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OPTIMAL DESIGN OF THE BATTENED BUILT-UP COLUMN OF THE CRANE RUNWAY BEAM

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Abstract

This study presents the analysis and the optimal design of the battened built-up column of the crane runway beam. One economic-inspired algorithm, called Supply-Demand-Based Optimization (SDO), was used for the optimization procedure. The objective function is the overall weight of the battened built-up column, which consists of two chords (the cold-formed U-profiles) and batten plates. This research uses all necessary stability and strength criteria (according to Serbian standards) and geometrical recommendations as the constraint functions. The justification for applying this method to the considered problem was confirmed by comparing the results with results from the published research. Achieved savings in the built-up column's weight are between 12,55% and 20,42%, depending on the number of batten plates and type of structural steel.

***Keywords**: built-up column, stability, channel section, metaheuristic, supply-demand-based optimization.*

1 INTRODUCTION

When standard steel profiles cannot withstand large compressive forces, engineers design built-up columns. It is often the case with the columns for the cranes' runway beams. A built-up column usually consists of two or more standard rolled steel profiles, acting like stand-alone chords, interconnected by lacing or batten plates. Stand-alone chords are often C, U, I or L steel profiles, although some other shapes or combinations can exist.

Structural analysis for this type of structure is commonly conducted in some finite element method (FEM) software using various types of finite elements. ABAQUS was used in [1], where a battened built-up column with two chords (web-stiffened C-profiles), was subjected to the eccentric load in a positive and negative direction. The results complied with the experiment, so applying the mentioned software was justified. Furthermore, the application of the ANSYS program was presented through a parametric study. The truss supporting structure was analyzed using ANSYS in the paper [2], where the main structure components were battened built-up columns with two chords (C-profiles). Steel and an aluminium alloy were considered as materials. Research results were compared to analytical ones obtained from Eurocode, and certain conclusions and directives were derived for the design of this type of structure.

The manner of combining the FEM analysis results with the ones obtained from some design code is present in many investigations, [3]-[7]. To determine the fastest and the most straightforward calculation of the axial capacity of the battened built-up column with two chords, the comparison of different methods was presented in [3], using Eurocode and Polish standards. Also, the FEM models with beam and plate finite elements were established and verified. The results were compared with the ones available in the literature. A battened built-up column with two chords made of C-profiles was considered in the paper [4], with different column lengths and distances between the chords. The number of batten plates was studied through FEM. The results were compared with the ones obtained from Eurocode and North-American standards. Applying FEM, a parametric study of a battened built-up column with two chords made of C-profiles was considered in [5] to investigate its nonlinear structural behaviour based on changeable global slenderness of the column, slenderness of the batten plates and yield strength. Obtained results help within the assessment of FEM results for this type of structure concerning the North-American and Eurocode standards. The paper [6] studied the influence of chord compactness and slenderness of battened built-up columns with two chords made of U-profiles by ABAQUS software. Varying parameters were width/thickness ratio, overall column slenderness ratio, and spacing of chords. The results were compared with the ones obtained from Eurocode and Norh-American standards. Based on reliability verification, some recommendations were given for the design of this type of supporting structure. Similar to the previous, the paper [7] identified the relative slendernesses of the chords in the steel battened built-up columns, which were in good agreement with North-American and Eurocode standards. Furthermore, new design rules were proposed and verified through reliability analysis.

Besides FEM, theoretical research and optimization of built-up columns are frequent, [8]-[11]. The theoretical analysis of the elastic stability of laced and battened built-up columns with two chords was done in the paper [8]. Similar to the previous, a theoretical study of the stability of battened built-up columns with two chords and the frames was conducted in [9]. The optimization of the number and dimensions of batten plates in built-up columns with two chords (for two design solutions) made of standard U-profiles was done in the paper [10]. It was monitored how the variables' optimum values were changing with the increase of the compression force. EA code was used through MS EXCEL software as an optimization method. Similar to the previous research, the weight of the battened built-up column with two chords was optimized, where the chords of the built-up column were welded I-profiles, [11]. This time, besides the number of batten plates and their dimensions, the optimization included the geometrical parameters of the welded I-profiles' plates. GRG2 code was used through MS EXCEL software as an optimization method. In two previous investigations conducted by EA and GRG2 code, it was possible to determine an optimal number of the batten plates since both codes can treat the variables as integers, which was very important.

