IMK-14 – Research and Development in Heavy Machinery 24(2018)3, EN77-84
UDC 621 ISSN 0354-6829

# Optimal Design of Welded I-beam of Slewing Pillar Jib Crane

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*In this paper, the process of analyzing and optimizing of jib boom is presented. The reduction in the weight of the welded I-beam, or the cross-sectional area of the beam, was set as the main objective of this study, with the essence of replacing the standard rolled profile with welded ones. Apart from the criteria of allowed deflection and stress, stresses in a weld, both in the carrier itself and in carrier connection with a swivel part of structure. Also, certain constructive and technological recommendations were used, which representing additional constraint function in the optimization process. Optimization was performed using by MATLAB software package for Adaptive Particle Swarm Optimization algorithm (APSO), the Firefly Algorithm (FA) and the Cuckoo Search Algorithm (CSA), as well as the Ms. EXCEL software package, i.e. Solver tool, where optimization algorithms for constrained nonlinear problems are used (the generalized reduced gradient method and the evolution optimization algorithm). The obtained results were verified on real examples of pillar jib cranes, and they are showing the justification of procedure application.*

**Keywords: Pillar jib crane, Matlab, Ms Excel, Optimization, Welded carrier**

## 1. INTRODUCTION

Today's industry requires versatile, efficient and cost-effective equipment, while at the same time it should provide more flexibility with significant savings through increased productivity. Pillar jib cranes can significantly help to improve the efficiency of manipulation with materials and work and production flows. More significant consideration should be given to an operational environment which requires more frequent repetition of lifting and transferring of loads within the fixed arc of rotation.

The need for continual improvement in material manipulation technologies remains a typical feature of many modern engineering problems. The right equipment selection and dimensioning entire system segments are most significant. All the necessary conditions must be met in order to achieve equipment stability and safety and the costs which should also be taken into account. Therefore, comprehensive analysis and optimization of design parameters of jib cranes are necessary. A reduction in the number of services should be ensured, as well as the undisturbed functioning of the equipment without interruptions in operation.

The cantilever beam of jib crane represents the most responsible part of the structure, and it is the subject of analysis and research in this paper. The construction of the column is not a topic of analysis and optimization since it is a segment made of a standard welded tube. The optimization of this geometry is not significant for the applied optimization procedure in this research, due to the economic aspect.

Optimization represents a process where the most superior values of the parameters (variables) are obtained based on the given constraint functions, for the observed objective function. The most common are optimization procedures aimed at minimizing mass and cost. Latterly, the most common have implemented the methods of multi-objective optimizations, where several objective functions exist in the optimization process. For the above reasons and due to the importance of these specific types of constructions, a large number of surveys and publications dealing with the problems of structures analysis and optimization of these cranes, and especially the jib boom structure as its most important and most responsible segment.

The most primary criterion in the process of analysis and optimization represent the deflection at end of the span, as well as the stress conditions of the structure. The analysis of the deflection and stress conditions is done in most cases using the FEM, whereby the results are compared with analytical ([1], [2], [3], [4], [6], [10] and [11]). In the paper [1], an analysis of the deflection and stress conditions of the jib boom was performed using the ANSYS software package, where the 3D model was implemented in the CATIA software package. In addition to the typical standard I-beam, which is most commonly used in these constructions, a standard box profile is also observed. Similar to the previous one, in the work [2], using the COSMOS software package, the analysis of jib boom in a form of I-beam was performed, while the 3D model was generated in the SOLIDWORKS software package.

In published articles [3] and [4], for the key difference to the previously mentioned works, the overall structures of the jib cranes (column and cantilever) were analyzed. In the paper [3], various types of steel were analyzed for the case of one column jib crane using the ANSYS software package, while the 3D model was made in the Pro/E software package. Specific recommendations for the choice of steel type are given, considering the concrete conditions in crane operation. In the paper [4], the authors carried out a comprehensive analysis of the jib crane structure, for various positions of the load and the boom angle, where the allowed deflection is set as the primary criterion, whereby the results were verified experimentally.

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FME analysis was performed using the and ANSYS software packages. The deflection at end of the span was analyzed in detail in [5], for different calculation models, where the results were verified using the CATIA and SAP2000 software packages. A detailed analysis of the column structure was performed by NX 10.0 [6]. Using the Inventor software package, in [7], the structure optimization of a wall mounted jib crane, is performed in order to reduce the mass of the existing structure.

The importance of appropriate modeling and structural analysis using the FEM was demonstrated in [8], where the procedure for modeling of the jib crane assembly is performed in the ANSYS software package.

In previously mentioned researches, the standard I-beam which is commonly used was observed. In the paper [9], by application of the ANSYS software package is analyzed the variable (conical) I-beam, for different conical, angular values and taking into account the deflections, stresses, and the grinder elastic stability.

