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OPTIMIZATION OF THE BOX SECTION OF THE SINGLE-GIRDER BRIDGE CRANE BY GRG ALGORITHM ACCORDING TO DOMESTIC STANDARDS AND EUROCODES

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Abstract: *The paper considers the problem of optimization of the box section of the main girder of the single-girder bridge crane. Reduction of the area of the box cross section is set as the objective function. The algorithm of generalized reduced gradient (GRG2 algorithm) was used as the methodology for determination of optimum geometrical parameters of the box section. The criteria of permissible stresses, local stability of plates, lateral stability of the girder, static deflection, dynamic stiffness, minimum plate thickness and production feasibility (distance between the webs) 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. The comparative optimization results show changes of the box section optimum geometric values due to domestic standards or eurocodes.*

Keywords: *single-girder bridge crane,box section, optimization, GRG2 algorithm, eurocodes.*

1. INTRODUCTION

Single-girder bridge cranes are widely applied in industrial plants. The box section of the main girder is most often used for medium and high carrying capacities of these cranes. The mass of this girder has the largest share in the total mass of the single-girder 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.

Most papers treat the problem of optimization or stress analysis of double-girder bridge cranes. It is known that double-girder cranes are intended for lifting and transportation of large loads and for larger spans than single-girder cranes. However, the number of single-girder cranes installed in plants is significant so that optimization of their main girders is justified. In some cases it is more economical to use the single-girder bridge crane in relation to the double-girder bridge crane from reduction of mass of the girders point of view, [1]. This is good reason to be pay more attention for these types of cranes.

In most cases, the optimization of the girders is performed by FEA. In paper [02] design optimization is performed using principal calculations and detailed 3D FEA by changing primarily thickness of the box girder plates. Principal static and d ynamic calculations for two models of double box girder, are given in the paper. As a result of optimization a reduction of mass of 38% achieved and stress-deformation characteristics considering yield stranght and stability of construction was not endangered. In paper [03] the main aim is to reduce the structural mass of a real-world double-girder overhead crane, through the use of modern computer modelling and simulation methods and applications by CATIA software. The structural mass reduction are designed and verified by structural static stress simulations. The numerical analysis of stress and strain field for double beam bridge crane is done under maximum load conditions by using ABAQUS software in [04], the distribution and largest area under load of bridge is obtained. At the same time three natural frequencies and mode shapes of double beam bridge crane is analyzed, which the results provide a theoretical basis and reference for double beam bridge crane designer. Similarly, in paper [05] FEA of main girder of bridge crane is conducted by ANSYS software. The natural frequencies and the vibration-made vectors of the first 6 orders are obtained, and the vibration hazardous areas are found. Rational optimization of girder is able to avoid the resonance frequency region, which will help to improve the reliability and life-span of the girder.

In addition to the application FEM, is increasingly being applied various analytical and numerical methods for optimization process. In paper [06] the optimum design of box-type of crane girders is considered by using nonlinear programming techniques. The limitations on the stresses and the deflections induced in the girder in different load conditions are stated in the form of inequality constraints. The effects of collision, wind loading and damping time of vibration are also considered in the problem formulation. The resulting nonlinear programming problem is solved by using an interior penalty function method. Similarly, in paper [07], by using the same method, the mass of the girder was reduced up to 17,11% for medium rank, and 11,56% for heavy rank. In paper [08] was made parametric synthesis of the span of beams bridge cranes on the basis of multivariate analysis of their geometrical parameters and combining design and test calculations. Developed the methodical and software for calculation of metal structures of bridge cranes with optimal weight and size characteristics. In paper [09] the method of Lagrange multipliers was used as the methodology for approximate determination of optimum dependences of geometrical parameters of the box section. The criteria of lateral stability and local stabiity of plates were applied as the contraint functions. The obtained results of optimization of geometrical parameters were verified on numerical examples. In order to solve the optimization of the bridge crane box girder, on the basis of the polyclonal selection algorithm, an improved polyclonal selection algorithm based on negative selection is proposed in paper [10]. By taking advantages of the clone deletion and supply operation based on negative selection, the optimization ability of the proposed algorithm is improved. The experiment results of the typical function test and the crane box girder optimization verify the effectiveness of this algorithm.

