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WEIGHT MINIMIZATION OF THE HYDRAULIC PRESS FRAME WITH METAHEURISTIC ALGORITHMS

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Abstract: *This study presents the lightweight optimization design of the cross-sectional areas of the welded press columns (I-profile) and the welded press traverse (box profile) used in hydraulic press machines for panel production. The objective function is the total weight of the press frame structure for this optimization problem. The research considers several constraint functions, including the maximum stresses at key points of the I and box profiles, the stability of the press traverse, the maximum stress in the welded connections, and the maximum deflection of the press traverse. Also, some geometric constraints are included. Stress and stability checks are performed in accordance with Eurocode. The obtained results are verified on one example of the hydraulic press machine used in panel production and compared with results from previous research. Savings in the weight of the press frame structure are shown in terms of the type of materials and geometrical limitations. Two physics-based optimization methods are chosen for this research: the Flow Direction Algorithm (FDA) and the Weighted Mean of Vectors (INFO) algorithm. A comparison between the results obtained from both algorithms is also performed in this research.*
Keywords: Hydraulic Press Frames, Lightweight Design, Metaheuristic, Optimization, Eurocode

1. INTRODUCTION

Press machines are widely used in various industrial manufacturing sectors to produce items quickly and cost-effectively. For adequate production frequency and dimensional accuracy of articles, the press's carrying structure must have sufficient stiffness and stability. To achieve the lowest possible weight of the press's carrying structure, while ensuring necessary strength, stiffness, and stability criteria are met, optimization is essential.
Analysis and optimization of the weight of the C-frame press carrying structure are a frequent topic of research [1-5]. In the paper [1], ANSYS software was used to reduce the weight of a 100-ton mechanical press structure. Similarly, in paper [2], ANSYS was utilized in the case of a 200-ton hydraulic press, achieving a weight reduction of 12.62%. Following this approach, the study in paper [3] utilized ANSYS to reduce the thickness of the plate in the press carrying structure, resulting in a cost reduction. Finite Element Analysis (FEA) plays a crucial role in the design of carrying structures. For example, in [4], there is an illustration of optimizing the carrying structure for a 10-ton pneumatic press. This example features both a C-frame press and an improved solution using an H-frame press.

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The FEA process was conducted using ANSYS software. A comparison of the performance of C-type and 4-column type hydraulic presses used in the automotive industry was performed in the paper [5], where ANSYS was used for FEA, while the models were created using CATIA software. The 4-column type was analyzed in [6], using the example of a 100-ton hydraulic press. ANSYS was also successfully applied in the paper [7] to optimize the weight of the upper beam of a press used in the ginning industry. On this occasion, the 3D model was created using Solid Edge software.
In addition to using FEA, the optimization of carrying structures can also be conducted analytically. In the paper [8], the frame structure of the press for panel production was optimized using two metaheuristic algorithms. The use of evolutionary optimization algorithms, neural networks, and other Artificial Intelligence (AI) methods is increasingly applied across various fields. The review paper [9] discusses the application of AI in frame structure optimization.
This study optimizes the weight of the frame structure for the panel production press frame according to Eurocode, comparing the results with those from [8]. Two new generation algorithms inspired by physics were selected as optimization methods: the Weighted Mean of Vectors (INFO) algorithm, [10] and the Flow Direction Algorithm (FDA), [11]. Also, it will be shown how the optimal weight and geometric parameters (variables) of the press frame structure change with the change of some input parameters.

2. OPTIMIZATION PROBLEM

This research aims to optimize (minimize) the total weight (the objective function) of the press frame structure (Figure 1), where all necessary conditions (constraints) must be fulfilled. The steel structure consists of two columns (welded I-profiles, S235 material) and a traverse beam (welded box profile, S355 material), [8]. All geometric parameters for the press structure, the I-profile, and the box profile are explained in detail in the paper [8], where L=670 cm is the length of the press traverse, $H=0.5\cdot L$ is the height of the press column, and $a=0.3\cdot L$, $b=0.7\cdot L$ are the positions of the hydro cylinders, respectively. Also, the value for the coefficient of the ratio between the rigidity of the traverse and the column of the press frame is $k\approx 2.5$ (for observed example), and must be lower than the permissible one (k_d).