In addition to deflections and stresses, some authors assert the importance of modular analysis of crane structure ([10], [11] and [12]). In the paper [10], with the application of the ANSYS software package is analyzed a jib crane structure, showing the frequency dependence on stresses and deflections in certain directions.In the paper [11], the optimal type of I-beam is determined by looking at several selected types of standard I profile, and results are verified experimentally. In the study [12], the authors present a modeling the dynamics of load lifting and its impact on the I-beam of the jib crane boom, where the simulation was performed implementing the MATLAB-Simulink software.

The topological analyzes and optimizations are increasingly being applied, and their significance and application are shown in the review paper [13], for the I-profile and in the double I-profiles. In addition, in the paper [14], various rib profiles and its parameters were varied on the I-beam, and influence on the deflection and stress states were monitored. In contrast to the above-mentioned publications, where FEM was applied, in the works [15] and [16] optimization of the boom cross-sectional are performed using certain numerical optimization algorithms. In the paper [15], the optimization of the box-shaped cross-sectional area is performed using the evolutionary optimization algorithm (EA) in the EXCEL software package. The significant savings were achieved in comparison with the existing solution. Using the improved genetic optimization algorithm (IGA), within [16], the geometric parameters of the jib boom structure were optimized and where the savings of about 20% was achieved.

In addition, the EXCEL software package has been successfully used in the crane structures optimization of the overhead crane with one girder, as shown in [17]. In the paper [18], the structure optimization of the two-girder overhead crane was carried out, using the analytical optimization method. The explicit value of the expression for the optimal geometric parameters and their relations were obtained.

Ultimately, the objective of this research is the analysis and multi-criteria optimization of the welded I-beam geometric parameters.

Analysis and optimization will be carried out on examples of jib cranes that are in exploitation.

## 2. APPLIED OPTIMIZATION ALGORITHMS

Various numerical methods (algorithms) of optimization are used in this research, using by MATLAB and EXCEL software packages. The metaheuristic optimization algorithms, Adaptive Particle Swarm Optimization algorithm (APSO), Firefly Algorithm (FA), and Cuckoo Search Algorithm (CSA) in the MATLAB software package are applied. Equally, the Generalized Reduced Gradient Algorithm (GRG2) and the Evolution Algorithm (EA) in the EXCEL software package are used.

The Adaptive Particle Swarm Optimization algorithm, Firefly Algorithm Cuckoo Search Algorithm optimization algorithms. The Adaptive Particle Swarm Optimization algorithm and the Firefly algorithm were developed in 2008 by X. S. Yang. In 2009, the identical author together with S. Deb presented the Cuckoo Search Algorithm. All these three algorithms were applied in this study in their source code ( [19], [20] and [21]). EXCEL Solver implements the generalized reduced gradient method (GRG2 algorithm) to optimize non-linear problems and was developed by L. Lasdon and A. Varen, 2011. Equally, Solver additionally implements an evolutionary algorithm (EA) to solve nonlinear optimization problems.

## 3.MATHEMATICAL FORMULATION OF OPTIMIZATION PROBLEM

The optimization process is aimed at determining the optimum geometric parameters of the welded I-beam, which will lead to a reduction in its mass and the cross-sectional area. The optimization problem is defined as follows:

minimizing of an objective function

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

in relation to the constraint functions

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

Also, the following conditions must be fulfilled:

$$l_i \leq X_i \leq u_i \tag{3}$$

where are:

$f(X)$ - objective function,

$g_i(X) \leq 0,\ i = 1,...,m$ - constraint functions,

$l_j, u_j$ - lower and upper limit of a variable,

$i = 1,...,m$ - number of constraint functions,

$j = 1,...,n$ - number of projected variables,

$X$ - project vector consisting of $n$ projected variables.

Project variables are the values which do have to determine during the optimization process (each project variable is defined by its lower and upper limit).

To define the objective function and constraint functions, firstly the engineering problem that is the basis of this research will be presented.In this paper, the main subjects of research are related to the analysis and optimization of the I-beam structure (Figure 1).

The main idea is to thoroughly analyze and optimize the welded I-beam or to demonstrate the justification of making such a carrier that would replace the standard INP or IPE profiles which are most commonly used in these types of structures to reduce the carrier weight.

In Figure 1, one type of pillar jib crane and the basic input geometric parameters are shown. The structure consists of two basic parts, column structure, with height $H_s$ and diameter $D_k$, and boom structure, with length $L_k$, which rotates around the axis of the column, over the axle with the length $H_1$, at distance a from the axis of the column. The hoist trolley is taken in the analysis at end of the span, or at a distance L from the axis of the column (the most unfavorable position).