The mentioned papers point to the importance of optimization of the main girder of the crane and creation of the model which can allow a more real description of the crane behaviour in operation.

Having in mind that there are a large number of single-girder bridge cranes in plants, this paper deals with the investigation into optimization of the box cross-section of single-girder bridge cranes. 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.

Having in mind previously stated results and conclusions, the objective of this paper is to define optimum values for box section geometric parameters of single-girder bridge crane, which would lead to mass reduction.

2. MATEMATHICAL FORMULATION OF THE OPTIMIZATION PROBLEM

As the optimization task represents mass minimization, it is necessatry to determine the values of geometrical parameters of the cross-section of the girder which define its minimum area.

Minimization of the mass corresponds to minimization of the volume, i.e. the area of the cross section of the girder, where the given boundary conditions must be satisfied. The area of the cross section primarily depends on: height and width of the girder and thickness of plates.

The optimization problem defined in this way can be given the following general mathematical formulation:

– minimize $f(X)$

– subject to: $g_i(X) \le 0,\ i = 1,...,m$

and $l_i \le X_i \le u_i,\ \ i = 1,...,n$

where:

– $f(x)$ - the objective function,

– $g_i(X) \le 0$ - the constraint function,

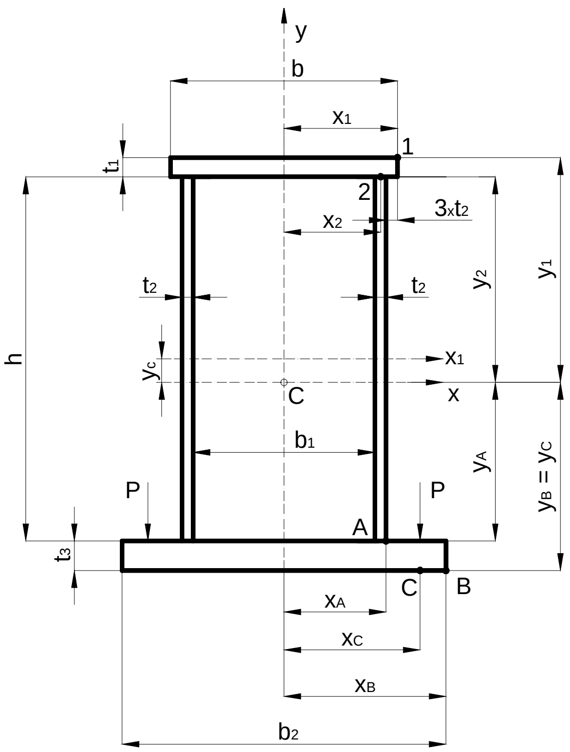
– m - the number of constraints,

– l_i, u_i - lower, i.e. upper boundary, where $u_i > l_i$.

– $X = \{x_1,...,x_n\}^T$ - represents the design vector made of n design variables.

3. OBJECTIVE FUNCTION

The model is presented in Picture 1.:



Picture 1. The box section of the single-girder bridge crane

The objective function is represented by the area of the cross-section of the box girder.

The vector of the given parameters is:

$$\vec{x} = (Q, L, M_{cv}, M_{ch}, k_a,\ m_k, d, ...) \quad (1)$$

where:

Q – the carrying capacity of the crane,

L – the span of the crane,

m_k – the mass of the trolley,

d – the distance between the wheels of the trolley,

M_{cv} and M_{ch} – the bending moments in the vertical and horizontal planes,

$k_a = 0,1$ - the dynamic coefficient of crane load in the horizontal plane, [11].

The area of the cross section (2), i.e. the objective function, is:

$$A = 2 \cdot h \cdot t_2 + b \cdot t_1 + b_2 \cdot t_3 \quad (2)$$

The geometrical properties in the specific points of box section (Picture 1) shall be determined by well-known expressions (W_{x1}, W_{y1}, W_{x2}, W_{y2}, S_{x2}, I_x, W_{xB}, W_{yB}, W_{xA}, W_{yA}, S_{xA}, W_{xC}, W_{yC}).

