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Analysis and low-weight design of the cold-formed battened built-up column

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ABSTRACT

This research presents the analysis and the low-weight optimization design of the cold-formed battened built-up column of the crane runway beam by the Marine Predators Algorithm (MPA). The objective function (the total weight of the battened built-up column) workflow uses slenderness and the geometric parameters of the channel section and batten plates as variables. This study uses the global stability of the built-up column, the buckling check of the built-up column about the material axis and non-material axis, the buckling and the strength check of the chord of the built-up column, the strength check of the batten plate of the built-up column, the strength of the batten plate's weld connections, as well as geometrical recommendations and limitations as the constraint functions. Achieved savings in column weight are between 38.66% and 51.66%, dependingly on the material and the number of batten plates of the considered example of the built-up column.

KEYWORDS

Buckling, Built-up column, Crane runway column, Marine Predators Algorithm, Nature-inspired algorithm, Optimal design.

1. INTRODUCTION

The built-up column usually consists of two or more standard cold-formed structural shapes, as standalone chords connected with batten plates or lancing bars. The standalone chords are usually made of U, C, I or L structural shapes, but the other shapes can be used as well as the different combinations of the shapes. Built-up columns are widely used as carrying structures, especially for crane runway supporting columns where the usual structural shapes do not meet the strength and stability criteria due to the pressure being the dominant load that acts upon the columns.

Structural analysis of the mentioned structures is the most commonly conducted using FEM software suits. In [1] the behaviour of the built-up battened column with two chords consisted of channel sections loaded with pressuring forces was observed. The numerical results acquired using the ABAQUS software were compared to the results available in the literature, as well as the North American Specifications (NAS), where the good matching of results was established. Parametric study was also conducted where the columns slenderness was varied, as well as the distance (of the toe-to-toe spacing) between the edges of the sections. Similarly to the precious research, the ABAQUS software was used on the built-up battened column with two chords, where the acquired results matched the results available in the literature in a good extent, [2]. In this case, the chords were consisted of C-sections. Parametric study varying the slenderness ratio and batten plates number was also conducted. Two different types of analytical models were used for obtaining intensities of the loads using Direct Strength Method (DSM) in AISI code. The same kind of column with C-sections was analyzed in [3] where the parametric study of the column with varying critical parameters (global column slenderness, geometric parameters, plate slenderness, and yield stress) using validated FEM model was conducted. This research gives effective guidelines for using the FEM methods for result verification using DSM and Effective Width Method (EWM) with AISI code, as well as for the use of the Eurocodes. The authors of the [4] dealt with the load capacity of the buildup columns consisted of two chords with channel sections (in two variants: with batten plates and with lancing bars) subjected to eccentric loading. The goal of the research was to purpose a design method for these types of structures, while the developed FEM model was verified with experimental research available from the literature. Also, the application of the Eurocodes expressions used for calculating the columns load capacity was discussed.

The analysis of the truss structure where the main structural parts of the bult up column with two chords with C-section done in ANSYS software suite was discussed in [5]. Steel and aluminum alloy were considered for the material of the structure. These results were compared to the results obtained by using analytical methods presented in Eurocodes and certain conclusions were drawn and the guidelines for the design of these types of carrying structures were given. The analytical analysis of a battened built-up column made out of aluminum by using Eurocodes was conducted by the same authors in [6]. The second order analysis was used on the structure of built-up battened column with two cords made out of I-section beams.

Analytical methods were used on these types of structures in [7-10]. In [7] the authors examined how the number of batten plates effect the elastic stability of the built-up column. Four different setups which differ in the number of chords and shape of cross section were observed. The optimization of the number and the dimension of the batten plates for a single built-up battened column with two chords was conducted in [8] where two configurations of channel sections were considered. For both configurations of the column the change of the variable's optimal values, as well as the total wight of the column, in function of the pressure load was observed. The Evolutionary Algorithm (EA) was the optimization method that was used through the MS Excel software. The same group of authors in [9] optimized the weight of the built-up column with two chords where the chords were consisted of welded, I sections. This time they included additional variables such as geometric dimensions of plates which make the welded I section. The MS Excel was used as well for the optimization with the use of the Generalized Reduced Gradient (GRG2) code. The observed quantities were the weight of the column and the optimal values of the optimized variables in function of the pressure load at the top of the column. In [10] authors analyzed and optimized the weight of the battened built-up column with two channel sections of the crane runway beam. One economic-inspired algorithm, called Supply-Demand-Based Optimization (SDO) was used as the method of optimization.

The goal of this research is the optimization with the goal of reducing the weight of the crane runway column. Instead of using the standard rolled profiles for the chords, the sections made up of folded steel plates will be considered. The geometric characteristics of the mentioned sections and dimensions of batten plates represent the variables for which the optimal values are to be found with the use of the optimization algorithm.

For this purpose, a novel nature inspired optimization algorithm was considered. In this paper the Marine Predators Algorithm (MPA) for solving this single-objective multi-criteria optimization problem.

The use of different types of metaheuristic algorithms is increasingly present in newer research, especially for solving engineering problems of optimization, like it is presented in [11, 12].