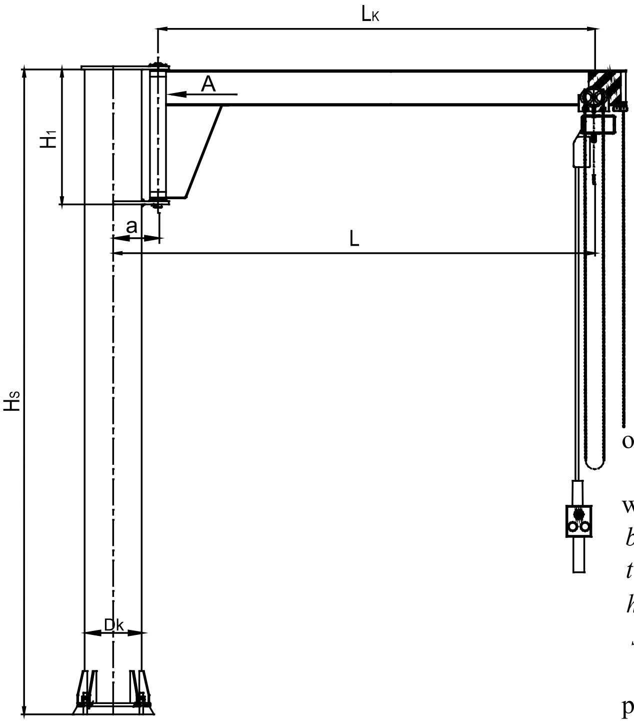

*Figure 1: Pillar jib crane*

The input values that are necessary for this analysis are shown via the vector of input parameters:

$$\vec{x} = \left(Q,\ m_t,\ L,\ a,\ H_S,\ H_1,\ I_{x,S},\ R_e,\ K_f ...\right) \quad (4)$$

where are:

$Q$ - load capacity,

$m_t$ - hoist trolley weight,

$L$ - the arc length of crane rotation,

$I_{x,S}$ - the main moment of area of the column,

$R_e$ - material yield strength,

$K_f$ - the coefficient that depends on the mode of crane operation and the drive class, according to [22].

The vector of the optimization parameter (projected variables) is:

$$X = \left(x_1\ x_2\ x_3\ x_4\ x_s\right)^T = \left(b\ t\ h\ s\ a_š\right)^T \quad (5)$$

The following text will show detailed optimization parameters (variables), objective function and constraint functions.

## 3. OBJECTIVE FUNCTION AND CONSTRAINT FUNCTIONS

### 4.1 Objective function

The objective function represents the I-beam cross-sectional area for an observed welded carrier of jib boom (Figure 2).

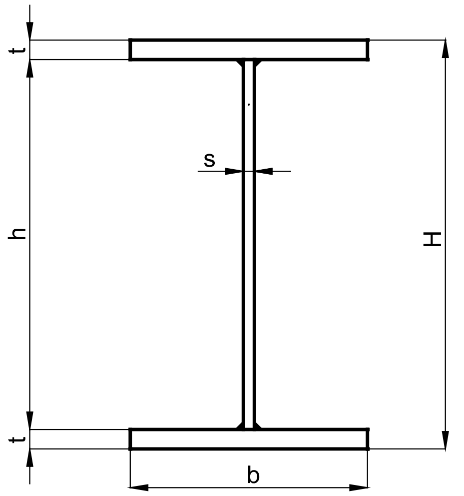

*Figure 2: Welded I- beam of the jib boom*

The cross-sectional area of the welded carrier, or the objective function is given by:

$$A = 2 \cdot b \cdot t + h \cdot s \quad (6)$$

where are:

$b$ - profile width of the welded carrier,

$t$ - flange sheet thickness of the welded carrier,

$h$ - web height of welded carrier,

$s$ - web thickness of welded carrier.

The above-mentioned values typically represent the project variables in the optimization process. The weld thickness does not figure in the objective function, and its influence is indirect on the optimal parameters of the I-beam cross-sectional area, across the geometric characteristics which influencing in the criteria in where the stress in the weld exists. The identical value of weld thickness was adopted for both of these criteria.

