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Analysis and Optimization of T-cross section of Crane Hook Considered as a Curved Beam

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This study presents analysis and optimization of the geometric parameters of T-cross section of crane hook. The reduction of the cross-sectional area of the hook is set as the main objective of this research. The permissible stresses in the crane hook characteristic points at the most critical place of her construction are taken as the limitation functions. Also, in the second part, analysis and optimization of certain geometric constraints are taken. The maximum stresses in characteristic points are calculated according to Winkler-Bach theory, where the construction of the hook is treated as a curved beam.

The optimization process is performed by using the five optimization algorithms i.e. by using the generalized reduced gradient method (GRG2) and the evolution algorithm (EA) in the Analysis module (Ms EXCEL software package), as well as the MATLAB software package (fmincon functions within the Optimization Toolbox module) and the genetic algorithm (GA) and by using a particle optimization algorithm (PSO).

Keywords: Crane Hook, Optimization, Stresses, Winkler-Bach theory

1. INTRODUCTION

Crane hooks are devices for hanging and lifting of heavy load capacities and they are an integral part of different types of crane hoists. Crane hooks are highly responsible components that are typically used for loads handling in industries. Due to their responsibility, the hoisting hooks are adequately attached to the supporting device (rope or chain), so that they meet all the necessary conditions in terms of health and safety at work.

Generally, the manipulation with materials and heavy loads occurs on construction sites, factories and other industrial facilities. Proper using of the equipment can lead to efficiently manipulation with heavy loads and reduced manual handling operations. Also, improper using of equipment and hoist hooks, which are with inadequate geometry and characteristics, can lead to function cancellation and disastrous accidents. Therefore, the proper design of crane hook is primary aim.

Optimization is a procedure through which the best possible values of decision variables are obtained under the given set of constraint functions and in accordance to objective function. The most common optimization procedure applies to a design that will minimize the total mass, area or any other specific objective.

Having in mind the above mentioned, there are a large number of papers and publications who dealing with the problems of optimization and analysis of crane hooks cross-section.

During the analysis and optimization of the hook construction, the stress conditions are observed in all cases, while in certain cases deformations are taken into account as well as the material fatigue.

The analysis of stress conditions is most often done by using the Finite Element Method (FEM). In the paper [1], the analysis of stress conditions of the typical trapezoidal cross-sectional hook is performed by using IDEAS software package. These results are compared with analytical, where the hook is observed as a curved beam, so the validity of such model is proven.

In studies [2], [3] and [4] are analyzed a different forms of full cross sections, where the 3D hook model is generated using CREO software package, while the analysis of the stresses is performed using ANSYS software package. In the paper [5], rectangular, trapezoidal, triangular and circular cross-section of the hook structure are analyzed also using ANSYS software package, while the 3D model is generated using CATIA software package.

Similar to the previous work, using CATIA and ANSYS software packages, besides the different full cross-sections, the T-cross section of the hook carrier is considered [6]. In this paper, different materials are analyzed in the analysis. The T-cross section is also discussed in works [7], [8], [9] and [10] using ANSYS software package for the analysis of stress states.

In the paper [8], a comparative analysis of the stress states is performed for the standard trapezoidal cross-section of the hook carrier, as well as for the T and I cross-section. Modeling of these carriers is done using CATIA software package. Comparison between the T and I transverse cross-section of the hook carrier is performed in [10], with 3D models generated in the SOLIDWORKS software package. Similar to the previous paper, in [9] a comparison of the T-profile is made with respect to the trapezoidal and circular profiles and different materials.

The T-cross section is optimized in [11], whereby optimization is performed from the aspect of optimization (shape optimization), using the PSO optimization method (particle digestion method). The aforementioned PSO method is successfully applied in the paper [12], where structural analysis and optimization of an elevator hook is performed.

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Very often in combination with FEM analysis, numerical optimization methods are combined, as shown in the previous paper [12], as well as in [13]. In the paper [13], a genetic algorithm (GA) is used in MATLAB software package for optimizing the geometric parameters of the trapezoidal cross-section of the hook, while the verification of the obtained parameters is performed in ANSYS software package.

In works [7] and [14], the optimization of the cross-sections of the hook structure is performed using the analytical procedure and certain optimization algorithms. In the paper [7], a comparison of the most often represented trapezoidal cross-section, in relation to the circular, rectangular, triangular, T and I cross-section is observed. The authors presented an algorithmic scheme for optimization.