2. ANALYSIS AND OPTIMIZATION PROBLEM

The optimization problem in this paper is the weight decrease of the cold-formed battened built-up column of the crane runway beam (Figure 1). The structure that is going to be analyzed and optimized in this paper with the cross section consisted of the cold-formed channel shown in Figure 1b is shown in the Figure 1a.

The main goal of this research is to show that the use of the folded steel plate profiles as chords instead of standard channel profiles can prove more weight effective because of the better use of its geometric characteristics. It will be also proven that the chosen number of batten plates and the type of material makes a difference in the weight of the column. These types of columns and structures of the same type carry different kinds of loads. It is of the most importance that these structures can satisfy all of the most important criteria, such as the stability and strength. The structure should also comply with certain design and geometric recommendations. The mentioned criteria and recommendation should be satisfied by all individual segments of the structure as well as the structure as a whole. In order to quantitatively justify the use of the proposed column model, the results of the optimization will be compared to those obtained in the research [8] where the chords of the column are consisted of the standard channel sections.

2.1. The objective function and optimization variables

The objective function in this paper is the total weight of the column (Figure 1a). The geometric characteristics that are important for the analysis and the optimization and make up the variables in the optimization process are shown in the Figure 1 and Figure 2. The welded connection between the chords and the batten plates is showed in Figure 3.

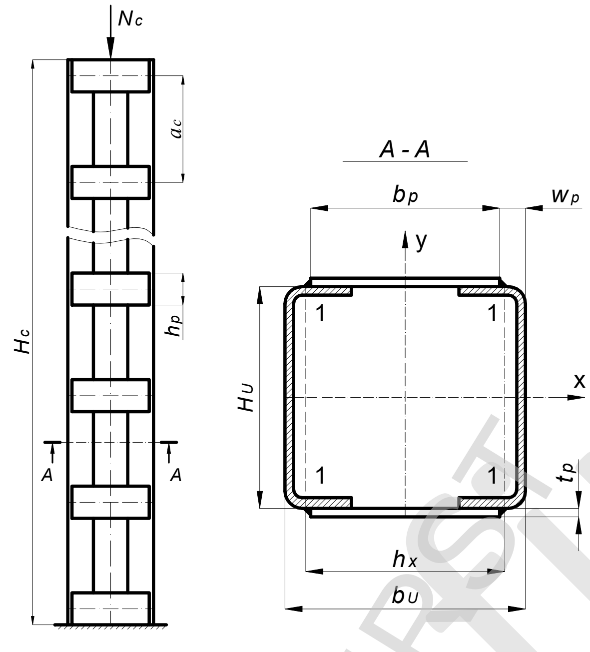

Figure 1: The structure of the built-up column (a) and the cross-section of the built-up column (b)

Input parameters necessary for this optimization problem are:

$$N_c\ ,\ n_c\ ,\ H_c\ ,\ \alpha_x\ ,\ \alpha_y\ ,\ \nu_1,\ r\ ,\ t\ ,\ \rho\ ,\ R_e \text{ and } E \tag{1}$$

where N_c is the compressive force acting on the column (Figure 1), n_c is the number of the batten plates, H_c is the column height, α_x, α_y are the coefficients, [13], ν_1 is load case 1 factored load coefficient, [13], r is the inner radius of the channel section (Figure 2), t is the channel section's plate thickness (Figure 2), ρ is the material density, R_e is the yield strength, and E is Young's modulus.

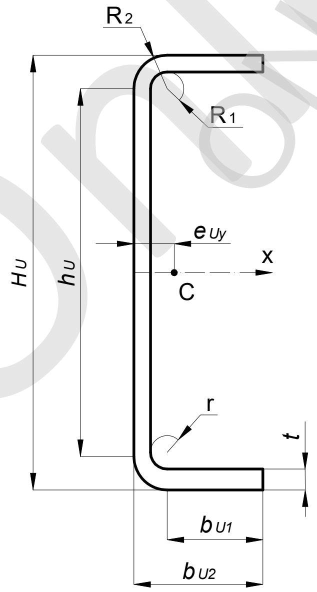

Figure 2: Cold-formed channel section

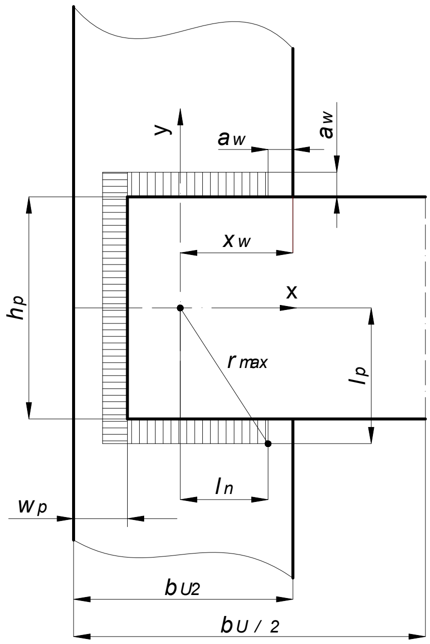

Figure 3: The weld connection between chord and batten plate

Other input parameters are: m is the number of the chords and β_x, β_y are the buckling coefficients for x and y axis, respectively.