The mathematical formulation of the target function is shown as follows:

$$f(X) = A(x_1\ x_2\ x_3\ x_4) = 2x_1 \cdot x_2 + x_3 \cdot x_4 \quad (7)$$

The expressions of cross-sectional area geometric characteristics of jib boom with the welded carrier which are necessary for further analysis are given through the following relations:

$$I_{x,K} = I_x = \frac{1}{12} \cdot s \cdot h^3 + \frac{1}{6} \cdot b \cdot t^3 + \frac{1}{2} \cdot b \cdot t \cdot \left(h + t\right)^2 \quad (8)$$

$$I_{y,K} = I_y = \frac{1}{12} \cdot \left(h \cdot s^3 + 2 \cdot t \cdot b^3\right) \quad (9)$$

$$H = h + 2 \cdot t \quad (10)$$

$$W_x = 2 \cdot \frac{I_x}{H} \quad (11)$$

$$W_y = 2 \cdot \frac{I_y}{b} \quad (12)$$

where are:

$I_x$, $I_y$ - the planar moments of inertia of welded jib boom in the x and y directions, respectively

$H$ - a height of the welded carrier,

$W_x, W_y$ - the resistant moment of welded jib boom about the axis x and y, respectively.

## 4.2 Constraint functions

In this research, four constraints were treated: the strength of the welded profile in its overloaded part, the stress in, as well as the stress in the weld for carrier connection with the swivel part and the maximum deflection of the cantilever at end of the span.

### 4.2.1 Strength criterion

The strength test is performed in the most heavily loaded part of the cantilever construction, at the proper place of I-beam connection with the swivel part. The effect of the lower reinforcement is neglected, which is precisely on the security side.

The maximum stress $\sigma_{\max}$ must be less than the allowed $\sigma_{dop}$, respectively:

$$\sigma_{\max} = \sqrt{\sigma_z^2 + 3 \cdot \tau_s^2} \le \sigma_{dop} \tag{13}$$

$$\sigma_{dop} = \frac{R_e}{\nu_1} \tag{14}$$

All necessary relations are determined as follows:

$$\sigma_z = \sigma_{zv} + \sigma_{zh} = \frac{M_v}{W_x} + \frac{M_h}{W_y} \tag{15}$$

$$\tau_s = \frac{F}{A} \tag{16}$$

$$F = \gamma \cdot (\psi \cdot Q + m_t) \cdot g \tag{17}$$

$$F_{st} = (Q + m_t) \cdot g \tag{18}$$

$$F_h = k_a \cdot F_{st} \tag{19}$$

$$M_v = F \cdot L_K + \gamma \cdot \frac{q_K \cdot L_K^2}{2} \tag{20}$$

$$L_K = L - a \tag{21}$$

$$M_h = \gamma \cdot \left( F_h \cdot L_K + k_a \cdot \frac{q_K \cdot L_K^2}{2} \right) \tag{22}$$

$$q_K = 1.1 \cdot \rho \cdot g \cdot A \tag{23}$$

where are:

$\sigma_{k1}$ - the maximum bending stress,

$\tau_s$ - the shear stress,

$\gamma$ - coefficient that depends on the driving class of the crane, [22],

$\psi$ - dynamic coefficient, [22],

$F$ - load,

$F_{st}$ - statical load,

$F_h$ - a horizontal force,

$k_a$ - dynamic load coefficient of the crane in the horizontal plane [22],

$M_v, M_h$ - the maximum bending stress in vertical and horizontal plane,

$q_K$ - the specific weight of the welded carrier (increased for 10 %).

The constraint function for this criterion has the following form:

$$g_1 = \sigma_{\max} - \sigma_{dop} \le 0 \tag{24}$$

### 4.2.1 Stress criterion of beam weld

In this criterion, checking the longitudinal angular weld that connects the parts of I-beam (flange sheets with a vertical sheet) is performed, [23].The stress comparing is given as follows:

$$\sigma_{\check{s}} = \frac{F \cdot S_x}{2 \cdot I_x \cdot a_{\check{s}}} \le \sigma_{\check{s},dop} \tag{25}$$

$$\sigma_{\check{s},dop} = 0.75 \cdot \frac{R_e}{\nu_1} \tag{26}$$

$$S_{x,\check{s}} = \frac{b \cdot t}{2} \cdot (h + t) \tag{27}$$

where are:

$\sigma_{\check{s}}$ - the stress in the weld,

$S_{x,\check{s}}$ - section modulus appropriate for weld calculation,

$\sigma_{\check{s},dop}$ - the allowed stress in weld.

The constraint function in this case has the following form:

$$g_2 = \sigma_{\check{s}} - \sigma_{\check{s},dop} \le 0 \tag{28}$$

### 4.2.2 Stress criterion of weld for connection between beam and swivel part

In this criterion, checking the angular welds that connect the welded I-beam with the swivel part (Figure 1 - Detail "A"). The design of this compound is shown in Figure 3a. The welds area which is relevant for the calculation is given in Figure 3b.