In the paper [14], a comparative analysis and optimization of different full cross sectional shapes is performed on the crane hook example. The most critical cross-section of the hook is observed in the analysis. In addition to the typical cross sections that are represented, the parabolic and elliptical cross sections are analyzed. As a method of optimization, the Lagrange multiplier method is implemented in the MATHCAD software package, as well as the GRG2 optimization method (Ms EXCEL software package). Significant savings are made in comparison with the standard solution.

It should be noted that in addition to the usual methods of analysis and optimization, more and more topological optimization has been used in these types of structures, as shown in [15]. Finally, taking into account the above mentoined i.e. the results and significance of optimization of these types of constructions, the main goal of this paper is the analysis and optimization of the geometric parameters of the T-cross section of the crane hook at its most critical place, based on the Winkler-Bach theory.

2. OPRIMIZATION ALGORITHMS

Optimization process for such an engineering problem is performed using different numerical methods (algorithms) of optimization, using the Ms EXCEL and MATLAB programs.

The GRG method is one of the class of the technique called a generalized reduced gradient or projection gradient that is based on the extension of the method for linear constraints to nonlinear constraints. This adjusts the variables so that the active constraints are still satisfied, and the process moves from one point to another. The GRG method is based on the idea of elimination of variables using the equality of constraints. The idea of a generalized reduced gradient method is to convert the constraint problem into one without limitation using a direct substitution. Ms EXCEL Solver Tool uses a generalized reduced gradient method (GRG2 algorithm) to optimize non-linear problems.

The evolutionary algorithm (EA) applies the principles of evolution that are in nature to the problems of finding the optimal solution for the given objective function. The evolutionary algorithm of project variables and problem functions are used directly. As in the previous case, Ms EXCEL Solver Tool uses this algorithm to optimize non-linear problems.

The MATLAB Optimization Toolbox can be used for both linear and non-linear engineering problems. Optimization of the parameters is done using the *fmincon* function, [16].

Similar to the previous one, it is used in MATLAB and the genetic algorithm (GA), using the function *ga*, [17]. The benefits of a genetic algorithm are simple procedure, strong robustness, coincidence and integrity. This optimization algorithm has a great application in engineering practice.

The particle optimization method (PSO), [18] was a global stochastic algorithm and its idea is based on the simulation of simplified social models. The PSO is independent of the mathematical characteristics of the object's problem (object function) and is successfully applied in different areas, mainly due to unlimited continual optimization problems, simple concepts, simple implementation and fast convergence.

3. MATHEMATICAL FORMULATION OF THE OPTIMIZATION PROBLEM

The task of optimization for this problem is to determine the optimal geometric parameters of the T-cross section of crane hook which will lead to the minimization of its cross sectional area.

The optimization problem is defined in following way:

minimization of objective function

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

subject to the constrain function:

$$g_i(X) \le 0,\ i = 1,...,m \tag{2}$$

where it is fulfilled:

$$X_j \ge 0 \tag{3}$$

and

$$l_i \le X_i \le u_i,\ \ i = 1,...,n \tag{4}$$

where are:

$f(X)$ - the objective function,

$g_i(X) \le 0,\ i = 1,...,m$ - the constrain function,

l_i, u_i - lower and upper contraint limit,

i - number of constrains,

j - number of design variables,

$X = \{x_1,...,x_n\}^T$ - a project vector of n variables; project variables are the values which should be determined during the optimization process (each project variable is defined by its lower and upper limit).

GRG2 and EA optimization methods are implemented in the Ms EXCEL software package, in the Analysis module, using the Solver Tool tool. As for the MATLAB software package, to use the functions fmincon and use the expressions (5) and (6), respectively:

$$[X,\ fval, exitflag, output, lambda, grad, hessian] = fmincon(\ fun, X0, A, b, Aeq, beq, lb, ub, nonlcon) \tag{5}$$

$$[X,\ fval, exitflag, output] = ga(\ fun, n, A, b, Aeq, beq, lb, ub, nonlcon) \tag{6}$$

where the explanations of the MATLAB function are shown:
fval - the value of solving target function,
exitflag - shows the reason for the termination of solving execution,
fun - objective function,
output - shows the output informationduring optimization,
nonlcon - calculating of non-linear inequality,
lambda - Laqngrange multiplier,
grad - the gradient of objective function in point X,
hessian - the Hessian value of objective function in point X,
$X0$ - the vector of initial values of optimization parameters,
b, beq - vectors, A, Aeq - matrices,
$C(X)$, $Ceq(X)$ - vector functions.