4. CONSTRAINT FUNCTIONS

4.1. The criterion of of strength

Strength check is conducted in specific points of girder. Actual stress σ_r has to be lower than critical stress σ_k which depends on load case.

$$\sigma_r \le \sigma_k \quad (3)$$

$$\sigma_k = \sigma_{k1} = f_y / \nu_1 \quad (4)$$

$$\sigma_k = \sigma_{k2} = f_y / \nu_2 \quad (5)$$

according to domestic standards, or:

$$\sigma_k = f_y / \gamma_m / \nu_1 \quad (6)$$

according to eurocodes,

where:

- f_y the minimum yield stress of the plate material,
- ν_1 the factored load coefficient for load case 1,
- ν_2 the factored load coefficient for load case 2,
- $\gamma_m = 1,1$ general resistance factor, [14].

The constraint function has the following form:

$$g_1 = \sigma_r - \sigma_k \le 0 \quad (7)$$

The highest stresses occur at the middle of the span. The values of the bending moments in the corresponding planes are:

$$M_{VI} = \gamma \cdot \left[R \cdot (L - e_1)^2 / 4 \cdot L + q \cdot L^2 / 8 \right] \quad (8)$$

$$M_{HI} = \gamma \cdot \left[R_h \cdot (L - e_1)^2 / 4 \cdot L + q \cdot L^2 \cdot k_a / 8 \right] \quad (9)$$

where:

$\gamma = 1,05$ - the coefficient which depends on the classification class (1,05 for classification class 2), [15],

$\psi = 1,15$ - the dynamic coefficient of the influence of load oscillation in the vertical plane, [11],

q – specifically weight per unit of length of the girder,

$e_1 = F_2 \cdot d / R$,

while the values of the corresponding forces are:

$$F_1 = F_2 = \gamma \cdot (\psi \cdot Q + m_k) / 2 \cdot g,\ R = F_1 + F_2 \quad (10)$$

$$F_{1,st} = F_{2,st} = (Q + m_k) / 2 \cdot g = F_{st} \quad (11)$$

$$F_{1,h} = F_{2,h} = F_{st} \cdot k_a,\ R_h = F_{1,h} + F_{2,h} \quad (12)$$

$$F_t = R \cdot (L - e_1) / 2 \cdot L + \gamma \cdot q \cdot L / 2 \quad (13)$$

$$P = R / n_k \quad (14)$$

where:

P - the vertical crane wheel load,

n_k - number of the wheels of trolley.

1. The strength in specific points of the girder:

Point 1:

Maximum normal stress at point 1:

$$\sigma_{1,u} = M_{VI} / W_{x1} + M_{HI} / W_{y1} \le \sigma_k \quad (15)$$

Point 2:

Maximum normal stress at point 2:

$$\sigma_{z2} = M_{VI} / W_{x2} + M_{HI} / W_{y2} \quad (16)$$

Maximum tangential stress at point 2:

$$\tau = F_t \cdot S_{x2} / (2 \cdot t_2 \cdot I_x) \le \sigma_k / \sqrt{3} \quad (17)$$

Maximum equivalent stress at point 2:

$$\sigma_{2,u} = \sqrt{\sigma_{z2}{}^2 + 3 \cdot \tau^2} \le \sigma_k \quad (18)$$

2. The strength in the bottom flange of the girder in specific points:

Point B:

I – According to domestic standards:

Maximum equivalent stress at point B:

$$\sigma_{B,u} = M_{VI} / W_{xB} + M_{HI} / W_{yB} \le \sigma_{k1} \qquad (19)$$

II – According to eurocodes:

The normal stresses due to the local pressure of the trolley wheel at point B, [13]:

$$\sigma^{B}_{ox,Ed} = c^{B}_{x} \cdot P / t_3^2 \le \sigma_k,\ \sigma^{B}_{oy,Ed} = c^{B}_{y} \cdot P / t_3^2 \le \sigma_k \qquad (20)$$

c^B_x, $c^B_y = 0$ - the corresponding coefficients for calculating stresses at point B, [13].