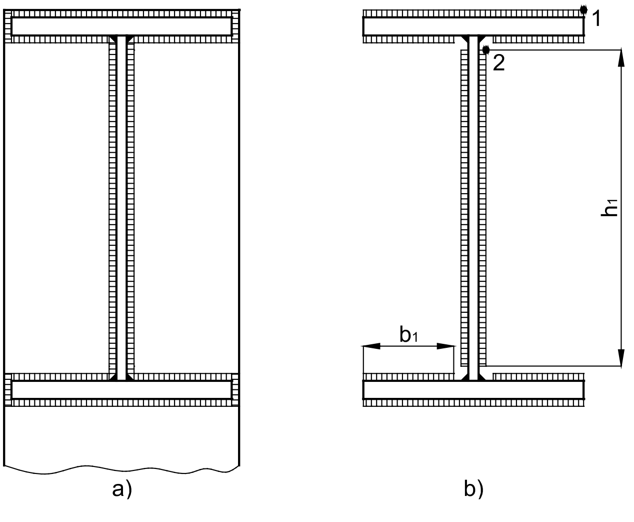

*Figure 3: I-beam cross section (a – detail of connection between the welded beam and swivel part, b – the area of the weld)*

The geometrical characteristics of the weld contour necessary for analysis are determined on the basis of the following relations:

$$I_{x,\check{s}} = \frac{1}{6}\cdot a_{\check{s}}\cdot h_1^3 + \frac{1}{6}\cdot b\cdot a_{\check{s}}^3 + \frac{1}{3}\cdot b_1\cdot a_{\check{s}}^3 + \frac{1}{2}\cdot b\cdot a_{\check{s}}\cdot\left(h + a_{\check{s}}\right)^2 + b_1\cdot a_{\check{s}}\cdot\left(h - a_{\check{s}}\right)^2 \quad (29)$$

$$I_{y,\check{s}} = \frac{1}{6}\cdot a_{\check{s}}\cdot b^3 + \frac{1}{3}\cdot a_{\check{s}}\cdot b_1^3 + b_1\cdot a_{\check{s}}\cdot\left(b - b_1\right)^2 + \frac{1}{6}\cdot h_1\cdot a_{\check{s}}^3 + \frac{1}{2}\cdot h_1\cdot a_{\check{s}}\cdot\left(s + a_{\check{s}}\right)^2 \quad (30)$$

$$W_{x1,\check{s}} = \frac{I_{x,\check{s}}}{y_{1,\check{s}}} \quad (31)$$

$$y_{1,\check{s}} = \frac{H}{2} + a_{\check{s}} \quad (32)$$

$$W_{y1,\check{s}} = \frac{I_{x,\check{s}}}{x_{1,\check{s}}} \quad (33)$$

$$x_{1,\check{s}} = \frac{b}{2} \quad (34)$$

$$W_{x2,\check{s}} = \frac{I_{x,\check{s}}}{y_{2,\check{s}}} \quad (35)$$

$$y_{2,\check{s}} = \frac{h_1}{2} \quad (36)$$

$$W_{y2,\check{s}} = \frac{I_{x,\check{s}}}{x_{2,\check{s}}} \quad (37)$$

$$x_{2,\check{s}} = \frac{s}{2} + a_{\check{s}} \quad (38)$$

$$A_{x,\check{s}} = 2\cdot b\cdot a_{\check{s}} + 4\cdot b_1\cdot a_{\check{s}} \quad (39)$$

$$A_{y,\check{s}} = 2\cdot h_1\cdot a_{\check{s}} \quad (40)$$

$$b_1 = \frac{1}{2}\cdot\left(b - 4\cdot a_{\check{s}} - s\right) \quad (41)$$

$$h_1 = h - 4\cdot a_{\check{s}} \quad (42)$$

where are:

$I_{x,\check{s}}$, $I_{y,\check{s}}$ - the planar moments of inertia of the weld contour in x and y direction,

$W_{x1,\check{s}}$, $W_{y1,\check{s}}$ - the resistant moment of the weld contour in x and y direction for point 1,

$W_{x2,\check{s}}$, $W_{y2,\check{s}}$ - the resistant moment of the weld contour in x and y direction for point 2,

$A_{x,\check{s}}$, $A_{y,\check{s}}$ - the area of the weld contour in x and y direction.