The PSO optimization algorithm is defined according to [18], and with that algorithm the optimal value are determined.

Figure 1 shows a standard crane hook according to [19], as well as a critical cross section (I - I) on which the T-cross section is viewed (the right part of the section from the axis of loading force).

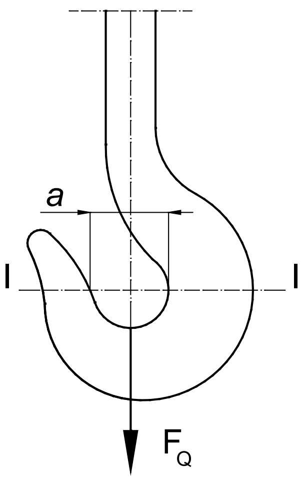

Figure 1: Crane hook

The mathematical formulation of the objective function is shown as follows (Figure 2):

$$f(X) = A_T(X) = A_T(x_1\ x_2\ x_3\ x_4) = A_T(b_t\ t\ h\ d) \quad (7)$$

The input parameters vector is:

$$\vec{x} = (Q,\ a,\ \sigma_d) \quad (8)$$

where are:
Q - load capacity of crane hook,
a - diameter of inner fiber of hook, [19] (Fig. 1),
σ_d - critical stress, [19].

Below text will showdetailed objectives and constraints.

4. OBJECTIVE FUNCTIONS AND CONSTRAINTS

4.1. Objective function

The objective function is represented by the area of T-cross section of crane hook at the most critical place. (Figure 2).

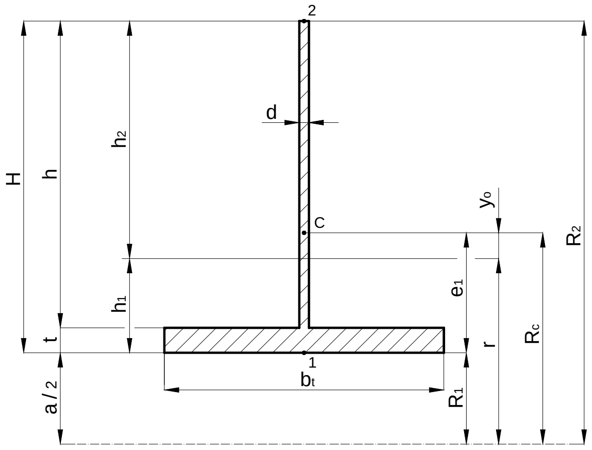

Figure 2: T-cross section

The cross-sectional area, or the objective function, is:

$$A_T = b_t \cdot t + h \cdot d \quad (9)$$

4.2. Constraint functions

Optimization processes are based on permissible stresses, according to Winkler-Bach theory. The total deformation of fibers in the curved beam is proportional to the distance of the fiber from the neutral surface (axis). The strains of the fibers are not proportional to these distances, since the fibers are not equal in length, unlike the straight beam. In the case of bending stress that does not exceed the permitted flow stress limit, the stress of any fiber of the beam is proportional to the stress of the fibers, so that the elastic stresses in the fibers of the curved beam are not proportional to the distance from the neutral surface. For the same reason, the neutral axis in the curved beam does not pass through the center of gravity of the cross-section.

The mathematical formulation of the constrain functions, according to the allowed stresses, [20] in characteristic points (Figure 2) is::

$$g_1 = \sigma_1 = \frac{F_Q}{A_T} + \frac{M_{\max}}{S_x} \cdot \frac{h_1}{R_1} \le \sigma_d \quad (10)$$

and

$$g_2 = |\sigma_2| = \frac{F_Q}{A_T} - \frac{M_{\max}}{S_x} \cdot \frac{h_2}{R_2} \le \sigma_d \quad (11)$$

where are:

$$h_1 = r - R_1 \quad (12)$$

$$h_2 = R_2 - r \quad (13)$$

$$H = h + t = h_1 + h_2 \quad (14)$$

$$R_1 = \frac{a}{2} \quad (15)$$

$$R_2 = \frac{a}{2} + H \quad (16)$$

$$R_c = R_1 + e_1 \tag{17}$$

$$e_1 = \frac{b_t \cdot t^2 + 2 \cdot h \cdot d \cdot t + h \cdot d^2}{2 \cdot A_T} \tag{18}$$

