y} > 0.831 \quad (75)$$

or

$$\kappa_{2y} = 1 \quad for \quad \lambda_{2y} \le 0.831 \quad (76)$$

where:
λ_{2y} - non-dimensional plate slenderness, [23]

$$\lambda_{2y} = \sqrt{\frac{f_y}{K\sigma_{2y} \cdot \sigma_{2e} \cdot \frac{a}{c_{2r}}}} \quad (77)$$

where:
$K\sigma_{2y}$ - a buckling factor for zone 2 (determined using Figure 11, [23])
c_{2r} - the width over which the transverse load is distributed (equivalent to l_{2r})

3.2.3. The criterion of static deflection

In order to satisfy this criterion, it is necessary that static deflection in the vertical plane has the value smaller than the permissible one.

$$f_{st} = \frac{F_{1,st} \cdot L^3}{48 \cdot E \cdot I_x} \cdot \left[1 + \alpha \cdot (1 - 6 \cdot \beta^2)\right] \le f_{dop} \quad (78)$$

$$\alpha = \frac{F_{2,st}}{F_{1,st}} = 1 \quad (79)$$

$$\beta = \frac{b_k}{L} \quad (80)$$

$$f_{dop} = k \cdot L \quad (81)$$

where:
f_{st} - static deflection in the vertical plane,
f_{dop} - the permissible deflection in the vertical plane, [22]
α, β - the coefficients, [22]
k - the coefficient which depends on the purpose of the crane and control condition of the crane, [22]

3.2.4. The criterion of permissible period of oscillation

To determine the time of damping of oscillation, it is necessary to analyse the vertical oscillation of the main girder with the payload. The analysis procedure was performed in compliance with [22] and [24].

The mass m_1 is determined according to the expression, [24]:

$$m_1 = \frac{Q + m_k}{2} + \frac{35 \cdot m_m}{72} \quad (82)$$

where:
$\frac{35 \cdot m_m}{72}$ - the reduced continual mass of the girder at midspan for the assumed function of displacement of the elastic line of the adopted discrete dynamic model for the simple girder, [24]

The time of damping of oscillation is determined from the expression, [22]:

$$T = \frac{6 \cdot \pi \cdot \sqrt{\delta_{11} \cdot m_1}}{\gamma_d} \le T_d \quad (83)$$

$$m_m = 1.1 \cdot \rho \cdot A \cdot L \quad (84)$$

$$\delta_{11} = \frac{1.0 \cdot L^3}{48 \cdot E \cdot I_x} \quad (85)$$

where:
m_m - the mass of the girder (increased by the mass of the diaphragms and the longitudinal stiffeners)

δ_{11} - the deflection of the girder caused by the action of the unit force

T_d - the permissible time of damping of oscillation (permissible period of oscillation), which depends on the purpose of the crane, [22]

γ_d - the logarithmic decrement which shows the rate of damping of oscillation, which depends on the ratio between the height of the girder H and the span L, [22]

4. NUMERICAL REPRESENTATION OF THE RESULTS OBTAINED

The optimization process is done by Optimization Toolbox module of Matlab software.

Existing solutions of the double beam bridge cranes that were used as examples for the optimization process are in classification class 2m/M5, so that certain input parameters necessary for the optimization process are adopted for mentioned classification class. Other input datas are shown in Table 1.

As initial conditions (vector X_0) in the optimization process are taken the dimensions of the rectangular box section of existing solutions of the double beam bridge cranes (shown in Table 1).

As additional criteria for the optimization process are taken production feasibility (distance between the webs) and the recommended minimum thicknesses of the plates.

Minimum thickness of the web plates is adopted to be 5 mm and minimum thickness of the bottom and top flange is adopted to be 6 mm, which are also the constraint functions. In addition, as one more constraint function, minimum distance between the web plates is taken to be: 20 cm, 25 cm and 30 cm. These values are shown by the minimum values (lower boundaries) of the optimization parameters (vector *lb*).

The boundaries for the optimization parameter y are taken as recommended values ($y = 3 \div 5$).

Table 1: Characteristics of existing solutions of the double beam bridge cranes

No.	Manufacturer	Q (t)	L (m)	m_k (kg)	D_t (mm)	Material	b_k (mm)	t_1 (mm)	t_2 (mm)	h (cm)	b_1 (cm)	b_f (cm)	A_g (cm^2)
1	Colpart	15	20.69	780	170	S355	1000	10	6	98	31	41	199.6
2	Colpart	10	23.3	690	140	S355	1000	10	6	98	30	40	185.6
3	Colpart	2x25	22.5	2x2920	230	S355	1350	12	8	147.6	41.8	52	360.96
4	Montavar Lola	20	18.95	860	170	S235	1000	10	8	98	31	41	238.8

Table 2: The values of optimum parameters and Savings

No.	t_1 (mm)	t_2 (mm)	h (cm)	b_1 (cm)	b_f (cm)	y	A_{opt} (cm^2)	Saving (%)
1	7	6	113.74	20	29.6	4.07	177.93	10.86
1	7	6	113.74	25.04	34.64	4.06	184.98	7.32
1	6	5	111.15	30	39.5	3.96	158.55	**20.57**
2	6	5	120.91	20	29.5	3.76	156.31	**15.78**
2	6	5	117.4	25	34.5	3.73	158.8	14.44
3	8	6	136.1	50	60.6	3.84	260.28	27.89
3	8	6	132.28	52.78	63.38	4.02	260.14	**27.93**
4	6	5	107.26	45.23	55.73	3.89	174.14	**27.08**

Table 2 shows the results of the optimization for four existing solutions of the double beam bridge cranes, according to euro codes and material saving at different initial conditions (the minimum value of b_1). It can be seen that in some cases of existing solutions of the double beam bridge cranes the optimization process gives different results. The plate thickness values are rounded to whole numbers. The values with the greatest savings of some examples are bolded.

5. CONCLUSION

Based on the optimization theory and the procedure for calculation of steel box girder of the bridge cranes, this paper combines the optimum design philosophy and the design of the rectangular box girder. The cross-sectional area is optimized making full use of the optimization function in the Matlab Optimization Toolbox. The result shows that the Matlab Optimization Toolbox is reliable, convenient and rapid. Therefore, it can be widely utilized in the optimization of the cross-sectional area of steel box girders for similar constructions.

Application of Matlab Optimizaiton Toolbox on sections of the rectangular box girders of the bridge cranes allows designers to concentrate their attention on the optimization rather than the realization of the specific calculation. The results of optimization (the main paremeters of the cross-sectional area of the rectangular box girder) represent the starting point for designers while designing box girders.The justification of application of Optimization Toolbox module of Matlab software was checked on four solutions of the double beam bridge cranes which are in operation. The optimization task – minimization of the cross-sectional area was successfully realized, which is seen in the comparison of the obtained results with the solutions made in practice. The application of this method resulted in significant savings in the material, within the range of 15.78 ÷ 27.93%. Similar procedure can be carried out for the situation with two rows of longitudinal stiffeners, which is the case for greater spans and load capacities.

The conclusion is that further research should be directed toward a multi-criteria analysis where it is necessary to include additional constraint functions, such as: influence of manufacturing technology, types of material, conditions of crane control and operation, material fatigue and economy. Previously mentioned is the basis for further research in order to save material, and also to minimize the cost of the girder manufacturing, [20]. The obtained results can be of great importance both for crane designers and for the researchers dealing with similar optimization problems.

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