The stress comparing will be performed in points 1 and 2 of the weld contour (Figure 3b), and must be fulfilled, [23]:

$$\sigma_{1,\check{s}} = \sqrt{\sigma_{z1,\check{s}}^2 + 3\cdot V_1^2} \le \sigma_{\check{s},dop} \quad (43)$$

$$\sigma_{2,\check{s}} = \sqrt{\sigma_{z2,\check{s}}^2 + 3\cdot V_2^2} \le \sigma_{\check{s},dop} \quad (44)$$

All the necessary relations contained in the above-mentioned terms are determined as follows:

$$\sigma_{z1,\check{s}} = \frac{M_v}{W_{x1,\check{s}}} + \frac{M_h}{W_{y1,\check{s}}} \quad (45)$$

$$V_1 = \frac{F_h}{A_{x,\check{s}}} \quad (46)$$

$$\sigma_{z2,\check{s}} = \frac{M_v}{W_{x2,\check{s}}} + \frac{M_h}{W_{y2,\check{s}}} \quad (47)$$

$$V_2 = \frac{F}{A_{y,\check{s}}} \quad (48)$$

where are:

$\sigma_{z1,\check{s}}$, $\sigma_{z2,\check{s}}$ - the bending stress of the weld in point 1 and 2,

$V_1$, $V_2$ - the shear stress of the weld for points 1 and 2.

The constraint functions are given as follows

$$g_{3,1} = \sigma_{1,\check{s}} - \sigma_{\check{s},dop} \le 0 \quad (49)$$

$$g_{3,2} = \sigma_{2,\check{s}} - \sigma_{\check{s},dop} \le 0 \quad (50)$$

### 4.2.3 A criterion of beam deflection

The deflection of cantilever top *fu* (at end position of the hoist trolley) which must be less than the allowed one *fd* is determined by the following expression (51), and consists of three components:

$$f_u = f_S + f_{K1} + f_{K2} \le f_d \quad (51)$$

$$f_d = (H_S + L)\cdot K_f \quad (52)$$

The cantilever deflection of jib crane at the top is accurately calculated as the superposition of the deflection due to the impact of the column, the boom deflection at the top causes by static force (concentrated load at end of the span) and deflection due to cantilever weights.

As seen in Figure 1, the cantilever is observed exactly to the point at which it is actually located, shifted by the value a from the axis of the column, so that the deflection of this part is unobserved, because it can be considered sufficiently rigid to move along with the column, primarily because of the connection with the column itself as well as the size of the value *a*.

The deflection components are determined based on the following relations:

$$f_S = tg\left(\frac{M_{v,st}\cdot(H_S - H_1/2)}{E\cdot I_{x,S}}\right)\cdot L_K \quad (53)$$

$$M_{v,st} = F_{st}\cdot L_K + \frac{q_K\cdot L_K^2}{2} \quad (54)$$

$$f_{K1} = \frac{F_{st}\cdot L_K^3}{3\cdot E\cdot I_{x,K}} \quad (55)$$

$$f_{K2} = \frac{q_K\cdot L_K^4}{8\cdot E\cdot I_{x,K}} \quad (56)$$

where are:

$f_S$ - deflection due to column structure influence,

$M_{v,st}$ - the moment of bending due to statical load,

$f_{K1}$ - deflection due to load weight and hoist trolley weight,

$f_{K2}$ - deflection due to welded I-beam weights.

The constraint function is given as follows:

$$g_4 = f_u - f_d \le 0 \quad (57)$$

## 5.NUMERICAL REVIEW OF OPTIMIZATION RESULT

The optimization process was performed using the following optimization algorithms: in the MATLAB software package using the Adaptive Particle Swarm

Optimization algorithm, Firefly Algorithm, and Cuckoo Search Algorithm. Also, the GRG2 algorithm and EA algorithm were applied, using the Solver tool in the Ms EXCEL software package. Optimization parameters are the rib height of the welded carrier *h*, the thickness *s*, the width of flanges *b* and thickness *t*, and the weld thickness $a_{sh}$ (Figure 2 and Figure 3).

In addition to the mentioned constraint functions (24), (28), (49), (50) and (57) there are additional constructive and technological constraints that must be met.

Regarding the thickness of the sheet metal for the welded carrier web, the minimum thickness must be $s_{min}=5$ *mm*, while the minimum thickness of flanges is $t_{min}=6$ *mm*.

It was also adopted in this analysis that the minimum web height is $h_{min} = 200$ mm, while the minimum width of flanges is $b_{min} = 100$ mm.

For the thickness of weld is used requirements, according to [21]:

$$a_{\check{s}} \le 0.7 \cdot \min(t,s) \tag{58}$$

Also, the minimum value of the weld thickness is $a_{\check{s}}=3$ *mm*, [23].

The presented optimization model will be implemented on examples of two pillar jib cranes, which are in exploitation. For cantilever structures, both cranes used standard IPE profiles made from conventional S235 structural steel.