$$y_o = R_c - r \tag{19}$$

$$r = \frac{A_T}{\int_A \frac{dA}{\rho}} \tag{20}$$

$$\int_A \frac{dA}{\rho} = b_t \cdot \ln \frac{a + 2 \cdot t}{a} + d \cdot \ln \frac{a + 2 \cdot H}{a + 2 \cdot t} \tag{21}$$

$$F_Q = Q \cdot g \tag{22}$$

$$M_{\max} = F_Q \cdot R_c \tag{23}$$

$$S_x = A_T \cdot y_o \tag{24}$$

where are:

R_1 - radius of inner fiber (Fig. 2),

R_2 - radius of outer fiber (Fig. 2),

R_c - poluprečnik težišne ose (Fig. 2),

r - radius of neutral axis (Fig. 2),

y_o - distance between centroidal axis and neutral axis (Fig. 2),

F_Q - axial force (Fig. 1),

$M_{\max}$ - maximum bending moment,

S_x - static moment of area.

5. NUMERICAL REPRESENTATION OF OPTIMIZATION RESULTS

Optimization is performed using the following optimization algorithms: GRG2 algorithm and EA algorithm, using the Solver Tool tool in the Analysis module in the Ms EXCEL software package; using the *fmincon* functions according to [16] and *ga* according to [17], in MATLAB software package; using the optimization algorithm for the PSO, according to [18], in MATLAB software package.

The optimization parameters are the height *h*, the thickness *d*, the width b_t and the thickness of the base *t*, of T-cross section (Figure 2).

The geometric parameter a (Figure 1) is taken as the input size, according to standard [19] and is not the subject of optimization.

Input optimization parameters are: $F_Q = 100\ kN$, $a = 12.5\ cm$ and $\sigma_d = 8\ kN/cm^2$. A standard crane hook with a load capacity of *10 t* is observed.

The cross sectional area of crane hook at the most critical place, in relation to which the optimal results are compared, is: $A_s = 109.9\ cm^2$, according to [19].

The values of minimum thicknesses *t* and *d* are not less than *1 cm*.

The following tables show the results of optimization (optimal geometric parameters of the cross-section, optimal cross-sectional area and savings) according to the above algorithms (Table 1 ÷ Table 5).

Table 1: Optimal geometric values of T-cross section to GRG2 and savings

b_t (cm)	22.717	Saving (%)
t (cm)	1.000	64.22
d (cm)	1.000	
h (cm)	16.599	
A_T (cm^2)	39.317	

Table 2: Optimal geometric values of T-cross section to EA and savings

b_t (cm)	20.139	Saving (%)
t (cm)	1.000	63.68
d (cm)	1.001	
h (cm)	19.755	
A_T (cm^2)	39.913	

Table 3: Optimal geometric values of T-cross section to fmincon and savings

b_t (cm)	22.717	Saving (%)
t (cm)	1.000	64.22
d (cm)	1.000	
h (cm)	16.600	
A_T (cm^2)	39.317	

Table 4: Optimal geometric values of T-cross section to ga and savings

b_t (cm)	19.718	Saving (%)
t (cm)	1.000	63.15
d (cm)	1.000	
h (cm)	20.779	
A_T (cm^2)	40.501	

Table 5 Optimal geometric values of T-cross section to PSO and savings

b_t (cm)	22.717	Saving (%)
t (cm)	1.000	64.22
d (cm)	1.000	
h (cm)	16.599	
A_T (cm^2)	39.317	

Also, the cases where the thickness d and t are equal (Table 6 ÷ Table 10) are observed.