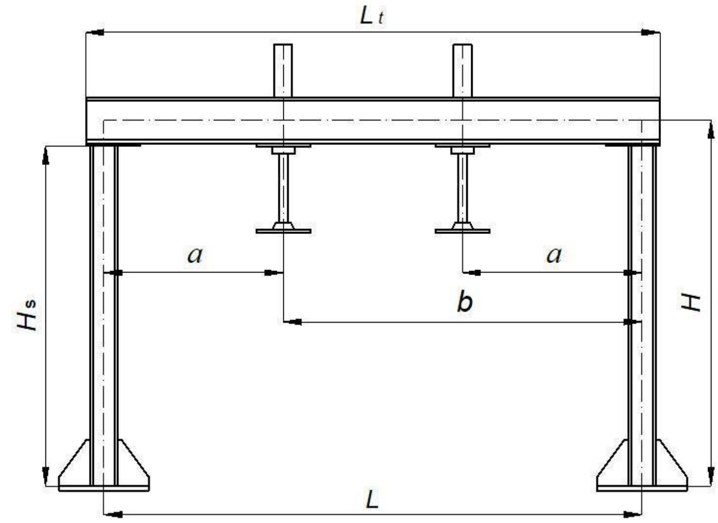

Figure 1. The steel structure of the press frame with hydro cylinders
Source: *[8]*

Optimization variables are: b_1, h_1, t_1, d_1, b_{2o}, h_2, t_2, d_2, a_{ws}, a_{wt},
where b_1 is the flange width of the welded I-profile, h_1 is the web height of the welded I-profile, t_1 is the flange thickness of the welded I-profile, d_1 is the web thickness of the welded I-profile, b_{2o} is the inner width of the welded box profile, h_2 is the web height of the welded box profile, t_2 is the flange thickness of the welded box profile, d_2 is the web thickness of the welded box profile, $a_{ws} \leq$

$0.7 \cdot min(t_1,d_1)$ is the weld throat thickness of the welded I-profile, and $a_{wt} \leq 0.7 \cdot min(t_2,d_2)$ is the weld throat thickness of the welded box profile, [8].

2.1 The objective function

Minimization of the total weight of the frame structure (Figure 1) implies minimizing the cross-sectional areas of the columns, the traverse beam, and the weld throat sizes. The objective function (M_p) is defined in the following way:

$$M_p = \rho \cdot [2 \cdot (A_s + A_{ws}) \cdot H_s + (A_t + A_{wt}) \cdot L_t] \tag{1}$$

where ρ=7850 kg/m^3 is the density of the press frame material, A_s, A_t are cross-sectional areas of I-profile and the box profile, respectively, A_{ws}, A_{wt} are cross-sectional areas of the weld throats of I-profile and the box profile, respectively, L_t is the total length of the press traverse, and H_s is the total height of the press column, as shown in Figure 1 and [8].

2.2 Constraints

In this research, it is necessary to satisfy several design criteria. The criteria relate to the strength of the press segments and their welded connections, the local stability of the press traverse, and the rigidity of the press traverse. For strength criteria, the maximum stresses (σ_r) at key points of I-profiles and the box profile must be less than the critical stresses (σ_c). The values of the maximum stresses are determined as shown in [8], while the critical stresses are determined according to Eurocode [12]:

$$\sigma_r \leq \sigma_c = \frac{f_y}{\upsilon_1 \cdot \gamma_{M1}} \tag{2}$$

where f_y is the yield strength of the press frame material, γ_{M1}=1.1 is the particular partial factor for the press frame material, and υ_1=1.5 is the factored load coefficient for load case 1.
Similar to the previous, the maximum stresses in welded joints of I-profiles and the box profile (σ_{rw}) must be less than the critical stresses (σ_{cw}). The values of the maximum stresses in welded joints are determined as shown in [8], while the critical stresses in welded joints are determined according to Eurocode [13]:

$$\sigma_{rw} \leq \sigma_{cw} = \frac{f_u}{\sqrt{3} \cdot \beta_w \cdot \gamma_{M2}} \tag{3}$$

where f_u is the ultimate strength for the press frame material, γ_{M2}=1.25 is the partial safety factor for welds, and β_w=0.8 is the appropriate correlation factor, [13].
When analyzing the press traverse as a simple beam subjected to forces from the hydro cylinders, it is essential to assess the stability of the box girder plates. According to Eurocode, the following stability conditions must be satisfied for both the web and the flange, respectively, [12]:

$$\frac{h_2 - 2 \cdot a_{wt}}{d_2} \leq 124 \cdot \sqrt{\frac{23.5}{f_{yt}}} \tag{4}$$

$$\frac{b_{2o}}{t_2} \leq 42 \cdot \sqrt{\frac{23.5}{f_{yt}}} \tag{5}$$

where f_{yt} is the yield strength for the press traverse material.