Maximum equivalent stress at point B:

$$\sigma_{B,u} = M_{VI} / W_{xB} + M_{HI} / W_{yB} + c^{B}_{x} \cdot P / t_3^2 \le \sigma_k \qquad (21)$$

Point A:

I – According to domestic standards:

The normal stresses due to the local pressure of the trolley wheel at point A, [15]:

$$\sigma^{P}_{x,A} = K_{Ax} \cdot P / t_3^2 \le \sigma_{k1},\ \sigma^{P}_{z,A} = K_{Az} \cdot P / t_3^2 \le \sigma_{k1} \qquad (22)$$

K_{Ax}, K_{Az} - the corresponding coefficients for calculating stresses at point A, [15].

Maximum normal stress in the direction of the z axis at point A:

$$\sigma_{zA} = K_{Az} \cdot P / t_3^2 + M_{VI} / W_{xA} + M_{HI} / W_{yA} \qquad (23)$$

Maximum tangential stress at point A:

$$\tau_A = F_t \cdot S_{xA} / (2 \cdot t_2 \cdot I_x) \le \sigma_{k1} / \sqrt{3} \qquad (24)$$

Maximum equivalent stress at point A:

$$\sigma_{A,u} = \sqrt{\sigma_{zA}{}^2 + \sigma^{P}_{x,A}{}^2 - \sigma_{zA} \cdot \sigma^{P}_{x,A} + 3 \cdot \tau_A{}^2} \le \sigma_{k1} \qquad (25)$$

II – According to eurocodes:

The normal stresses due to the local pressure of the trolley wheel at point A, [13]:

$$\sigma^{A}_{ox,Ed} = c^{A}_{x} \cdot P / t_3^2 \le \sigma_k,\ \sigma^{A}_{oy,Ed} = c^{A}_{y} \cdot P / t_3^2 \le \sigma_k \qquad (26)$$

c^A_x, c^A_y - the corresponding coefficients for calculating stresses at point A, [13].

Maximum normal stress in the direction of the z axis at point A:

$$\sigma_{zA} = c^{A}_{x} \cdot P / t_3^2 + M_{VI} / W_{xA} + M_{HI} / W_{yA} \qquad (27)$$

Maximum equivalent normal stress at point A:

$$\sigma_{A,u} = \sqrt{\sigma_{zA}{}^2 + \sigma^{A}_{oy,Ed}{}^2 - \sigma_{zA} \cdot \sigma^{A}_{oy,Ed} + 3 \cdot \tau_A{}^2} \le \sigma_k \qquad (28)$$

Point C:

I – According to domestic standards:

The normal stresses due to the local pressure of the trolley wheel at point C, [15]:

$$\sigma^{P}_{x,C} = K_{Cx} \cdot P / t_3^2 \le \sigma_{k1},\ \sigma^{P}_{z,C} = K_{Cz} \cdot P / t_3^2 \le \sigma_{k1} \qquad (29)$$

K_{Cx}, K_{Cz} - the corresponding coefficients for calculating stresses at point C, [15].

Maximum normal stress in the direction of the z axis at point C:

$$\sigma_{zC} = K_{Cz} \cdot P / t_3^2 + M_{VI} / W_{xC} + M_{HI} / W_{yC} \qquad (30)$$

Maximum equivalent normal stress at point C:

$$\sigma_{C,u} = \sqrt{\sigma_{zC}{}^2 + \sigma^{P}_{x,C}{}^2 - \sigma_{zC} \cdot \sigma^{P}_{x,C}} \le \sigma_{k2} \qquad (31)$$

II – According to eurocodes:

The normal stresses due to the local pressure of the trolley wheel at point C, [13]:

$$\sigma^{C}_{ox,Ed} = c^{C}_{x} \cdot P / t_3^2 \le \sigma_k,\ \sigma^{C}_{oy,Ed} = c^{C}_{y} \cdot P / t_3^2 \le \sigma_k \qquad (32)$$

c^C_x, c^C_y - the corresponding coefficients for calculating stresses at point C, [13].