Table 6: Optimal geometric values of T-cross section to GRG2 and savings

b_t (cm)	22.712	Saving (%)
t=d (cm)	1.000	64.22
h (cm)	16.605	
A_T (cm^2)	39.317	

Table 7: Optimal geometric values of T-cross section to EA and savings

b_t (cm)	22.184	Saving (%)
t=d (cm)	1.000	64.20
h (cm)	17.154	
A_T (cm^2)	39.339	

Tabela 8: Optimal geometric values of T-cross section to fmincon and savings

b_t (cm)	22.717	Saving (%)
t=d (cm)	1.000	64.22
h (cm)	16.600	
A_T (cm^2)	39.317	

Table 9: Optimal geometric values of T-cross section to ga and savings

b_t (cm)	21.033	Saving (%)
t=d (cm)	1.001	64.00
h (cm)	18.495	
A_T (cm^2)	39.561	

Table 10: Optimal geometric values of T-cross section to PSO and savings

b_t (cm)	22.718	saving (%)
t=d (cm)	1.000	64.22
h (cm)	16.599	
A_T (cm^2)	39.317	

What is seen from the previous tables (Table 1 ÷ Table 10) is that they are quite large for the optimal parameters h and b_t. For this reason, additional geometric constraints have been introduced such that the width b_t and the height of the profile H are less than the standard value h_s=*14cm*, according to [19], so that:

$$b_t,\ H \le h_s \tag{25}$$

Based on the relation (25) and with repeating of the optimization procedures, as carried out for the previous tables (Table 1 ÷ Table 10), the following table of results are obtained (Table 11 ÷ Table 20):

Table 11: Optimal geometric values of T-cross section to GRG2 and savings

b_t (cm)	14.000	Saving (%)
t (cm)	2.547	41.91
d (cm)	2.461	
h (cm)	11.453	
A_T (cm^2)	63.840	

Table 12: Optimal geometric values of T-cross section to EA and savings

b_t (cm)	13.999	Saving (%)
t (cm)	2.526	41.89
d (cm)	2.485	
h (cm)	11.471	
A_T (cm^2)	63.867	

Table 13: Optimal geometric values of T-cross section to fmincon and savings

b_t (cm)	14.000	Saving (%)
t (cm)	2.547	41.91
d (cm)	2.461	
h (cm)	11.453	
A_T (cm^2)	63.840	

Table 14: Optimal geometric values of T-cross section to ga and savings

b_t (cm)	13.999	Saving (%)
t (cm)	2.602	41.87
d (cm)	2.408	
h (cm)	11.398	
A_T (cm^2)	63.881	

Table 15: Optimal geometric values of T-cross section to PSO and savings

b_t (cm)	14.000	Saving (%)
t (cm)	2.561	41.91
d (cm)	2.446	
h (cm)	11.439	
A_T (cm^2)	63.843	

Table 16: Optimal geometric values of the T-cross section for same thickness, with GRG2 and savings

b_t (cm)	14.000	Saving (%)
t=d (cm)	2.505	41.89
h (cm)	11.495	
A_T (cm^2)	63.862	

Table 17 Optimal geometric values of the T-cross section for same thickness, with EA and savings

b_t (cm)	13.998	Saving (%)
t=d (cm)	2.506	41.88
h (cm)	11.494	
A_T (cm^2)	63.876	

Table 18: Optimal geometric values of the T-cross section for same thickness, according to fmincon and savings

b_t (cm)	14.000	Saving (%)
t=d (cm)	2.505	41.89
h (cm)	11.495	
A_T (cm^2)	63.862	

Table19: Optimal geometric values of the T-cross section for same thickness, according to ga and savings

b_t (cm)	13.955	Saving (%)
t=d (cm)	2.519	41.70
h (cm)	11.479	
A_T (cm^2)	64.075	

Table 20: Optimal geometric values of the T-cross section for same thickness, according to PSO and savings

b_t (cm)	14.000	Saving (%)
t=d (cm)	2.505	41.89
h (cm)	11.495	
A_T (cm^2)	63.862	

The following figures show the convergence diagrams for the PSO method in the MATLAB software package for all variants, as far as geometric optimization conditions are concerned.

6. CONCLUSION

The optimal geometrical parameters of the T-cross section of the crane hook at the most critical place are calculated for a load capacity of *10 t*, where the hook construction is treated as a curved beam. As a objective function, the cross-sectional area is observed at the most critical place of the hook structure, where the maximum stress limitations are satisfied. The optimization is carried out using the Ms EXCEL software package, GRG2 algorithm and EA optimization algorithm, as well as using the MATLAB software package, using the *fmincon* and *ga* function (genetic algorithm) and applying the particle algorithm (PSO).

The optimization task, the reduction of the cross-sectional area, has been successfully implemented, as can be seen from the results in the previous tables (Table 1 ÷ Table 20).

The choice of appropriate optimization methods shows their justification, as savings of up to 64.22% have been achieved. With a geometric limit, savings of up to 41.91% are achieved.

