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Optimization of crane hooks considered as curved beams with different cross-sections – a comparative study using MATLAB

This paper presents the analysis and the optimization of the geometric parameters of different crane hook cross-section types. The study included trapezoidal, rectangular, square, elliptic, circular and T cross-section. The reduction of hook critical cross-section area was set as the primary goal for the optimization process. The criterion of maximum permissible stress is set as the constraint function, while the maximum stress values at the characteristic points were calculated according to Winkler-Bach theory, considering the hook as a curved beam. The optimization procedure was conducted using some metaheuristic optimization methods, in conjunction with known MATLAB functions. The goal of this research was to determine the optimum geometric parameters of mentioned cross-section types and to compare them in other to gain some conclusions and choice recommendations.

Keywords: *Crane Hook, Optimization, Metaheuristic algorithms, MATLAB, Winkler-Bach theory*

1. INTRODUCTION

Crane hooks are the means for lifting the heavy loads and are an integral part of different types of hoists. By proper use of the hoisting equipment, heavy loads can be effectively manipulated, while reducing manual handling operations. On the other side, the use of hoisting equipment and hooks with inadequate geometry and characteristics can lead to malfunctions and heavy accidents. Therefore, the proper choice and usage of this equipment is of great importance.

In this research, obtained optimization results were compared to standard crane hooks according to [1]. The reduction of hook critical cross-section area was set as the primary goal for the optimization process.

Stress and strain analysis of a crane hook and the optimization of its cross-sections were the subject of research of numerous authors, so there are many published papers on this issue [2-12]. The most frequently used approach for such analysis and optimization was finite element method (FEM) [2-9]. Rectangular, trapezoidal, triangular and circular cross-sections were analysed in ANSYS software in [2]. Similarly to previous, rectangular, trapezoidal and circular shapes were analysed in [3], using the same software and for the different payload. Recently, T-section has frequently been included in the analysis. For example, [4] showed the advantage of that cross-section type over circular and trapezoidal type, with various materials used. Similar to this research, the author in [5] presented how maximum stress values are changed in different types of cross-sections while maintaining the same cross-sectional area. Besides stress and strain, the fatigue is frequently used for analysis and optimization of such structure types, as presented in [6, 7]. Also, many authors combined FEM analysis and various numerical optimization procedures [8, 9]. In [8], genetic algorithm (GA) was used to optimize geometric parameters of trapezoidal cross-section, and the verification was done in ANSYS package. Particle Swarm Optimization (PSO) method was used to obtain an optimum shape of a crane hook through a multi-criteria optimization process in [9]. The same method was applied in [10], determining optimum T-section geometric parameters. In [11, 12], the optimization of crane hook cross-sections was done by the analytical approach and some optimization algorithms. Optimized values of cross-sectional areas for trapezoidal, circular, rectangular, triangular, T and I shape were compared in [11], where the authors presented optimization algorithm in detail. Comparative analysis and optimization of various types of cross-sections were conducted in [12], where, besides common types, parabolic and elliptic type were additionally considered. Lagrange multiplier and GRG2 algorithm were used as optimization methods.

The publications mentioned above indicate the significance and justification of the analysis and optimization of these structures. Hence, the goal of this research was to determine the optimum geometric parameters of mentioned cross-section types and to compare them in other to choice recommendations.

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2. OPTIMIZATION PROBLEM

Static analysis of the crane hook critical cross-section was conducted (Fig. 1). The criterion of maximum permissible stress is set as the constraint function, while the maximum stress values at the characteristic points were calculated according to Winkler-Bach theory, considering the hook as a curved beam, [13]. Also, some geometric constraints were taken into account.

The crane hooks within payload range between 5 and 16 tonnes were considered. The study included T (Fig. 2), trapezoidal (Fig. 3), rectangular, square, elliptic (Fig. 4) and circular cross-section. The rectangular and square sections were considered as special cases of trapezoidal shape, while the circular section was considered a special case of elliptic shape.