The optimization variables are:

$$b_{U1},\ \lambda,\ h_p,\ t_p \text{ and } a_w \tag{2}$$

where b_{U1} is the width of the channel section (from the radius r, Figure 2), λ is a slenderness of the built-up column, h_p is the batten plate height (Figure 2), t_p is the batten plate thickness (Figure 2), and a_w is the weld thickness (Figure 2). The total weight of the battened built-up column (M_c) consists of the weight of U-profiles (channel sections), the weight of batten plates, and the weight of welded connections:

$$M_c = m \cdot \rho \cdot \left(A_U \cdot H_c + n_c \cdot A_p \cdot t_p + 2 \cdot n_c \cdot A_w \cdot L_w \right) \tag{3}$$

whereby the members of (3) are calculated according to the following expressions:

$$A_U = \left(h_U + 2 \cdot b_{U2} \right) \cdot t + 2 \cdot A_R \tag{4}$$

$$h_U = H_U - 2 \cdot (r + t) \tag{5}$$

$$H_U \approx \frac{\beta_x \cdot H_c}{\alpha_x \cdot \lambda} \tag{6}$$

$$b_{U2} = b_{U1} + (r + t) \tag{7}$$

$$A_R = \pi \cdot \left(R_2^{\,2} - R_1^{\,2} \right) / 4 \tag{8}$$

$$R_1 = r,\ R_2 = r + t \tag{9}$$

$$A_p = b_p \cdot h_p \tag{10}$$

$$b_p = b_U - 2 \cdot w_p \tag{11}$$

$$b_U \approx \frac{\beta_y \cdot H_c}{\alpha_y \cdot \lambda} \le 60 \tag{12}$$

$$w_p \approx r + t + a_w \tag{13}$$

$$h_p = (0.5 \div 0.7) \cdot b_U \tag{14}$$

$$t_p \ge h_p / 30,\ t_p = 0.6 \div 1.2 \tag{15}$$

$$A_w = a_w^{\,2} / 2 \tag{16}$$

$$L_w = h_p + 2 \cdot \left(b_{U2} - w_p \right) \tag{17}$$

where A_U is the area of the channel section (Figure 2), H_U is the height of the channel section (Figure 2), h_U is the inner height of the channel section (Figure 2), b_{U2} is the width of the channel section (Figure 2), b_U is the width of the column cross-section (Figure 2), A_R is the area of the circular part of the channel section (Figure 2), R_1, R_2 are the inner and outer radius, respectively (Figure 2), A_p is the area of the batten plate (Figure 2), b_p is the batten plate width (Figure 2), w_p is the distance (necessary for welding, Figure 2), A_w is the area of the batten plate's weld (Figure 3), and L_w is the total length of the batten plate's weld (Figure 3).

It can be noticed that the objective function (3) is a function of a great number of different parameters.

The geometric characteristics of the channel section are: I_{Uy} – the principal moment of inertia about y-axis, i_{Uy} – the radius of gyration about y-axis, e_{Uy} – the position of the center of gravity about y-axis, W_{Uy} – the section moduli about y-axis, and i_{Ux} – the radius of gyration about x-axis. These geometric characteristics in the continuation of this paper are being calculated by using the well-known expressions for the used cross section shown in Figure 2.

2.2. The constraint functions

The cold-formed battened built-up column has to meet the strength and stability criteria as well as some specific limitations in design and geometry. The most of these limitations will be incorporated into the objective function of this optimization problem while some shall be defined as variable limitation.

The criterion of the global stability of the built-up column is one of the most important criteria in this analysis. The global stability check for the built-up column was done according to [13]:

$$N_{Sc} = \nu_1 \cdot N_c \le N_{E,Q} = \pi^2 \cdot E \cdot m \cdot A_U / \lambda_{y,i}{}^2 \tag{18}$$

whereby the members of (18) are calculated according to the following expressions:

$$\lambda_{y,i} = \sqrt{\lambda_y{}^2 + m/2 \cdot \lambda_1{}^2} \tag{19}$$

$$\lambda_y = \beta_y \cdot H_c / i_y \le \lambda \tag{20}$$

$$i_y = \sqrt{\frac{I_y}{m \cdot A_U}} \tag{21}$$

$$I_y = m \cdot \left[I_{Uy} + A_U \cdot (h_x / 2)^2 \right] \tag{22}$$

$$h_x = b_U - 2 \cdot e_{Uy} \tag{23}$$

$$\lambda_1 = a_c / i_{Uy} \le 50 \tag{24}$$

$$a_{\max} = 50 \cdot i_{Uy} \tag{25}$$

$$a_c = \frac{H_c - h_p}{n_c - 1} \tag{26}$$

where N_{Sc} is the factored compressive force, $N_{E,Q}$ is the critical compressive force, $\lambda_{y,i}$ is the slenderness of the built-up column about y-axis, λ_y is the slenderness of the chord about y-axis, λ_1 is the slenderness of the chord about 1-axis (Figure 1), I_y is the principal moment of inertia of the column cross-section about y-axis, i_y – the radius of gyration of the column cross-section about y-axis, h_x is the distance between the chords (Figure 1), a_c is the distance between the batten plates (Figure 1), and a_{max} is the maximum distance between the batten plates. Thus, the constraint functions for this criterion are as follows:

$$g_1 = N_{Sc} - N_{E,Q} \le 0 \tag{27}$$

$$g_2 = a_c - a_{\max} \le 0 \tag{28}$$

$$g_3 = \lambda_y - \lambda \le 0 \tag{29}$$

The buckling (stability) check of the built-up column about the material axis (x-axis) was done according to [13]:

$$\sigma_{Nm} = \frac{N_c}{m \cdot A_U} \le \sigma_{im,cr} = \chi_{im} \cdot \sigma_{cr} \tag{30}$$

$$\chi_{im} = f\left(\overline{\lambda_x}\right) \tag{31}$$

whereby the member of (30) and (31) are calculated according to the following expressions:

$$\overline{\lambda_x} = \lambda_{i,x} / \lambda_v \tag{32}$$

$$\lambda_{i,x} = \beta_y \cdot H_c / i_{Ux} \le \lambda \tag{33}$$

$$\lambda_v = \pi \cdot \sqrt{E / R_e} \tag{34}$$

$$\sigma_{cr} = R_e / \nu_1 \tag{35}$$

where σ_{Nm} is the buckling stress for the built-up column about the material-axis, $\sigma_{im,cr}$ is the critical buckling stress for the built-up column about the material axis, σ_{cr} is the critical stress, χ_{im} is the reduction factor for the built-up column about the material-axis, $\lambda_{i,x}$ is the slenderness of the chord about x-axis, $\overline{\lambda_x}$ is the relative slenderness of the chord about x-axis, and λ_v is the yield slenderness. Thus, the constraint functions for this criterion are as follows:

$$g_4 = \sigma_{Nm} - \sigma_{im,cr} \le 0 \tag{36}$$

$$g_5 = \lambda_{i,x} - \lambda \le 0 \tag{37}$$

The buckling (stability) check of the built-up column about the non-material axis (*y*-axis) was done according to [13]:

$$\sigma_{Nn} = \frac{N_c}{m \cdot A_U} \leq \sigma_{in,cr} = \chi_{in} \cdot \sigma_{cr} \tag{38}$$

$$\chi_{in} = f\left(\overline{\lambda_{y,i}}\right) \tag{39}$$

whereby the member of (39) is calculated according to the following expression:

$$\overline{\lambda_{y,i}} = \lambda_{y,i} / \lambda_v \tag{40}$$

where σ_{Nn} is the buckling stress for the built-up column about the non-material-axis, $\sigma_{in,cr}$ is the critical buckling stress for the built-up column about the non-material axis, χ_{in} is the reduction factor for the built-up column about the non-material-axis, and $\overline{\lambda_{y,i}}$ is the relative slenderness of the built-up column about *y*-axis. Thus, the constraint function for this criterion is as follows:

$$g_6 = \sigma_{Nn} - \sigma_{in,cr} \leq 0 \tag{41}$$

The buckling (stability) check of the chord of the built-up column about 1-axis was done according to [13]:

$$\sigma_{N1} = \frac{N_{c1}}{A_U} \leq \sigma_{i,cr} = \chi \cdot \sigma_{cr} \tag{42}$$

whereby the members of (42) are calculated according to the following expressions:

$$\chi = f\left(\overline{\lambda}\right) \tag{43}$$

$$\overline{\lambda} = \lambda_1 / \lambda_v \tag{44}$$

$$N_{c1} = \frac{N_c}{m} + \frac{M_y \cdot A_U \cdot h_x}{2 \cdot I_y} \tag{45}$$

$$M_y = \frac{w_o \cdot N_c}{1 - \frac{N_{Sc}}{m \cdot A_U \cdot R_e} \cdot \overline{\lambda_{y,i}}^2} \tag{46}$$

where σ_{N1} is the buckling stress for the chord of the built-up column about 1-axis, $\sigma_{i,cr}$ is the critical buckling stress for the chord of the built-up column about 1-axis, χ is the reduction factor for the chord of the built-up column about 1-axis, N_{c1} is the compressive force acting on the chord of the built-up column, M_y is the bending moment acting on the built-up column, and $w_o = H_c/500$ is the initial geometric imperfection of the built-up column.

Thus, the constraint function for this criterion is as follows:

$$g_7 = \sigma_{N1} - \sigma_{i,cr} \leq 0 \tag{47}$$

The strength check of the chord of the built-up column (at the end field) was done according to [13]:

$$\sigma_{\max} = \frac{N_c}{m \cdot A_U} + \frac{Q_{\max} \cdot a_c}{2 \cdot m \cdot W_{Uy}} \leq \sigma_{cr} \tag{48}$$

$$Q_{\max} = \frac{\pi}{H_c} \cdot \frac{w_o \cdot N_c}{1 - N_{Sc} / N_{E,Q}} \tag{49}$$

where σ_{max} is the maximum stress for the chord of the built-up column and Q_{max} is the transverse force causing the bending of the chord of the built-up column. Thus, the constraint function for this criterion is as follows:

$$g_8 = \sigma_{\max} - \sigma_{cr} \leq 0 \tag{50}$$

The strength check of the batten plate of the built-up column was done according to [13]:

$$\sigma_{p\max} = \frac{3 \cdot Q_{\max} \cdot a_c}{m \cdot t_p \cdot h_p^2} \leq \sigma_{cr} \tag{51}$$

where σ_{pmax} is the maximum stress for the batten plate of the built-up column.