This research aims to decrease the weight of the crane runway beam column, which has two U-profiles acting as the chords.

The main goal in this research is to justify the usage of U-profiles made by bending the plates to the exact dimensions, which are the optimization parameters, instead of standard rolled U-profiles. In addition, the batten plates' dimensions are also optimized, where their number is the input parameter. The number of batten plates and the material of the crane runway beam column are varied. Applying the proposed solution of a battened built-up column is justified through one example.

Since the application of metaheuristic algorithms increases in a variety of engineering problems, both single-objective and multi-objective, a new-generation metaheuristic algorithm, the Supply-Demand-Based Optimization (SDO) algorithm, [12] and [13], is chosen for this research.

2 THE OPTIMIZATION PROBLEM

The optimization problem in this paper is the weight minimization of the battened built-up column of the crane runway beam (Fig. 1).

Fig. 1 shows the design of the battened built-up column (crane runway column). The distance between the batten plates is designated as *a*, while the *A-A* section view depicts the cross-section and positioning of the chords (U-profiles).

The main goal of this research is to use U-profiles made by bending steel plates with the thickness of t=6mm instead of standard rolled U-profiles to gain material savings while satisfying all necessary criteria. Furthermore, it will be shown how the number of batten plates and material type selection impact the overall weight of the battened built-up column.

The nature of the load for this column type imposes numerous criteria that must be met concerning overall stability, partial stability, and strength of the column elements and welded connections. Also, some geometric and design recommendations must be taken into account, according to [14].

The results will be compared to those from the paper [10], through a column design example to justify the application of the proposed optimization model.

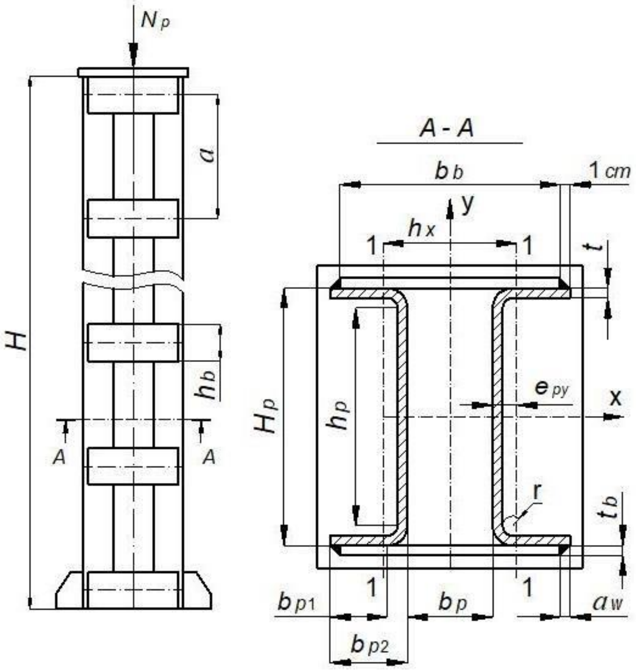

Fig. 1 *The structure of the battened built-up column with two chords and the view A-A (cross-sectional area)*

3 THE OBJECTIVE FUNCTION AND CONSTRAINT FUNCTIONS

The objective function is the total weight of the buttened built-up column (Fig. 1). The column consists of two chords, i.e. U-profiles, connected by welded batten plates, where the thickness of the fillet welds is a_w.

Fig. 1 shows the variables and all significant geometric parameters necessary for the analysis and optimization procedure.

The variables (x) in the optimization are:

$x_1 = b_{p1}$, $x_2 = \lambda$, $x_3 = h_b$, $x_4 = t_b$, $x_5 = a_w$,

where b_{p1} is the width of U-profile (from the radius r, Fig. 1), λ is a slenderness of the built-up column, h_b is the batten plate height (Fig. 1), t_b is the batten plate thickness (Fig. 1), and a_w is the weld thickness (Fig. 1).