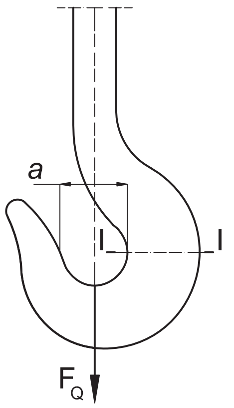

Figure 1. Crane hook

The optimization is based upon stress criterion, according to Winkler-Bach theory, for cross-section characteristic points 1 and 2, (1):

$$\sigma_{1,2} = \frac{F_Q}{A} \pm \frac{M_{max}}{S_x} \cdot \frac{h_1}{R_1} \le \sigma_d \quad (1)$$

The permissible stress is taken within the interval σ_d = 8 - 10 kN/cm^2, for the case of stress check in a model where the hook curvature is not considered. Since the curvature of the hook makes the equivalent stress increase for 20 – 30 %, the permissible stress will also be increased by 20 % in further analysis (adopted value is σ_d = 9,6 kN/cm^2).

The parameters which figure in (1) are calculated in (2-6).

In all cases it is $R_1 = a/2$, $F_Q = Q \cdot g$, $M_{max} = F_Q \cdot R_c$, $S_x = A \cdot y_o$.

$$r = \frac{A}{\int_A \frac{dA}{\rho}} \quad (2)$$

$$h_1 = r - R_1 \quad (3)$$

$$h_2 = R_2 - r \quad (4)$$

$$R_c = R_1 + e_1 \quad (5)$$

$$y_o = R_c - r \quad (6)$$

All necessary relations for calculation of geometric properties for each cross-section type are presented in the following text.

2.1 T cross-section geometric properties

Fig. 2 shows T cross-section with all necessary geometric parameters.

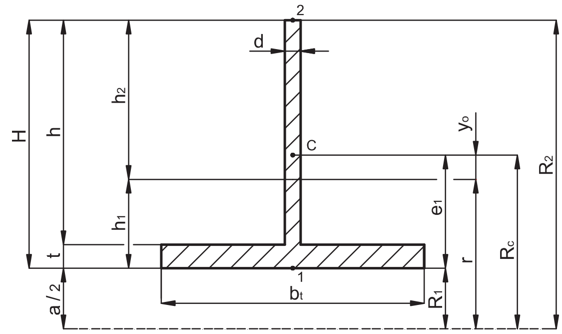

Figure 2. T cross-section

$$A = b_t \cdot t + h \cdot d \quad (7)$$

$$r = b_t \cdot \ln \frac{a + 2 \cdot t}{a} + d \cdot \ln \frac{a + 2 \cdot H}{a + 2 \cdot t} \quad (8)$$

$$e_1 = \frac{b_t \cdot t^2 + 2 \cdot h \cdot d \cdot t + h \cdot d^2}{2 \cdot A} \quad (9)$$

2.2 Trapezoidal cross-section geometric properties

Fig. 3 shows trapezoidal cross-section with all necessary geometric parameters.

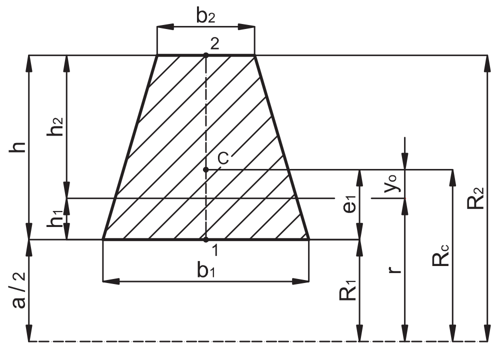

Figure 3. Trapezoidal cross-section

$$A = (b_1 + b_2) \cdot h / 2 \quad (10)$$

$$r = \frac{A}{\left(b_2 + R_2 \frac{b_1 - b_2}{h_1}\right) \cdot \ln \frac{R_2}{R_1} - (b_1 - b_2)} \quad (11)$$

$$e_1 = \frac{h}{3} \cdot \frac{b_1 + 2 \cdot b_2}{b_1 + b_2} \quad (12)$$

The rectangular cross-section is a special case of trapezoidal section, where $b_1=b_2=b$. Square cross-section is a special case of rectangular section, where $b=h$.