Thus, the constraint function for this criterion is as follows:

$$g_9 = \sigma_{p\max} - \sigma_{cr} \le 0 \tag{52}$$

The strength check of the batten plate's weld connections was done according to [13]:

$$\sigma_w \le \sigma_{w,cr} = 0.75 \cdot \sigma_{cr} \tag{53}$$

$$\sigma_w = \sqrt{\left(V_{nT} + V_n\right)^2 + {V_p}^2} \tag{54}$$

whereby the members of (54) are calculated according to the following expressions:

$$V_{nT} = \frac{T}{2 \cdot \left(h_p + 2 \cdot a_w\right) \cdot a_w} \tag{55}$$

$$T = Q_{\max} \cdot a_c \,/\, h_x \tag{56}$$

$$V_n = T_o \cdot l_n \,/\, r_{\max} \tag{57}$$

$$V_p = T_o \cdot l_p \,/\, r_{\max} \tag{58}$$

$$T_o = M_w \cdot r_{\max} \,/\, I_{ow} \tag{59}$$

$$M_w = \frac{T}{2} \cdot \left(x_w + \frac{b_U}{2} - b_{U2} \right) \tag{60}$$

$$I_{ow} = I_{xw} + I_{yw} \tag{61}$$

$$r_{\max} = \sqrt{{l_n}^2 + {l_p}^2} \tag{62}$$

where σ_w is the maximum stress of the batten plate's weld connections, $\sigma_{w,cr}$ is the critical stress of the batten plate's weld connections, T is the transverse force, M_w is the torsion, V_{nT} is the transverse stress component (from the force T), T_o is the torsional stress, V_n is the transverse stress component (from the torsion M_w), V_p is the longitudinal stress component (from the torsion M_w), I_{xw}, I_{yw} are the principal moments of inertia for the weld connections about x and y directions, respectively, I_{ow} is the polar moment of inertia for the weld connections, and x_w, r_{max}, l_n, l_p are weld dimensions (Figure 3). These geometric characteristics of welded connections are being calculated by using the well-known expressions.

The following condition must be met, too:

$$a_w \le a_{wm} = 0.7 \cdot \min\left(t, t_p\right) \tag{63}$$

where a_{wm} is the minimum weld thickness, [13].

Thus, the constraint functions for this criterion are as follows:

$$g_{10} = \sigma_w - \sigma_{w,cr} \le 0 \tag{64}$$

$$g_{11} = a_w - a_{wm} \le 0 \tag{65}$$

2.3. The geometric constraints and recommendations

Some of these types of limitations are defined through the variable limits (Chapter 4), and some through the constraint functions. The constraint functions, which incorporate geometric limitations and design recommendations, according to [13] take the following form:

$$g_{12} = 0.5 \cdot b_U - h_p \le 0 \tag{66}$$

$$g_{13} = h_p - 0.7 \cdot b_U \le 0 \tag{67}$$

$$g_{14} = h_p \,/\, 30 - t_p \le 0 \tag{68}$$

$$g_{15} = b_U - 60 \le 0 \tag{69}$$

3. OPTIMIZATION METHOD

Novel bio-inspired metaheuristic optimization algorithm, the Marine Predators Algorithm (MPA) [14] was chosen for solving this optimization problem. This metaheuristic optimization algorithm proved efficient in solving different kinds of engineering problems which is proven in [14], which is the reason why it was considered as the method of choice. The efficiency in solving different engineering optimization problems was also displayed in [15, 16]. The algorithm was described in details in [14]. It should be noted that the algorithm was applied in this research in its basic form, without modifications, [17].

4. RESULTS OF OPTIMIZATION AND DISCUSSION

The optimization process was conducted on one column from the study [8], where the obtained results were compared with those from the mentioned study. It was completed using MATLAB software, by the code provided in [17] for the chosen MPA optimization method. The height of the column is H_s=5 m, the compressing force acting at the top of the column is N_c=300 kN, the material of the column is S235 (R_e=23.5 kN/cm^2, E=21000 kN/cm^2, and ρ=7850 kg/m^3), steel plate thickness out of which the cold-formed chords were made of equals t=6 mm, and the radius on the profile of the chords equals r=6 mm. The rest of the input data is: m=2, α_x=0.38, α_y=0.44, [13], β_x=1, β_y=2, and v_1=1.5.

The optimization was conducted in such way where the change of the objective function in favour of lowering the number of the plates was monitored: n_c=8 (Case 1), n_c=7 (Case 2), and n_c=6 (Case 3). The control parameters of the MPA method, for all cases are: N_p=100 – the population size and M_{iter}=600 – the maximum number of iterations. Bound values of variables are: $3.5 \le b_{U1} \le 20$, $60 \le \lambda \le 80$, $10 \le h_p \le 28$, $0.6 \le t_p \le 1.2$, $0.3 \le a_w \le 0.7$. The objective function is defined by (3). Constraints are defined by (27)-(29), (36), (37), (41), (47), (50), (52) and (64)-(69).

The lengths are expressed in [cm], slenderness is dimensionless, loads are in [kN], stresses in [kN/cm^2], area is in [cm^2], weights in [kg], and savings in [%]. It should be pointed out that the objective function value after each conducted simulation was the same which confirms the efficiency of the chosen optimization method.