The input parameters for the optimization are:

N_p, n, H, α_1, α_2, β_1, β_2, v_1, r, ρ, R_e, λ_v, E,

where N_p is the compressive force (Fig. 1), n is the number of the batten plates, H is the column height (Fig. 1), α_1, α_2 are the coefficients, [14], β_1, β_2 are the buckling coefficients, v_1=1,5 is load case 1 factored load coefficient, [14], r=6mm is the inner radius of U-profile (Fig. 1), ρ is the material density, R_e is the yield strength, [14], λ_v is the yield slenderness (depends on R_e), [14], and E is the elastic modulus, [14].

The total weight of the battened built-up column with two chords (M_{co}), i.e. the objective function $f(x)$, is defined as follows:

$$f(x) = M_{co} = 2\rho\left(A_p \cdot H + n \cdot x_3 \cdot x_4 \cdot b_b\right) \tag{1}$$

$$A_p = \left[\left(h_p + 2x_1\right) + \pi(2r + t)/2\right] \cdot t \tag{2}$$

$$h_p = H_p - 2(r + t) \tag{3}$$

$$H_p = (\beta_1 \cdot H)/(\alpha_1 \cdot x_2) \tag{4}$$

$$b_b = b_p + 2(b_{p2} - 1) \tag{5}$$

$$b_p = (\beta_2 \cdot H)/(\alpha_2 \cdot x_2) \tag{6}$$

$$b_{p2} = x_1 + r + t \tag{7}$$

where A_p is the area of U-profile (Fig. 1), H_p is the height of U-profile (Fig. 1), h_p is the inner height of U-profile (Fig. 1), b_{p2} is the width of U-profile (Fig. 1), b_p is the distance between the chords (Fig. 1), and b_b is the batten plate width (Fig. 1).

Noticeably, the variable x_5 is not present in the objective function. It is to be defined within the criterion of welded connections' strength.

The geometric characteristics of the U-profile are: I_{py} – the principal moment of inertia about y-axis, i_{px} – the radius of gyration about x-axis, i_{py} – the radius of gyration about y-axis, e_{py} – the position of the centre of gravity about y-axis (Fig. 1), and W_{py} – the section moduli about y-axis. These characteristics are present in the analysis and are calculated by well-known relations.

The battened built-up column must meet the criteria related to global stability, stability and strength checks of its segments, welded connections and some geometric and design recommendations. The majority of the criteria herein will be introduced as the constraint functions, while some will act as the limits of the variables (lower and upper bounds).

The constraint functions for the criterion of the global stability of the battened built-up column with two chords, according to [14], have the form:

$$g_1 = \nu_1 N_p - N_{EQ} \leq 0 \tag{8}$$

$$g_2 = a - 50 i_{py} \leq 0 \tag{9}$$

$$g_3 = \lambda_y - x_2 \leq 0 \tag{10}$$

where:

$$N_{EQ} = 2\pi^2 \cdot E \cdot A_p/{\lambda_{yi}}^2 \tag{11}$$

$$\lambda_{yi} = \sqrt{{\lambda_y}^2 + {\lambda_1}^2} \tag{12}$$

$$\lambda_1 = a/i_{py} \tag{13}$$

$$a = (H - x_3)/(n - 1) \tag{14}$$

$$\lambda_y = (\beta_2 \cdot H)/i_y \tag{15}$$

$$i_y = \sqrt{I_y/(2A_p)} \tag{16}$$

$$I_y = 2\left[I_{py} + A_p \cdot (h_x/2)^2\right] \tag{17}$$

$$h_x = b_p + 2e_{py} \tag{18}$$

where N_{EQ} is the critical compressive force, I_y is the principal moment of inertia of the battened built-up column cross-section about y-axis, i_y is the radius of gyration of the battened built-up column cross-section about y-axis, λ_{yi} is the slenderness of the battened built-up column about y-axis, λ_y is the slenderness of the chord (U-profile) about y-axis, λ_1 is the slenderness of the chord about 1-axis (Fig. 1), h_x is the axial distance between the chords (Fig. 1), and a is the axial distance between the batten plates (Fig. 1).