The geometric limit significantly influences the results of optimization and the achieved savings, as can be seen from the results obtained. For a variant without restrictions, high values for h and b_t are obtained. It has also been shown that for variants both with and without limitation, the requirement of equality of thickness does not affect the value of the optimal surface area of the cross section. In the optimization process without geometric limitations, the minimum thickness of *1 cm* in all cases was obtained as optimum thickness (Table 1 ÷ Table 10). With the restriction variant, as the optimal width and height, limit values were obtained, ie values were very close to the limit values (Table 11 ÷ Table 20). In this variant with a geometric limitation, the optimum values for the thickness t are slightly greater than the thickness d (Table 11 ÷ Table 15), for the variant when the thickness t and d are not equal.

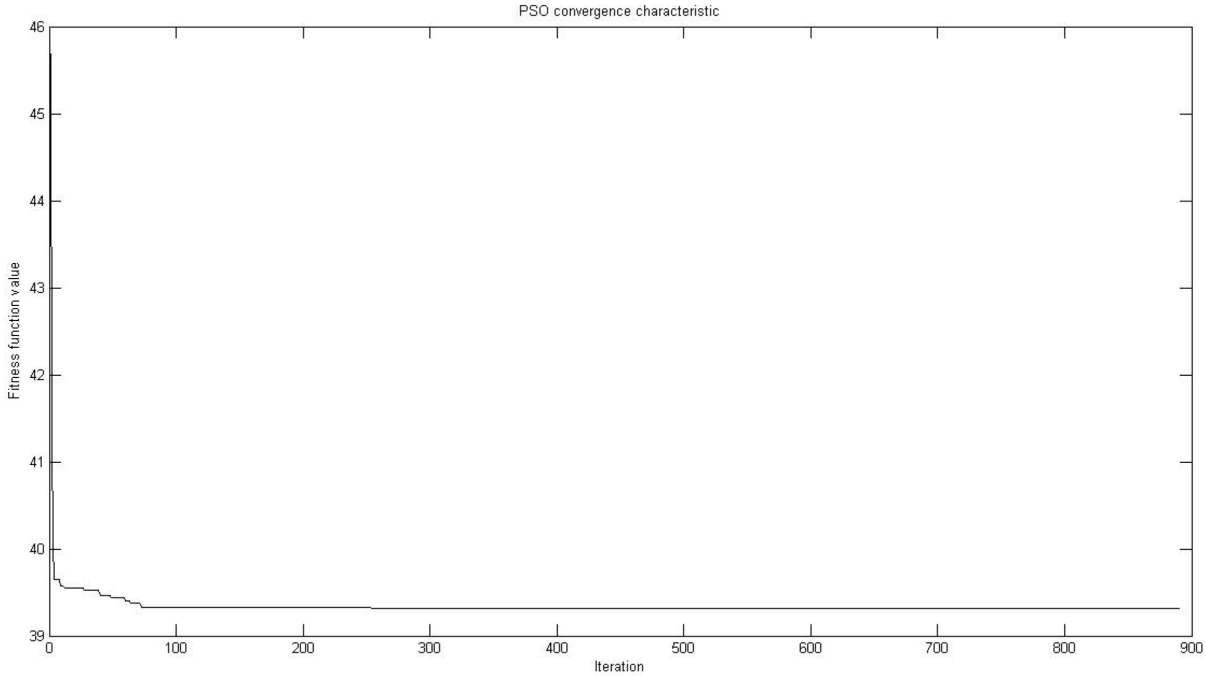