Both cranes use an electrically hoist trolley with floor control. Turning the jib arm is done manually, over the chain. The coefficients taken for optimization have the following values:

$\gamma = 1.05$, $\psi = 1.15$, ka = 0.05, Kf = 1/250

Both cranes are second propulsion classes with a load capacity of Q = 500 kg, hoist trolley weight $m_t = 40$ kg and column height $H_S = 4$ m. Other data for cranes are shown in the following table (Table 1):

*Table 1: Characteristics of pillar jib crane*

| No. | L (m) | a (mm) | $H_1$ (m) | $I_{x,S}$ ($cm^4$) | Profil | b (cm) | t (mm) | h (cm) | s (mm) | $A_p$ ($cm^2$) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 3 | 280 | 0.72 | 3560 | IPE-220 | 11 | 9.2 | 20.16 | 5.9 | 33.4 |
| 2 | 5 | 305 | 0.90 | 19870 | IPE-270 | 13.5 | 10.2 | 24.96 | 6.6 | 45.9 |

In addition to the geometrical characteristics of pillar jib cranes, the previous table also shows the geometric characteristics of standard IPE profiles. The following tables show the results of optimization (optimal geometric parameters of the cross-sectional area and optimal cross-sectional area) according to the above algorithms (Table 2 ÷ Table 6).

*Table 2: Optimization results obtained by APSO algorithm*

| | **b (cm)** | **t (mm)** | **h (cm)** | **s (mm)** | **$a_{\check{s}}$ (mm)** | **$A_{opt}$ ($cm^2$)** |
|---|---|---|---|---|---|---|
| 1 | 10.36 | 6 | 24.81 | 5.02 | 3.51 | 24.88 |
| 2 | 13.82 | 6 | 32.59 | 5.08 | 3.56 | 33.14 |

*Table 3: Optimization results obtained by FA algorithm*

| | **b (cm)** | **t (mm)** | **h (cm)** | **s (mm)** | **$a_{\check{s}}$ (mm)** | **$A_{opt}$ ($cm^2$)** |
|---|---|---|---|---|---|---|
| 1 | 11.79 | 6 | 21.07 | 5.19 | 3.63 | 25.09 |
| 2 | 15.87 | 6 | 28.51 | 5 | 3.5 | 33.30 |

*Table 4: Optimization results obtained by CSA algorithm*

| | **b (cm)** | **t (mm)** | **h (cm)** | **s (mm)** | **$a_{\check{s}}$ (mm)** | **$A_{opt}$ ($cm^2$)** |
|---|---|---|---|---|---|---|
| 1 | 10.66 | 6 | 24.12 | 5 | 3.5 | 24.86 |
| 2 | 14.39 | 6 | 31.62 | 5 | 3.5 | 33.08 |

*Table 5: Optimization results obtained by GRG2 algorithm*

| | **b (cm)** | **t (mm)** | **h (cm)** | **s (mm)** | **$a_{\check{s}}$ (mm)** | **$A_{opt}$ ($cm^2$)** |
|---|---|---|---|---|---|---|
| 1 | 10.66 | 6 | 23.37 | 5 | 3.5 | 24.48 |
| 2 | 14.48 | 6 | 30.63 | 5 | 3.5 | 32.69 |

*Table 6: Optimization results obtained by EA algorithm*

| | **b (cm)** | **t (mm)** | **h (cm)** | **s (mm)** | **$a_{\check{s}}$ (mm)** | **$A_{opt}$ ($cm^2$)** |
|---|---|---|---|---|---|---|
| 1 | 10.54 | 6 | 23.44 | 5.06 | 3.54 | 24.50 |
| 2 | 14.23 | 6 | 30.94 | 5.06 | 3.54 | 32.71 |

As it can be seen on the basis of the obtained results, there are unobtained whole values of the sheet metal thickness, so these values are rounded to the first higher whole value. In addition, the other values are rounded. In this way, an accurate picture of the analyzed results is obtained.

The following tables show the rounded values of the optimal geometric parameters, the optimal cross-sectional area and the achieved savings in relation to the standard profile (Table 7 ÷ Table 11):

*Table 7: Optimization results obtained by APSO algorithm and achieved savings*

| **No.** | **b (cm)** | **t (mm)** | **h (cm)** | **s (mm)** | **$a_{\check{s}}$ (mm)** | **$A_{opt}$ ($cm^2$)** | **Saving (%)** |
|---|---|---|---|---|---|---|---|
| 1 | 10.4 | 6 | 24.9 | 6 | 4 | 27.42 | 17.90 |
| 2 | 13.9 | 6 | 32.6 | 6 | 4 | 36.24 | 21.05 |

*Table 8: Optimization results obtained by FA algorithm and achieved savings*

| **No.** | **b (cm)** | **t (mm)** | **h (cm)** | **s (mm)** | **$a_{\check{s}}$ (mm)** | **$A_{opt}$ ($cm^2$)** | **Saving (%)** |
|---|---|---|---|---|---|---|---|
| 1 | 11.8 | 6 | 21.1 | 6 | 4 | 26.82 | 19.70 |
| 2 | 15.9 | 6 | 28.6 | 5 | 4 | 33.38 | 27.28 |
| | | | | | | | |