Table 1 presents the optimization results, optimal parameters and the convergence characteristics of the optimization process: the lowest (best), the highest (worst), the average (mean) values, and the standard deviation (Std) for Cases 1-3. Table 2 presents the optimization results (strength and stability check) for Cases 1-3. Table 3 presents rounded values of optimal geometric parameters, the weight of the battened built-up column, and savings in material for Cases 1-3.

The results of the optimization show very small variation in the value of the objective function (Table 1) which implies that the variation in the number of plates did not make a significant impact on its value. In all three cases the same dimension of the plates were obtained (Table 1 and Table 3) and the thickness of the steel plates took the lower boundary values. The optimal slenderness was also close to the same in all three observed cases (Table 1), while the only visible change in dimension is the width of the cold-formed profiles. The optimal thickness of the welds took the minimal values defined in lower boundary vector (Table 1). The optimization process in all three cases was completed for approximately the same amount of time.

The strength and stability criteria, as constraint functions in all three cases around the non-material axis took the borderline values (Table 2) which implies that this criterion are the most critical. The stability criterion around the material axis was also close to the critical values. The stability criterion of the chord at the end field takes values close to limits in all three cases (Table 2), where it can be seen that obtained values are getting closer to the limits with the reduction of the number of the batten plates. When the strength criteria of the batten plates and the welded connections is considered, the obtained values are far below the critical values (Table 2), and when the global stability criterion is considered, it can be noted that with the reduction of the number of batten plates, the critical values of the criterion are getting lower.

Based on the data displayed in the Table 3, it can be noticed that the savings of material are evident when the chords are consisted of the cold formed sections (S_1) and that the total weight of the column (S_2) is lower. These results were compared with the [8] where the standard channel profile was used in combination with EA algorithm as the optimization method for determining the number and dimensions of the batten plates.

Table 1: Optimization results: Optimal parameters and characteristics of the optimization process for Cases 1-3

Case	b_{U1}	λ	h_p	t_p	a_w	time	best	worst	mean	Std
1	4.7657	79.5806	14.5	0.6	0.3	15.10	154.5481	167.7786	155.0580	1.6389
2	5.1008	79.3882	14.5	0.6	0.3	15.20	154.2644	185.9228	154.8776	3.0559
3	5.5628	79.6493	14.5	0.6	0.3	14.99	155.1774	198.3817	155.6075	2.6002

Table 2 Optimization results: Strength and stability check for Cases 1-3

Case	N_{Sc}	$N_{E,Q}$	σ_{Nm}, σ_{Nn}	$\sigma_{im,cr}$	$\sigma_{in,cr}$	σ_{N1}	$\sigma_{i,cr}$	σ_{max}	σ_{pmax}	σ_{cr}	σ_{w}	$\sigma_{w,cr}$
1	450.0	911.05	9.27	9.96	9.27	10.66	13.90	15.05	3.07	15.67	2.97	11.75
2	450.0	887.23	9.05	10.03	9.05	10.44	13.57	15.26	3.68	15.67	3.47	11.75
3	450.0	858.75	8.76	10.12	8.76	10.16	13.16	15.47	4.57	15.67	4.16	11.75

Table 3: Rounded values of geometric parameters, the weight of
the battened built-up column and savings in material for Cases 1-3

Case	b_{U1}	b_{U2}	h_U	H_U	A_U	S_1	b_p	h_p	t_p	a_w	M_c	S_2
1	4.8	6.0	14.6	17.0	16.22	42.08	25.0	14.5	0.6	0.3	154.87	35.57
2	5.1	6.3	14.6	17.0	16.58	40.80	25.0	14.5	0.6	0.3	154.26	35.83
3	5.6	6.8	14.6	17.0	17.18	38.66	25.0	14.5	0.6	0.3	155.53	35.30

The graphs on Figures 4-6 show the convergence diagrams for Cases 1-3, respectively. The data implies that the lowest value of weight is achieved in the Case 2, where n_c=7 (Table 1). For this reason, the Case 2 will be considered as relevant for further optimization in this work.