Maximum normal stress in the direction of the z axis at point C:

$$\sigma_{zC} = c^{C}_{x} \cdot P / t_3^2 + M_{VI} / W_{xC} + M_{HI} / W_{yC} \qquad (33)$$

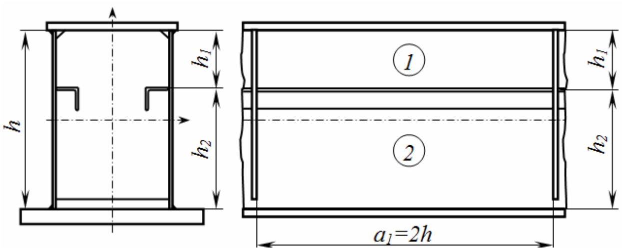
Maximum equivalent normal stress at point tački C:

$$\sigma_{C,u} = \sqrt{\sigma_{zC}{}^2 + \sigma^{C}_{oy,Ed}{}^2 - \sigma_{zC} \cdot \sigma^{C}_{oy,Ed}} \le \sigma_k \qquad (34)$$

4.2. The criterion of local stability of plates

1. Local stability according to domestic standards:

Local stability check is done in the same manner for both the flange and web plates. The paper considers the case with one row of horizontal stiffeners, along with vertical stiffeners being placed at the distance 2h (Picture 2).



Picture 2. Stiffeners of the box girder

To satisfy the stability condition it must be:

$$\sigma_{\max} \le \sigma_{ux} \le \sigma_v \qquad (35)$$

where:

$\sigma_{\max}$ - maximum pressure stress,

σ_{ux} - buckling stress limit, [12],

σ_v - yield stress, [12].

The constraint function has the form:

$$g_2 = \sigma_{\max} - \min(\sigma_{ux}, \sigma_v) \le 0 \qquad (36)$$

Maximum pressure stress of the top flange:

$$\sigma_p = -\nu_1 \cdot (M_{VI} / W_{x1} + M_{HI} / W_{y2}) \qquad (37)$$

Maximum pressure stresses for the webs in zone 1 and zone 2, respectively:

$$\sigma_1 = -\nu_1 \cdot (M_{VI} / W_{x2} + M_{HI} / W_{y2}) \qquad (38)$$

$$\sigma_2 = -\nu_1 \cdot \left[\frac{M_{VI}}{W_{x2}} \cdot \frac{y_1 - t_1 - h_1}{y_1 - t_1} + \frac{M_{HI}}{W_{y2}} \right] \qquad (39)$$

<u>2. Local stability according to eurocodes</u>:

The criterion of local stability of the top flange plate is:

$$\left|\sigma_p\right| \le \kappa_x \cdot f_y / \gamma_m \qquad (40)$$

where:

κ_x - a reduction factor, [14].

The criterion of local stability of the web in zone 1 and zone 2, respectively:

$$\left|\sigma_1\right| \le \kappa_{x1} \cdot f_y / \gamma_m \qquad (41)$$

$$\left|\sigma_2\right| \le \kappa_{x2} \cdot f_y / \gamma_m \qquad (42)$$

4.3. The criterion of lateral stability

Safety check for lateral stability of the girder is done in compliance with [12]. So, it has to be fulfilled:

$$\sigma_{zV1} = M_{VI} / W_{x1} \le \sigma_{k3} = \chi \cdot f_y / \nu_I \qquad (43)$$

where:

χ - the buckling coefficient, [12].

Using the above mentioned relations, the constraint function reads:

$$g_3 = M_{VI} / W_{x1} - \chi \cdot f_y / \nu_I \le 0 \qquad (44)$$

4.4. The criterion of girder stiffness

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

$$f = F_{1,st} \cdot L^3 \cdot \left[1 + \alpha \cdot (1 - 6 \cdot \beta^2)\right] / 48 \cdot E \cdot I_x \le f_{dop} \qquad (45)$$

where:

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

f_{dop} - permissible deflection in vertical plane,

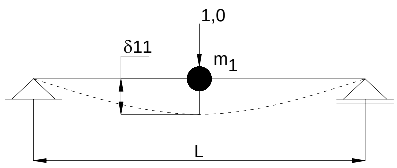
$\alpha = 1$, $\beta = d/L$, [15].