2.3 Elliptic cross-section geometric properties

Fig. 4 shows elliptic cross-section with all necessary geometric parameters.

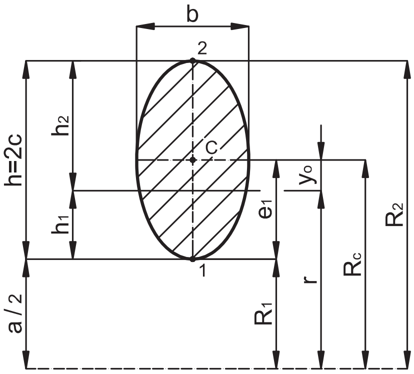

Figure 4. Elliptic cross-section

$$A = b \cdot c \cdot \pi / 2 \tag{13}$$

$$r = \frac{b \cdot \pi}{c} \cdot \left(R_c - \sqrt{R_c^{\,2} - c^2} \right) \tag{14}$$

The circular cross-section is a special case of elliptic section, where $2c = b$.

3. NUMERICAL REPRESENTATION OF THE OBTAINED RESULTS

The optimization procedure was conducted using some metaheuristic optimization methods, e.g. Firefly Algorithm (FA), Cuckoo Search algorithm (CS), Simulated Annealing (SA) and Harmony Search (HS), in conjunction with known MATLAB functions *fmincon* and *pattern search*. It should be mentioned that the metaheuristic algorithms were utilized in their source form, without any modifications.

Geometrical data for the cross-sections of the crane hooks are given in Table 1, according to [1].

Table 1. Crane hooks geometrical data

Q	a	b_1	h_s	b_2	A
5	8	7.1	9	2.84	44.73
6.3	9	8	10	3.2	56.00
8	10	9	11.2	3.6	70.56
10	11.2	10	12.5	4.0	87.50
12.5	12.5	11.2	14	4.48	109.76
16	14	12.5	16	5.0	140.00

As the constraints within the optimization process, it was taken that the heights and the widths of the cross-sections must be less than standard profile height h_s (Table 1). Also, it was taken that the variables cannot be less than 1 cm.

The values of optimized variables are given in [cm] and cross-sectional areas are given in [cm^2]. In addition, a percentage deviations between optimized and standard areas are given in the last column, according to [1].

The following tables (Table 2 - Table 7) present the optimization results for T cross-section.

Table 2. T cross-section optimization results (FA)

Q	b_t	t	d	h	A	%
5	9.00	1.41	1.81	7.59	26.38	41.0
6.3	10.00	1.80	1.87	8.20	33.35	40.4
8	11.20	2.21	2.00	8.99	42.80	39.3
10	12.42	2.15	3.32	9.77	59.23	32.3
12.5	14.00	2.56	2.70	11.44	66.73	39.2
16	16.00	2.90	2.79	13.10	82.85	40.8

Table 3. T cross-section optimization results (CS)

Q	b_t	t	d	h	A	%
5	9.00	1.61	1.53	7.39	25.76	42.4
6.3	10.00	1.85	1.82	8.15	33.31	40.5
8	11.20	2.10	2.10	9.10	42.66	39.5
10	12.50	2.37	2.37	10.13	53.61	38.7
12.5	14.00	2.63	2.63	11.37	66.66	39.3
16	16.00	2.90	2.79	13.10	82.84	40.8

Table 4. T cross-section optimization results (SA)

Q	b_t	t	d	h	A	%
5	8.96	1.65	1.52	7.35	25.91	42.1
6.3	10.00	1.78	1.91	8.22	33.47	40.2
8	11.18	2.12	2.11	9.07	42.82	39.3
10	12.50	2.44	2.31	10.06	53.74	38.6
12.5	13.99	2.59	2.68	11.41	66.75	39.2
16	15.98	2.88	2.83	13.12	83.05	40.7