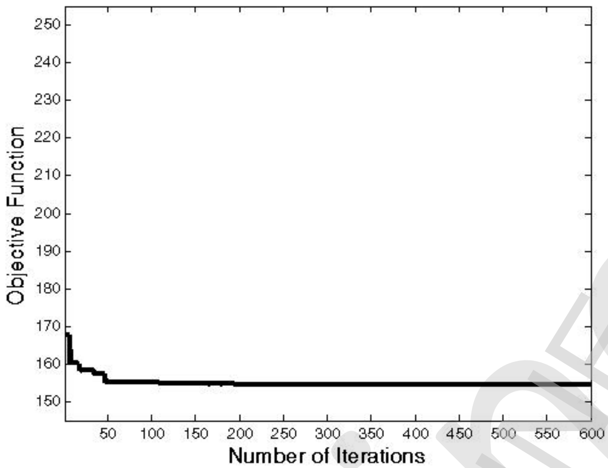

Figure 4: Convergence diagram for Case 1

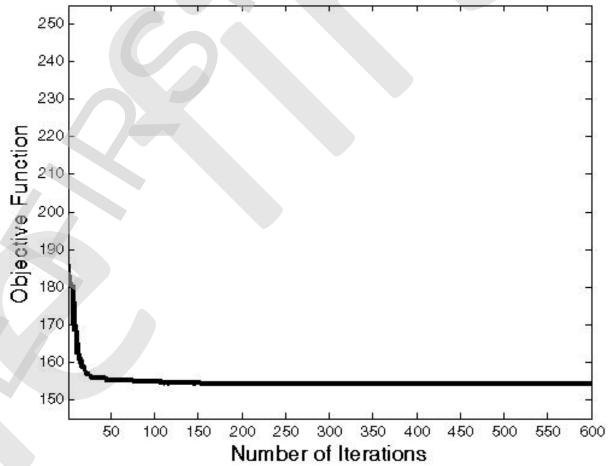

Figure 5: Convergence diagram for Case 2

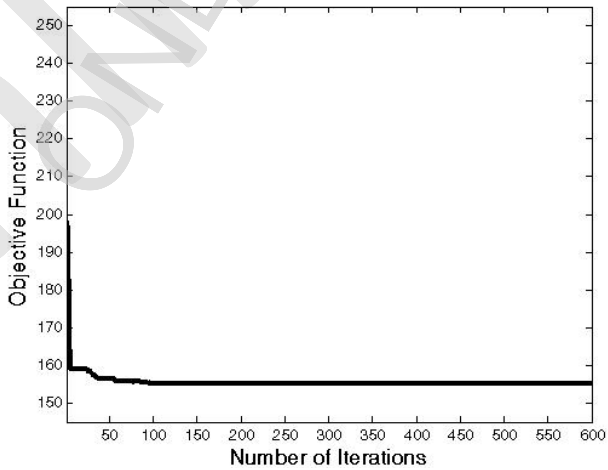

Figure 6: Convergence diagram for Case 3

In following text, the focus will be on the change of the objective function as the thickness of the cold formed section reduces to t=5 mm (Case 4), as well as for the change of the material to S275 (Case 5), and S355 (Case 6), while R_e=27.5 kN/cm^2 for S275 and R_e=35.5 kN/cm^2 for S355. Table 4 presents the optimization results, optimal parameters and the convergence characteristics of the optimization process: the lowest (best), the highest (worst), the average (mean) values, and the standard deviation (Std) for Cases 4-6. Table 5 presents the optimization results (strength and stability check) for Cases 4-6. Table 6 presents rounded values of optimal geometric parameters, the weight of the battened built-up column, and savings in material for Cases 4-6.

The results from the Table 4 show that reduction of the thickness of the chords (Case 4) has an impact on the value of the objective function (Case 2, Table1). The change is also evident when the material is changed, especially when it is changed from S235 (Case 4, Table 4) to S355 (Case 6, Table 4). Based on the data from the Table 4 and Table 6, it can also be noticed how the change of the material effects the dimensions of the cold formed section of the chords, as well as the dimensions of the batten plates. The optimal values for the weld thickness and the thickness of the batten plates are equal to the lower boundary limits (Cases 4-6). The time it took for the optimization process to finish varies from case to case (Table 4).

As in the previous, for the Case 4 and Case 5 the stability criterion around the non-material axis is the most critical (Table 5) since the maximal boundary values were obtained, while for the stability criterion around the material axis have values that are slightly lower than the highest boundary values. This is also the case for the stability criterion for the chord at the end field. For the Case 6, the most critical criterion is the stability of the chord at the end field, while the stability criteria around both axes take values that are slightly below the high boundary values (Table 5). It can be noticed that the increase of the yield stress of the material reduces the critical value of the global stability criterion (Table 5).

Based on values displayed in the Table 6 it can be noticed that the savings of material with the use of the cold formed section (S_1) and total weight of the column (S_2) are getting higher when the use of the higher graded steel with better mechanical properties.

Table 4: Optimization results: Optimal parameters and characteristics of the optimization process for Cases 4-6

Case	b_{U1}	λ	h_p	t_p	a_w	time	best	worst	mean	Std
4	6.1237	73.6640	15.5	0.6	0.3	16.22	148.4200	226.1549	149.1681	4.2627
5	5.2056	74.2887	15.5	0.6	0.3	14.87	141.1945	197.3489	141.7552	4.0334
6	4.7890	79.9737	14.0	0.6	0.3	12.55	128.5363	229.9664	129.2484	5.7078

Table 5: Optimization results: Strength and stability check for Cases 4-6

Case	N_{Sc}	$N_{E,Q}$	σ_{Nm}, σ_{Nn}	$\sigma_{im,cr}$	$\sigma_{in,cr}$	σ_{N1}	$\sigma_{i,cr}$	$\sigma_{\max}$	$\sigma_{p\max}$	σ_{cr}	σ_w	$\sigma_{w,cr}$
4	450.0	970.33	9.77	10.65	9.77	11.07	14.14	14.89	2.95	15.67	2.66	11.75
5	450.0	870.17	10.39	11.54	10.39	11.90	15.50	17.80	3.28	18.33	3.16	13.75
6	450.0	670.44	11.09	12.38	12.79	12.72	18.49	23.67	5.92	23.67	5.67	17.75

Table 6: Rounded values of geometric parameters, the weight of the battened built-up column and savings in material for Cases 4-6

Case	b_{U1}	b_{U2}	h_U	H_U	A_U	S_1	b_p	h_p	t_p	a_w	M_c	S_2
4	6.2	7.3	15.8	18.0	15.44	44.87	27.0	15.5	0.6	0.3	149.02	38.00
5	5.2	6.3	15.8	18.0	14.44	48.45	27.0	15.5	0.6	0.3	141.15	41.28
6	4.8	5.9	14.8	17.0	13.54	51.66	24.0	14.0	0.6	0.3	128.62	46.49

The following graphs (Figures 7-9) show the convergence diagrams for Cases 4-6, respectively.