*Table 9: Optimization results obtained by CSA algorithm and achieved savings*

| **No.** | **b (cm)** | **t (mm)** | **h (cm)** | **s (mm)** | **$a_{\check{s}}$ (mm)** | **$A_{opt}$ (cm$^2$)** | **Saving (%)** |
|---|---|---|---|---|---|---|---|
| 1 | 10.7 | 6 | 24.2 | 5 | 4 | 24.94 | 25.33 |
| 2 | 14.4 | 6 | 31.7 | 5 | 4 | 33.13 | 27.82 |

*Table 10: Optimization results obtained by GRG2 algorithm and achieved savings*

| **No.** | **b (cm)** | **t (mm)** | **h (cm)** | **s (mm)** | **$a_{\check{s}}$ (mm)** | **$A_{opt}$ (cm$^2$)** | **Saving (%)** |
|---|---|---|---|---|---|---|---|
| 1 | 10.7 | 6 | 23.4 | 5 | 4 | 24.54 | 26.53 |
| 2 | 14.5 | 6 | 30.7 | 5 | 4 | 32.75 | 28.65 |

*Table 11: Optimization results obtained by EA algorithm and achived savings*

| **No.** | **b (cm)** | **t (mm)** | **h (cm)** | **s (mm)** | **$a_{\check{s}}$ (mm)** | **$A_{opt}$ (cm$^2$)** | **Saving (%)** |
|---|---|---|---|---|---|---|---|
| 1 | 10.6 | 6 | 23.5 | 6 | 4 | 26.82 | 19.70 |
| 2 | 14.3 | 6 | 31.0 | 6 | 4 | 35.76 | 22.09 |

From the previous tables (Table 7 ÷ Table 11) it can be seen that the new optimal cross-sectional area values are now larger than those shown in Table 2 ÷ Table 7. In certain optimization algorithms, it is possible to introduce a constraint that the variable takes the whole value. In this case, this can be accomplished when using the Solver tool in the EXCEL software package, the GRG2, and EA optimization algorithms, using the integer option, but it is specified in a way that the results can be compared with those obtained by the algorithms in the MATLAB software package.

## 6.CONCLUSION

The paper presents the optimal geometric values for the welded I-beam of the pillar jib crane, for example of two jib cranes with a load capacity of 500 kg. As an object of optimization, the cross-sectional area of the cantilever is observed, where all the constraint functions are satisfied. In addition to the constraint functions, other construction and technological criteria could be used.

Optimization was carried out using the MATLAB software package by APSO, FA and CSA algorithm, as well as using the Ms EXCEL software package by GRG2 and the EA optimization algorithm. The selection of appropriate optimization methods presents their justification and achieved a saving of 28.65% (first crane) and 26.53% (second crane).

The optimization tasks have been successfully performed, as can be seen from the results in the tables (Table 2 ÷ Table 11) and shows the correctness of using the presented model for analysis and optimization.

It is seen that the best results were given by the GRG2 algorithm and the weakest by the FA (Table 2 - Table 6). In addition to the nature-inspired algorithms, the best results are achieved by CSA.In addition, it can be seen that in all cases the minimum thickness of flanges t=6 mm is obtained. The best results are given by GRG2, utilizing the Solver tool in the Ms EXCEL software package, or by CSA, using the MATLAB software package (Table 2 ÷ Table 6). This is equally seen from the table where the values of the results obtained are rounded (Table 7 ÷ Table 11).

The particular conclusion based on the analysis and optimization carried out obtain the fact that the welded I-beam provides significant material savings in comparison to the standard rolled I-profiles.

For intended research in this area, it is necessary to include other constraint functions that are important for analysis. In addition to the imperfections and stress conditions in the material and welds, the elastic stability of the carrier can also be analyzed. Also, other forms of the cross-sectional area used for these types of structures, as well as other potential forms of cross-sectional area and materials that can be considered.

As a possible objective function, in further studies could be taken into account the area of the weld contour. In that case one of the multi-objective optimizations, procedures would be applied. The costs of carrier design, in addition, could be used as the goal function in the optimization process. The results obtained in this way can be verified and compared with FEM analysis, to demonstrate justification of the application of the given methods. Furthermore, in this way, some conclusions can be made as properly as a guideline for the design and optimization. Optimization can equally be done by hybrid methods, combining some of the numerical optimization procedures with FEM software packages.

## ACKNOWLEDGMENT

Part of this research is a contribution to the projects of the Ministry of Education, Science and Technological Development of the Republic of Serbia, Project III 44006 and Project TR 35038.

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