Table 5. T cross-section optimization results (HS)

Q	b_t	t	d	h	A	%
5	8.94	1.75	1.44	7.25	26.1	41.6
6.3	10.00	1.77	1.91	8.23	35.52	36.6
8	11.20	2.21	2.16	8.80	44.00	37.6
10	12.50	2.35	2.39	10.15	53.74	38.6
12.5	14.00	2.50	2.78	11.50	66.91	39.0
16	16.00	2.73	2.98	13.27	83.23	40.6

Table 6. T cross-section optimization results (fmincon)

Q	b_t	t	d	h	A	%
5	9.00	1.61	1.53	7.39	25.76	42.4
6.3	10.00	1.85	1.82	8.15	33.31	40.5
8	11.20	2.10	2.10	9.10	42.66	39.5
10	12.50	2.36	2.38	10.14	53.61	38.7
12.5	14.00	2.63	2.63	11.37	66.66	39.3
16	16.00	2.90	2.79	13.10	82.84	40.8

Table 7. T cross-section opt. results (pattern search)

Q	b_t	t	d	h	A	%
5	9.00	1.69	1.46	7.30	25.89	42.1
6.3	10.00	2.11	1.64	7.89	33.98	39.3
8	11.20	2.17	2.11	9.03	43.29	38.6
10	12.45	2.55	2.62	9.54	56.79	35.1
12.5	13.96	2.99	2.40	11.01	68.10	38.0
16	15.94	3.18	2.59	12.82	83.94	40.0

The following tables (Table 8 - Table 13) present the optimization results for trapezoidal cross-section.

Table 8. Trapezoidal cross-section optimization results (FA)

Q	b_1	b_2	h	A	%
5	7.69	1.50	9.00	41.38	7.5
6.3	9.06	1.33	10.00	51.92	7.3
8	10.66	1.05	11.20	65.57	7.1
10	11.81	1.32	12.50	82.08	6.2
12.5	11.92	3.10	13.96	104.89	4.4
16	13.83	2.66	16.00	131.91	5.8

Table 9. Trapezoidal cross-section optimization results (CS)

Q	b_1	b_2	h	A	%
5	8.11	1.00	9.00	41.00	8.3
6.3	9.35	1.00	10.00	51.75	7.6
8	10.71	1.00	11.20	65.56	7.1
10	12.12	1.00	12.50	82.01	6.3
12.5	13.53	1.10	14.00	102.43	6.7
16	15.11	1.20	16.00	130.50	6.8

Table 10. Trapezoidal cross-section optimization results (SA)

Q	b_1	b_2	h	A	%
5	8.11	1.00	9.00	41.01	8.3
6.3	9.36	1.00	9.99	51.76	7.6
8	10.71	1.00	11.20	65.57	7.1
10	12.07	1.06	12.50	82.02	6.3
12.5	13.58	1.05	14.00	102.43	6.7
16	15.02	1.30	16.00	130.52	6.8

Table 11. Trapezoidal cross-section optimization results (HS)

Q	b_1	b_2	h	A	%
5	8.46	1.42	8.45	41.79	6.6
6.3	9.10	1.27	10.00	52.06	7.0
8	10.29	2.81	10.43	68.32	3.2
10	11.67	1.48	12.50	82.23	6.0
12.5	12.38	2.42	14.00	103.59	5.6
16	14.31	2.07	16.00	131.05	6.4

Table 12. Trapezoidal cross-section optimization results (fmincon)

Q	b_1	b_2	h	A	%
5	8.11	1.00	9.00	41.00	8.3
6.3	9.35	1.00	10.00	51.75	7.6
8	10.71	1.00	11.20	65.56	7.1
10	12.12	1.00	12.50	82.01	6.3
12.5	13.53	1.10	14.00	102.43	6.7
16	15.11	1.20	16.00	130.50	6.8

Table 13. Trapezoidal cross-section optimization results (pattern search)

Q	b_1	b_2	h	A	%
5	8.11	1.00	9.00	41.00	8.3
6.3	9.35	1.00	10.00	51.75	7.6
8	8.84	3.57	11.20	69.47	1.5
10	10.07	3.71	12.50	86.10	1.6
12.5	13.62	1.01	14.00	102.43	6.7
16	14.00	2.44	16.00	131.54	6.0

The following tables (Table 14 - Table 19) present the optimization results for rectangular cross-section.