The constraint functions for the criterion of stability of the battened built-up column with two chords about the material axis (x-axis), according to [14], have the form:

$$g_4 = \sigma_N - \chi_{im} \cdot \sigma_d \leq 0 \tag{19}$$

$$g_5 = \lambda_{ix} - x_2 \leq 0 \tag{20}$$

where:

$$\sigma_N = N_p/(2A_p) \tag{21}$$

$$\sigma_d = R_e/\nu_1 \tag{22}$$

$$\chi_{im} = f(\lambda_{ix}/\lambda_v) \tag{23}$$

$$\lambda_{ix} = (\beta_1 \cdot H)/i_{px} \tag{24}$$

where σ_N is the buckling stress for the battened built-up column, σ_d is the critical stress, χ_{im} is the reduction factor for the battened built-up column about the material-axis (x-axis), and λ_{ix} is the slenderness of the chord (U-profile) about x-axis.

The constraint function for the criterion of stability of the battened built-up column with two chords about the non-material axis (y-axis), according to [14], has the form:

$$g_6 = \sigma_N - \chi_{in} \cdot \sigma_d \leq 0 \tag{25}$$

where:

$$\chi_{in} = f(\lambda_{yi}/\lambda_v) \tag{26}$$

where χ_{in} is the reduction factor for the battened built-up column about the non-material-axis (y-axis).

The constraint function for the criterion of stability of the battened built-up column with two chords about 1-axis, according to [14], has the form:

$$g_7 = \sigma_{N1} - \chi \cdot \sigma_d \leq 0 \tag{27}$$

where:

$$\sigma_{N1} = N_{p1}/A_p \tag{28}$$

$$N_{p1} = N_p/2 + M_y \cdot A_p \cdot h_x/(2I_y) \tag{29}$$

$$M_y = N_p \cdot w_o/\left[1 - \nu_1 N_p \cdot {\lambda_{yi}}^2/(2A_p \cdot R_e)\right] \tag{30}$$

$$\chi = f(\lambda_1/\lambda_v) \tag{31}$$

where σ_{N1} is the buckling stress for the chord (U-profile) of the battened built-up column about 1-axis, χ is the reduction factor for the chord of the battened built-up column about 1-axis, N_{p1} is the compressive force acting on the chord of the battened built-up column, M_y is the bending moment acting on the battened built-up column, and $w_o = H/500$ is the initial geometric imperfection of the battened built-up column, [14].

The constraint function for the criterion of the strength of the chord (U-profile) of the battened built-up column with two chords (at the end field), according to [14], has the form:

$$g_8 = \sigma_m - \sigma_d \leq 0 \tag{32}$$

where:

$$\sigma_m = N_p/(2A_p) + Q_m \cdot a/(4W_{py}) \tag{33}$$

$$Q_m = (\pi/H) \cdot N_p \cdot w_o/(1 - \nu_1 N_p/N_{EQ}) \tag{34}$$

where σ_m is the maximum stress for the chord of the battened built-up column and Q_m is the transverse force of the chord of the battened built-up column.

The constraint function for the criterion of the strength of the batten plate of the battened built-up column with two chords, according to [14], has the form:

$$g_9 = \sigma_{bm} - \sigma_d \leq 0 \tag{35}$$

where:

$$\sigma_{bm} = 3Q_m \cdot a/(2 \cdot x_4 \cdot x_3{}^2) \tag{36}$$

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

The constraint functions for the criterion of the strength of the fillet weld connection (Fig. 2), according to [14], have the form:

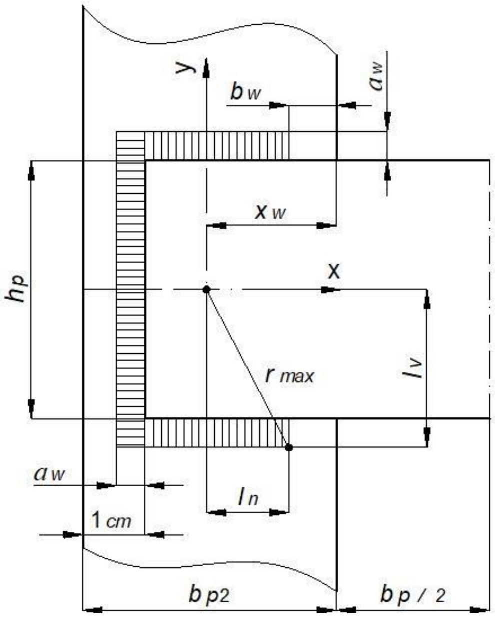

Fig. 2 *The fillet weld connection*

$$g_{10} = \sigma_w - 0{,}75 \cdot \sigma_d \leq 0 \tag{37}$$

$$g_{11} = x_5 - a_{wd} \leq 0 \tag{38}$$

where:

$$\sigma_w = \sqrt{(V_{nt} + V_n)^2 + V_v{}^2} \tag{39}$$

$$V_{nt} = T/[2(x_3 + 2x_5) \cdot x_5] \tag{40}$$

$$T = Q_m \cdot a/h_x \tag{41}$$

$$V_n = T_o \cdot l_n/r_{max} \tag{42}$$

$$V_v = T_o \cdot l_v/r_{max} \tag{43}$$

$$T_o = M_w \cdot r_{max}/I_{ow} \tag{44}$$

$$l_n = x_w - b_w \tag{45}$$

$$l_v = h_p/2 + x_5 \tag{46}$$

$$r_{max} = \sqrt{l_n{}^2 + l_v{}^2} \tag{47}$$

$$b_w = x_5 + r + t \tag{48}$$

$$M_w = T \cdot (x_w + 0{,}5 \cdot b_p)/2 \tag{49}$$

$$a_{wd} = 0{,}7 \cdot min(t,\ x_4) \tag{50}$$

where σ_w is the maximum stress of the fillet weld connection (Fig. 2), a_{wd} is the permisible weld thickness, V_{nt} is the transverse stress component, V_n is the transverse stress component, V_v is the longitudinal stress component, T is the transverse force, T_o is the torsional stress, M_w is the torsion, I_{ow} is the polar moment of inertia of the fillet weld conection (Fig. 2), x_w is the position of the centre of gravity of the fillet weld conection (Fig. 2), and b_w, r_{max}, l_n, l_v are weld dimensions (Fig. 2). The constraint functions related to the geometric and design recommendations, according to [14], are:

$$g_{12} = 0{,}5 \cdot b_p - x_3 \leq 0 \tag{51}$$

$$g_{13} = x_3 - 0{,}7 \cdot b_p \leq 0 \tag{52}$$

$$g_{14} = x_3/30 - x_4 \leq 0 \tag{53}$$

$$g_{15} = b_p - 60 \leq 0 \tag{54}$$

4 THE OPTIMIZATION RESULTS AND DISCUSSION

The optimization was conducted using the original SDO code in MATLAB software, [13].

Supply-Demand-Based Optimization (SDO) is a novel metaheuristic algorithm inspired by the supply-demand mechanism in economics, which mimics both the demand relation of consumers and the supply relation of producers, [12]. The paper [12] gives a detailed description of this algorithm and many application examples in engineering, showing its solution's high accuracy, convergence rate, and efficiency compared to many considered algorithms.

The optimization procedure is applied to one column example, based on the paper [10], and the results from both researches were compared.

The column height is H=5m, the compression force at the top is N_p=400kN and the column material is S235 (R_e=23,5kN/cm^2, ρ=7850kg/m^3, and E=21000kN/cm^2). Other input parameters are: α_1=0,41, α_2=0,52 and β_1=1, β_2=2. The optimization was done for different numbers of batten sheets, for n=8 (Case 1) and n=7 (Case 2).

The control parameters of the SDO algorithm, for all cases are: N_{pop}=100 – the population size (the market size) and $Max,iter$=800 – the maximum number of iterations.