Figure 3: Convergence diagram for PSO and T-cross section

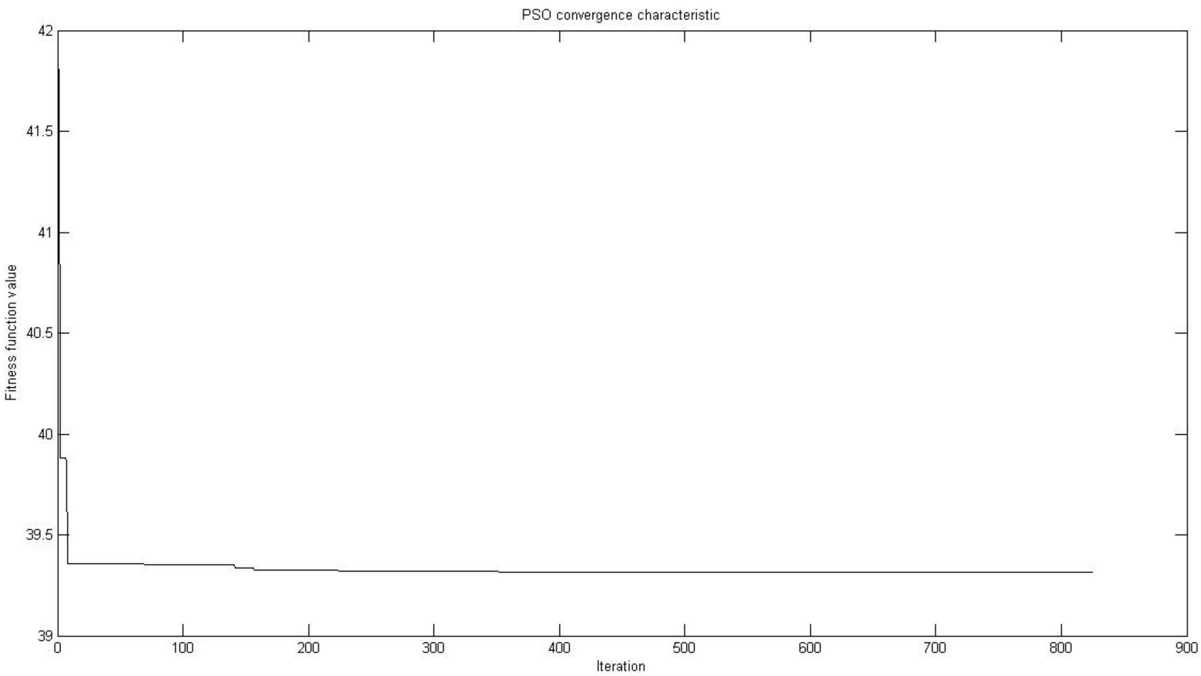

Figure 4: Convergence diagram for PSO and T- cross section with equal ticknesss

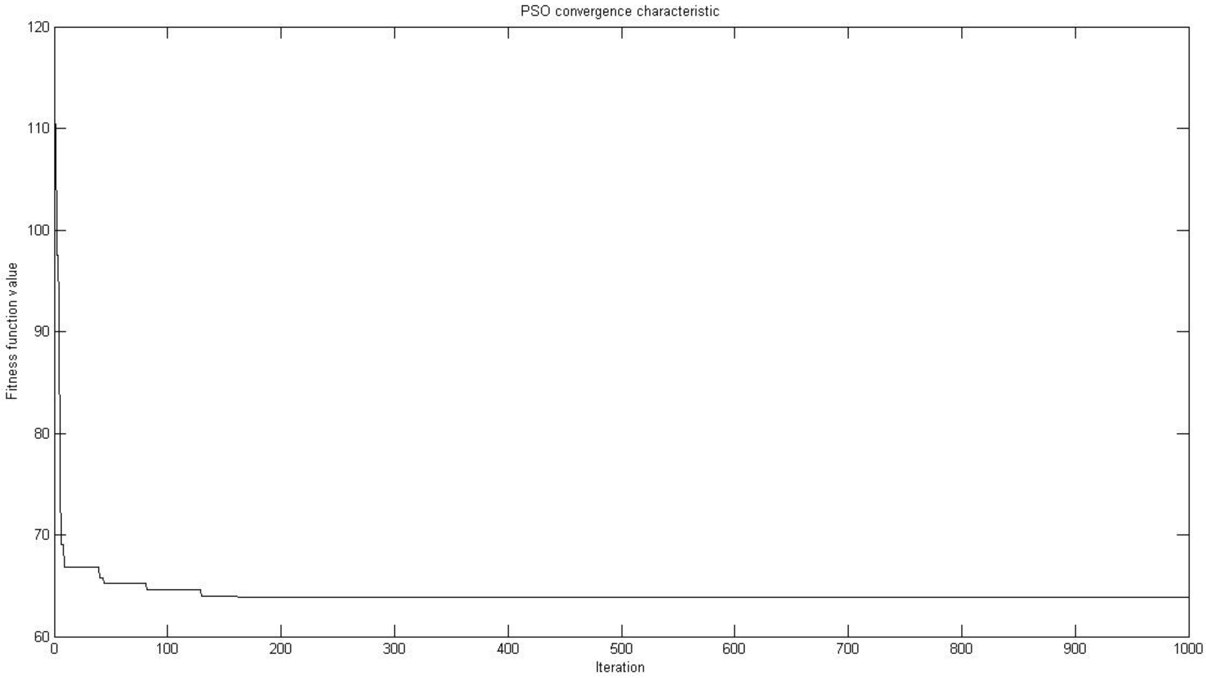

Figure 5: Convergence diagram for PSO and T- cross section, with constraints

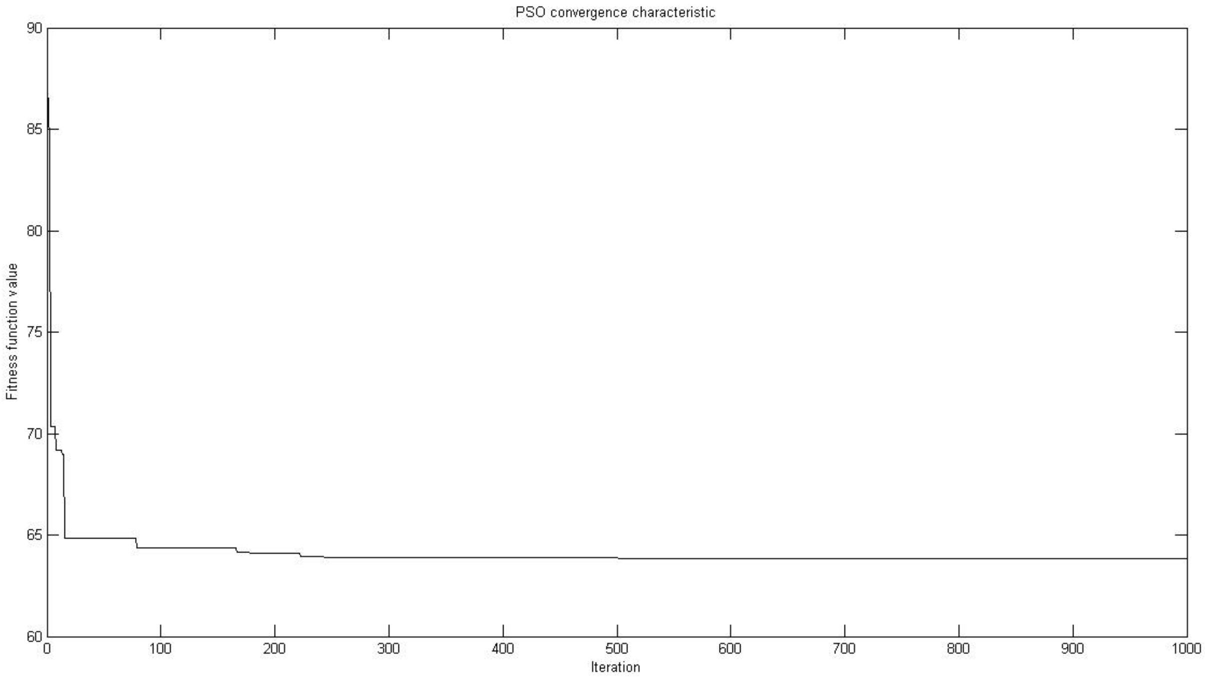

Figure 6: Convergence diagram for PSO and T- cross section, with constraints

As for the applied optimization algorithms, the best results are given by the GRG2 and PSO algorithm, as well as the application of the fmincon function. Something higher values give GA and EA optimization algorithms. The main conclusion based on the analysis and optimization carried out is that the observed T-cross section gives significant savings in the material compared to the standard performance of a crane with a trapezoidal cross-section. Also, the geometric constraint is very important in the optimization process and it is necessary to introduce all the necessary limitations in further analysis, as far as the functionality of the crane hook and the technology are concerned.

For further research in this area, it is necessary to include other geometric parameters of the structure of the crane hook, and also to consider other characteristic sites and segments of the structure of the hook important for analysis. In addition to stress conditions, hook deformation as well as fatigue can be analyzed. It is also necessary to analyze all potential other cross-sectional forms that may be considered, and make their comparison, as well as the types of materials that may be considered. In addition to the analytical solution of the problem, the obtained results can be verified and compared to those obtained on the basis of an FEM in one of the software packages, in order to draw certain conclusions and provide guidance in the analysis and optimization of this type of construction.

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