Table 14. Rectangular cross-section optimization results (FA)

Q	b	h	A	%
5	5.64	9.00	50.79	-13.5
6.3	6.41	10.00	64.12	-14.5
8	7.26	11.20	81.32	-15.2
10	8.13	12.50	101.7	-16.2
12.5	9.08	14.00	127.06	-15.8
16	10.17	15.95	162.23	-15.9

Table 15. Rectangular cross-section optimization results (CS)

Q	b	h	A	%
5	5.64	9.00	50.79	-13.5
6.3	6.41	10.00	64.11	-14.5
8	7.26	11.20	81.32	-15.2
10	8.14	12.50	101.70	-16.2
12.5	9.08	14.00	127.06	-15.8
16	10.13	16.00	162.15	-15.8

Table 16. Rectangular cross-section optimization results (SA)

Q	b	h	A	%
5	5.64	9.00	50.79	-13.5
6.3	6.41	10.00	64.12	-14.5
8	7.26	11.20	81.33	-15.3
10	8.14	12.49	101.72	-16.3
12.5	9.08	13.99	127.07	-15.8
16	10.14	16.00	162.16	-15.8

Table 17. Rectangular cross-section optimization results (HS)

Q	b	h	A	%
5	7.08	7.45	52.72	-17.9
6.3	7.83	8.44	66.13	-18.1
8	7.30	11.15	81.44	-15.4
10	9.26	11.19	103.78	-18.6
12.5	11.23	11.70	131.29	-19.6
16	12.97	12.98	168.44	-20.3

Table 18. Rectangular cross-section optimization results (fmincon)

Q	b	h	A	%
5	5.64	9.00	50.79	-13.5
6.3	6.41	10.00	64.11	-14.5
8	7.26	11.12	81.32	-15.2
10	8.14	12.5	101.70	-16.2
12.5	9.08	14.00	127.06	-15.8
16	10.13	16.00	162.15	-15.8

Table 19. Rectangular cross-section optimization results (pattern search)

Q	b	h	A	%
5	5.75	8.86	50.91	-13.8
6.3	7.05	9.21	64.99	-16.1
8	8.10	10.12	82.59	-17.0
10	8.17	12.47	101.83	-16.4
12.5	9.08	14.00	127.06	-15.8
16	10.13	16.00	162.15	-15.8

Since there is only one variable for square cross-section, by solving (1) it is obtained (Table 20):

Table 20. Square cross-section optimization results

Q	b	A	%
5	7.27	52.85	-18.2
6.3	8.16	66.62	-19.0
8	9.18	84.36	-19.6
10	10.27	105.49	-20.6
12.5	11.48	131.81	-20.1
16	12.98	168.383	-20.3

The optimization of the elliptic cross-section has given no results because of set geometric constraints. Without them, the following results are obtained (Table 21 – Table 26):

Table 21. Elliptic cross-section optimization results (FA)

Q	b	c	A	%
5	6.80	6.46	69.05	-54.4
6.3	8.21	6.73	86.91	-55.2
8	9.50	7.39	110.37	-56.4
10	10.15	8.66	137.98	-57.7
12.5	11.48	9.56	172.45	-57.1
16	12.50	11.25	220.92	-57.8

Table 22. Elliptic cross-section optimization results (CS)

Q	b	c	A	%
5	7.32	6.00	68.98	-54.2
6.3	8.20	6.75	86.91	-55.2
8	9.37	7.50	110.36	-56.4
10	10.46	8.40	137.95	-57.7
12.5	11.71	9.37	172.44	-57.1
16	13.38	10.50	220.73	-57.7