Bound values of variables are: $3{,}5 \le b_{p1} \le 20$, $60 \le \lambda \le 80$, $10 \le h_b \le 28$, $0{,}6 \le t_b \le 1{,}2$, $0{,}3 \le a_w \le 0{,}7$.

The objective function is defined by (1) and constraint functions are defined by (8)-(10), (19), (20), (25), (27), (32), (35), (37), (38), and (51)-(54). Table 1 shows optimal parameters and the time of the optimization process for Case 1 and Case 2, respectively.

Table 1 The optimization results for Case 1 and Case 2

Case	b_{p1} (cm)	λ (-)	h_b (cm)	t_b (cm)	a_w (cm)	time (s)
1	7,34	76,13	12,5	0,6	0,32	24,22
2	7,34	75,59	12,5	0,6	0,39	20,39

Table 2 shows optimal geometric parameters, column weight and savings in material for Case 1 and Case 2, respectively.

Table 2 Optimal geometric parameters, weight of the column and savings in material for Case 1 and Case 2

Case	$b_{p1,o}$ (cm)	$H_{p,o}$ (cm)	$b_{b,o}$ (cm)	$h_{b,o}$ (cm)	$M_{co,o}$ (cm^2)	Saving (%)
1	7,4	17,0	40,2	12,5	189,66	12,23
2	7,4	17,0	40,2	12,5	184,93	14,42

As can be seen in Table 2, the optimum weight is smaller for n=7 (Case 2) compared to Case 1 (n=8), which is expected, as shown in the paper [10], using the EA method. Index o designates optimal values.

The following figures (Figs. 3 and 4) show the convergence graphs for Case 1 and Case 2, respectively.

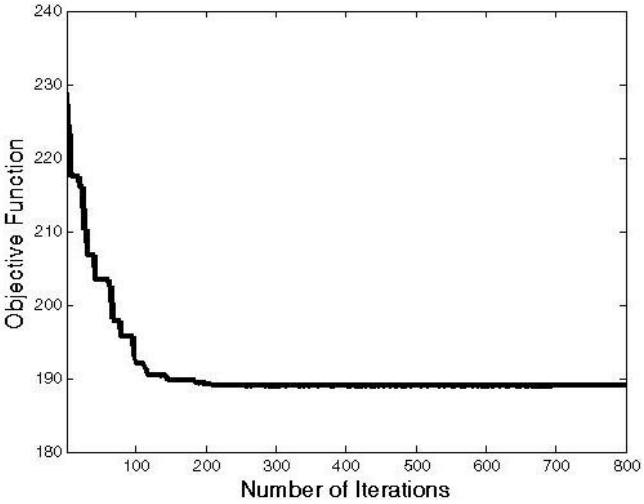

__Fig. 3__ The convergence graph for Case 1

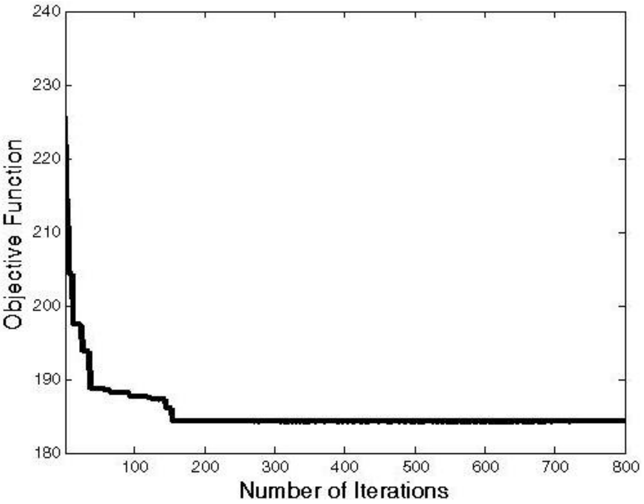

__Fig. 4__ The convergence graph for Case 2

Further on, the material of the column elements was changed for the case with n=7, where S275 (Case 3) and S355 (Case 4) were applied with their yield strengths R_e=27,5kN/cm^2 and R_e=35,5kN/cm^2, respectively.

Table 3 shows optimal parameters and the time of the optimization process for Case 3 and Case 4, respectively.