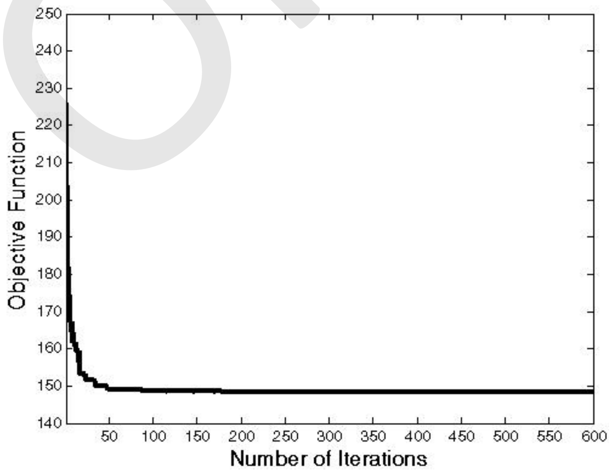

Figure 7: Convergence diagram for Case 4

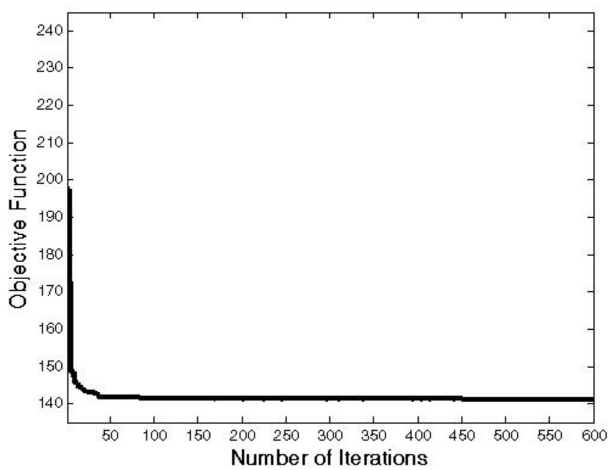

Figure 8: Convergence diagram for Case 5

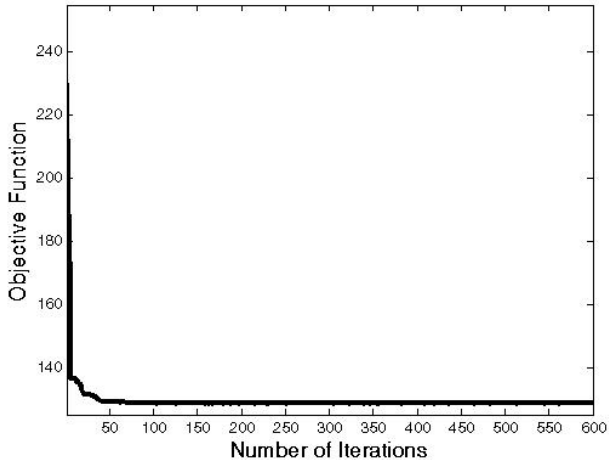

Figure 9: Convergence diagram for Case 6

5. CONCLUSION

This paper deals with the analysis and optimization of the total weight of the cold-formed battened built-up column with two chords for crane runways. The Marine Predators Algorithm (MPA) was used for the optimization process. The single-objective function is the total weight of the battened built-up column. The criteria of stability (buckling) of structure and structural elements and criteria of strength of structural elements and welded connections were used as constraint functions, as well as specific design recommendations. The results were compared to those obtained in [8].

In this research, savings in the material are in the range of 38.66–51.66% for the area of the chord and 35.30–46.49% for the total weight of the column (Table 3 and Table 6, respectively). The results obtained in this research justify the approach for analysis and optimization design of the cold-formed battened built-up column with two chords for the observed optimization example. This way it was shown that the use of the cold-formed chords made out of steel plates with optimized dimensions (instead of using standard profiles) contributes to reduction of weight of the chords and the column in total. Through the described conditions under which the structure was observed it was shown how the number of batten plates effects on the optimal areas of the cross section of the column (Table 3). In Table 6 it was shown how the change of material effects the weight of the column as well. Based on the data from the Table 2 and Table 5 it can be noticed that the most critical criteria for these kinds of structures are stability criteria around the both axis (material and non-material), as well as the stability criterion of the chord at the end field.

The use of MPA method proved to be very efficient in solving this complex optimization problem, reaching to the optimal solution in relatively short time (Table 1 and Table 4). Based on the Figures 4-9 it can be noticed that the optimal solution is reached within first 200 iterations of the optimization process.

It is important to analyses the how the change of different parameters, such as the thickness of the steel plate, material characteristics of both chords and batten plates, cross section geometry and number of batten plates, types of connections between the chords and batten plates can contribute to reduction of the structures weight, which is, alongside the FEM verification of the model, going to be the subject of future research.

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