Table 23. Elliptic cross-section optimization results (SA)

Q	b	c	A	%
5	7.34	5.98	68.98	-54.2
6.3	8.25	6.70	86.91	-55.2
8	9.31	7.55	110.36	-56.4
10	10.47	8.39	137.95	-57.7
12.5	11.70	9.38	172.44	-57.1
16	13.40	10.49	220.73	-57.7

Table 24. Elliptic cross-section optimization results (HS)

Q	b	c	A	%
5	7.52	5.84	68.99	-54.2
6.3	7.12	7.79	87.25	-55.8
8	6.45	11.21	113.70	-61.1
10	14.36	6.22	140.33	-60.4
12.5	13.35	8.25	172.98	-57.6
16	14.86	9.47	221.17	-58.0

Table 25. Elliptic cross-section optimization results (fmincon)

Q	b	c	A	%
5	7.32	6.00	68.98	-54.2
6.3	8.20	6.75	86.91	-55.2
8	9.37	7.50	110.36	-56.4
10	10.46	8.40	137.95	-57.7
12.5	11.71	9.37	172.44	-57.1
16	13.38	10.50	220.72	-57.7

Table 26. Elliptic cross-section optimization results (pattern search)

Q	b	c	A	%
5	4.83	9.43	71.61	-60.1
6.3	7.13	7.79	87.24	-55.8
8	5.62	13.26	117.07	-65.9
10	7.21	12.54	142.08	-62.4
12.5	7.60	15.04	179.64	-63.7
16	13.26	10.69	222.66	-59.0

Since there is only one variable for circular cross-section, by solving (1) it is obtained (Table 27):

Table 27. Circular cross-section optimization results

Q	R	A	%
5	4.88	74.82	-67.3
6.3	5.41	92.05	-64.4
8	6.04	114.50	-62.3
10	6.70	140.94	-61.1
12.5	7.45	174.18	-58.7
16	8.39	221.24	-58.0

4. CONCLUSION

The optimization procedures were successfully applied in the considered case, in order to decrease the cross-sectional area of the crane hook at its critical section.

It can be noted that the smallest cross-sectional area was obtained for T section, for given conditions and constraints. Savings are up to 42,4 % (Table 2 – Table 7), which is almost identical with achieved savings in the paper [10], for somewhat different considered conditions and the same geometric constraints. As in the paper [10], the *fmincon* method gave the maximum savings.

Less savings are achieved with trapezoidal cross-section due to geometric constraint, and they are up to 8,3 % (Table 8 – Table 13). In comparison with the results from paper [12], it can be seen that, for certain ratios b_2/b_1, the same saving value is achieved by usage of GRG2 method.

The rectangular cross-section, due to the geometric constraints, yielded greater areas in relation to considered areas (Table 14 – Table 19), where cross-sectional area exceeded the limit by 3,5 – 20,3 %. For the same geometric constraints, with somewhat different conditions and utilization of GRG2 procedure, this overrun was 13,1 % in paper [12]. The square cross-section gave a little higher area values than rectangular cross-section (Table 20).

The elliptic cross-section gave very unfavourable results, both with height and the area of the cross-section (Table 21 – Table 26). For the considered conditions, the overruns are even 65,9 %. In the paper [12], for somewhat different conditions, the value of crane hook cross-sectional area is also high. The circular cross-section yields even worse results in comparison to the elliptic one (Table 27).

The most favourable results for the considered optimization problem are obtained with the appliance of CS method and *fmincon* function. A bit worse results are achieved with HS method, as well as with *pattern search* function, depending from the case. Quite good results are obtained by usage of FA method and SA method. For these types of structures, T and trapezoidal cross-sections (and similar shapes such as triangular shape) should be exploited.

Further researches should include all potential cross-sectional shapes and materials as well, in order to get lighter crane hooks. Aside the stress states, the deformations and the fatigue of the crane hooks can be analysed.

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