Table 3 The optimization results for Case 3 and Case 4

Case	b_{p1} (cm)	λ (-)	h_b (cm)	t_b (cm)	a_w (cm)	time (s)
3	6,48	76,21	12,5	0,6	0,36	20,41
4	6,84	80,00	12,0	0,6	0,37	20,74

Based on Tables 1 and 3, it is noticeable that the optimization time is almost the same, except for Case 1.

Table 4 shows rounded values of geometric parameters, column weight and savings in material for Case 3 and Case 4, respectively.

Table 4 Optimal geometric parameters, weight of the column and savings in material for Case 3 and Case 4

Case	$b_{p1,o}$ (cm)	$H_{p,o}$ (cm)	$b_{b,o}$ (cm)	$h_{b,o}$ (cm)	$M_{co,o}$ (cm^2)	Saving (%)
3	6,5	17,0	38,4	12,5	174,96	19,03
4	6,9	16,0	38,2	12,0	172,60	20,13

The following figures (Figs. 5 and 6) show the convergence graphs for Case 3 and Case 4, respectively.

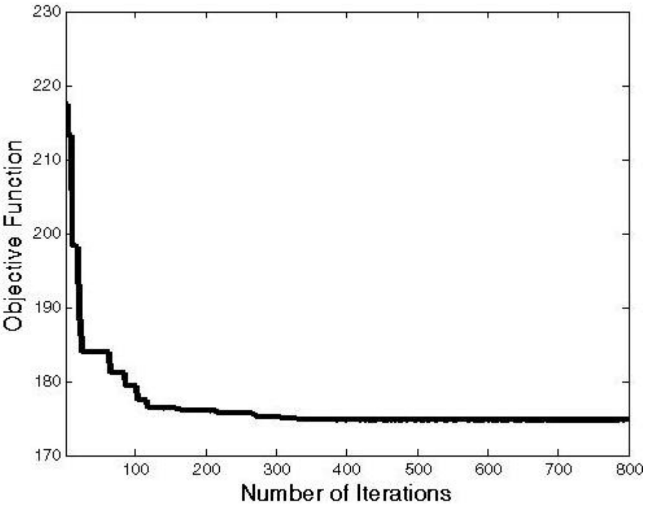

__Fig. 5__ The convergence graph for Case 3

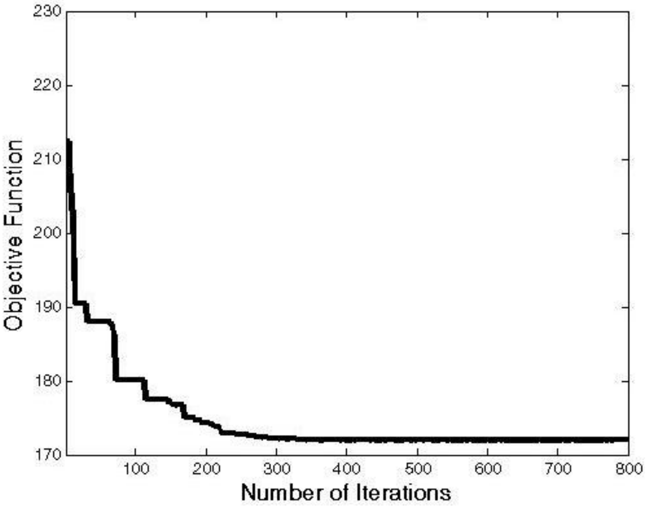

Fig. 6 *The convergence graph for Case 4*

In all the cases, material savings were achieved compared to [10], where standard rolled U-profiles were used as the chords.

Also, in all the cases, the optimal weld thickness (rounded value) is $a_{w,o}$=4mm, and plate thickness is $t_{b,o}$=6mm.

Based on Tables 2 and 4, it is noticeable that the material change decreases the column weight, especially when changing from S235 (Case 2) to S275 (Case 3).