The constraint function has the form:

$$g_4 = f - f_{dop} \le 0 \qquad (46)$$

4.5. The criterion of dynamic stiffness

To determine dynamic stiffness, it is necessary to analyse the vertical oscillation of main girder with the payload (Picture 3).



Picture 3. The model of oscillation of the main girder with concentrated mass

The mass m_1 is determined according to the expression, [15]:

$$m_1 = Q + m_k + 0{,}486 \cdot m_m \qquad (47)$$

where:

m_m - the mass of the girder.

The time of damping of oscillation is determined from the expression, [15]:

$$T = 3 \cdot \tau / \gamma_d \le T_d \qquad (48)$$

where:

$\tau = 2 \cdot \pi \cdot \sqrt{\delta_{11} \cdot m_1}$ - the period of oscillation,

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

T_d - the permissible time of damping of oscillation, [15],

γ_d - the logarithmic decrement which shows the rate of damping of oscillation, [15].

The constraint function for the criterion of dynamic stiffness is:

$$g_5 = T - T_d \le 0 \qquad (49)$$

5. NUMERICAL PRESENTATION OF OBTAINED RESULTS

The optimization is done by generalized gradient method (GRG2 algorithm) and using Solver tool from Analysis module of EXCEL software.

Variable parameters are section height and width and plates thicknesses, (50). All constraint functions stated in previous chapters are taken into analysis.

$$\left(h,b,b_1,b_2,t_1,t_2,t_3\right) \tag{50}$$

The case with one row of longitudinal stiffeners is analysed. Also, the longitudinal stiffeners are adopted to be placed at the distance of *h/4*.

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 25 *cm*.

Table 1. Opimization results according to domestic standards

	Q (t)	L (m)	A_1 (cm^2)	A_2 (cm^2)	*Saving (%)*
Amiga 8t	8	15,1	208,8	151,8	27,30
Amiga 5t	5	15,2	177,2	138,3	21,95
Radijator 10t	10	16,8	248,8	161,8	34,97
JEEP 16t	16	15	237,6	192,87	18,83
Lola 5t	5	16,5	256,6	172,8	32,66

Table 1 and Table 2 show the results of the optimization for five solutions of single-girder bridge cranes, according to domestic standards and eurocodes, respectively. A_1 and A_2 are the values of the area of the box cross-section before and after optimization, respectively.

Table 2. Opimization results according to eurocodes

	Q (t)	L (m)	A (cm^2)	A (cm^2)	*Saving (%)*
Amiga 8t	8	15,1	208,8	180,24	13,68
Amiga 5t	5	15,2	177,2	159,3	10,10
Radijator 10t	10	16,8	248,8	182,95	26,47
JEEP 16t	16	15	237,6	231,15	2,71
Lola 5t	5	16,5	256,6	180,24	13,68

6. CONCLUSION

The paper presented optimum dimensions of box section of single-girder bridge crane by GRG2 optimization method. The criteria of permissible stresses, local stability of plates, lateral stability of the girder, static deflection, dynamic stiffness, production feasibility (distance between the webs) and minimum thicknes of the plates were applied as the constraint functions. The objective function was minimum cross-sectional area, whereby given constraint conditions were satisfied.

The justification of application GRG2 algorithm was checked on five solutions of single-girder bridge cranes which are in operation. It can be observed that greater area of box girder cross section are obtained according to eurocodes in comparison with those which are calculated due to domestic standarads.

The conclusion is that further research should be directed toward a multicriteria analysis where it is necessary to include additional constraint functions, such as: material fatigue, influence of manufacturing technology, optimization of the ratio of plate thicknesses, types of material, conditions of crane operation and economy.

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