5 CONCLUSIONS

This research analyses and optimizes the battened built-up column with two chords. Supply-Demand-Based Optimization (SDO) metaheuristic algorithm was used for the optimization process. The objective function is the weight of the crane runway beam's column (consists of two chords and batten plates). All necessary stability and strength criteria (strength of chords, batten plates and the welded connections), and some geometric and design are constraint functions. The results were compared with the ones from [10] through an example of a crane runway column.

In this research, savings in the material range from 12,23% to 20,13% (Tables 2 and 4), depending on the number of batten plates and type of structural steel. It was shown how using cold-formed U-profiles as the column chords (instead of standard rolled U-profiles) gained material savings in overall weight. This research justifies applying the proposed design solution with non-standard profiles and the employed optimization method.

The applied optimization algorithm relatively quickly achieved the optimal solution for this complex engineering problem (Tables 1 and 3), reaching the optimal solution in less than 500 iterations (convergence graphs, Figs. 3-6).

Further research could include different shapes for the column chords, variations of batten plates number, increase of the compression force, change of the material (chords and batten plates), and the influence of connection type between the chords and the batten plates. In addition, many new-generation algorithms can be tested to identify the most convenient one for this type of engineering problem.

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REFERENCES

1. Zhou, X., Chen, M., 2018, *Experimental investigation and finite element analysis of web-stiffened coldformed lipped channel columns with batten sheets*, Thin-Walled Structures, 125, pp. 38–50.
2. Baláž, I., Koleková, Y., Moroczová, L., 2020, *Built-up CFS column with lacings and battens*, MATEC Web of Conferences, 310, 00025.
3. Pieczka, P., Iwicki, P., 2021, *Axial capacity of steel built-up battened columns*, Chapter from the book: Modern Trends in Research on Steel, Aluminium and Composite Structures, Taylor & Francis Group, England, pp. 442–448.
4. Rahnavard, R., Craveiro, H.D., Simões, R.A., 2022, *Design of cold-formed steel battened built-up columns*, Proc. the Cold-Formed Steel Research Consortium Colloquium, New York, 12 p.
5. Sharma, D., Singh, R., 2023, *A Parametric Study: To Investigate Nonlinear Structural Behaviour of CFS Built-up Battened Columns*, International Journal of Economic Perspectives, 17(06), pp. 162-172.
6. Dar, M.A., Sahoo, D.R., Jain, A.K., 2020, *Influence of chord compactness and slenderness on axial compression behavior of built-up battened CFS columns*, Journal of Building Engineering, 32, 101743.
7. Dar, M.A. Verma, A., Anbarasu, M., Pang, S.D., Dar, A.R., 2022, *Design of cold-formed steel battened built-up columns*, Journal of Constructional Steel Research, 193, 107291.
8. Razdolsky, A.G., 2018, *Determination of Slenderness Ratio for Laced and Battened Columns*, Pract. Period. Struct. Des. Constr., 23(4), 04018019.
9. Bekdache, J.A.H., 2003, *A Study of the Critical Condition of a Battened Column and a Fram by Classical Methods*, MSc thesis, College of Engineering, University of South Florida, USA, 30 p.
10. Pavlović, G., Savković, M., Marković, G., Zdravković, N., 2020, *Analysis of Variants of Structures of Built-up Columns on Examples of Columns for Crane Runways*, Proc. The Fifth Conference on Mechanical Engineering Technologies and Applications "COMETa 2020", Jahorina, pp. 235-242.
11. Pavlović, G., Savković, M., Zdravković, N., Marković, G., 2020, *Stability and Optimization of the Crane Runaway Support Column*, IMK–14 - Research & Development in Heavy Machinery, 26(2), pp. 43-48.
12. Zhao, W., Wang, L., Zhang, Z., 2019, *Supply-Demand-Based Optimization: A Novel Economics-Inspired Algorithm for Global Optimization*, EEE Access, 7, pp. 73182-73206.

13. https://www.mathworks.com/matlabcentral /fileexchange/71764-supply-demand-based-optimization.
14. Petković, Z., Ostrić, D., 1996, *Metal Structures in Heavy Machinery I*, Institute for Mechanization of the Faculty of Mechanical Engineering of the University in Belgrade, Serbia, 1996.

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