In the stiffness conditions, the press traverse is also considered as a simple beam, where the following condition must be met:

$$f_{max} = \frac{p \cdot D_p{}^2 \cdot \pi \cdot L^3}{24 \cdot E \cdot I_{xt}} \cdot \left(\frac{a}{L}\right) \cdot \left[\frac{3}{4} - \left(\frac{a}{L}\right)^2\right] \leq K_p \cdot L \quad (6)$$

where f_{max} is the maximum deflection of the traverse beam, p=100 bar is the working pressure for the press machine, D_p=14 cm is the piston diameter of a hydro cylinder, E=21000 kN/cm^2 is the elastic modulus of the traverse material, I_{xt} is the axial moment of inertia about x-axis for the box profile, and K_p=1/1000 is the coefficient of rigidity of the traverse beam, [8].

3. OPTIMIZATION RESULTS

In this research, two metaheuristic algorithms inspired by physics were chosen as methods of optimization, the Weighted Mean of Vectors (INFO) algorithm [10] and the Flow Direction Algorithm (FDA), [11]. A detailed description of both algorithms can be found in the mentioned papers. The optimization was carried out using the methods mentioned above in the MATLAB software on one example of a hydraulic press machine for panel production. Control parameters for both algorithms are: 100 – the population size, 1000 – the maximum number of iterations. The input and initial data in the optimization procedure are: M_{p1}=1598.07 kg, $b_{2o,min}$=20 cm, f_{yt}=35.5 kN/cm^2, f_{ut}=49 kN/cm^2, f_{ys}=23.5 kN/cm^2, f_{us}=36 kN/cm^2, and k_d=2.5,
where M_{p1} is the weight of the frame structure for the considered example of a hydraulic press.

The bounds (the lower and the upper limits) of the variables are: $15 \leq b_1 \leq 30$, $20 \leq h_1 \leq 40$, $0.6 \leq t_1$, $t_2 \leq 4$, $0.5 \leq d_1$, $d_2 \leq 3$, $b_{2o,min} \leq b_{2o} \leq 30$, $30 \leq h_2 \leq 70$, $0.3 \leq a_{ws}$, $a_{wt} \leq 0.7$, where $b_{2o,min}$ is the minimum value for the inner width of the welded box-profile.
The dimensions of the variables are in centimetres, while the weight is in kilograms. Seven cases were considered, as in the study [8]. First, the material of the press traverse was changed (Case 1, f_{yt}=35.5 kN/cm^2, f_{ut}=49 kN/cm^2, Case 2, f_{yt}=27.5 kN/cm^2, f_{ut}=43 kN/cm^2, and Case 3, f_{yt}=23.5 kN/cm^2, f_{ut}=36 kN/cm^2), then the inner width of the press traverse (Case 3, b_{2o}=20 cm, Case 4, b_{2o}=18 cm, and Case 5, b_{2o}=16 cm), and finally the coefficient k_d (Case 5, k_d=2.5, Case 6, k_d=3, and Case 7, k_d=4).
Tables 1 and 2 present the optimization results for all cases, detailing the optimal geometric parameters and the optimal weight achieved using both algorithms. A greater saving in materials was achieved in this case by using the exact expressions defined by the Eurocode for the stability criteria of the plates. In contrast, the study referenced as [8] relied on specific recommendations regarding the ratios of the heights and thicknesses of the plates, rather than following the expressions according to the appropriate standard.
It is noted that changing the inner width (b_{2o}) does not have a major impact on the optimal weight (Case 3 – Case 5, Table 1), while changing the type of traverse material, as well as the k_d coefficient, has a significant impact on the results obtained (Tables 1 and 2). The minimum set values were obtained as the optimal values for the web thickness of the I-profile (d_1), as well as the weld throat thickness of the I-profile (a_{ws}). Also, the maximum set values were obtained as the optimal values for the height of the I-profile (h_1) and the box profile (h_2) in almost all cases (Tables 1 and 2). In most cases, the INFO algorithm achieves better results compared to the FDA (Tables 1 and 2).
Tables 3 and 4 present adopted values for optimal geometric parameters, weight, and material savings using both algorithms. The plate thicknesses are rounded to conform to standard values for plates.

Table 1. The optimal geometric parameters and optimal weight for the INFO algorithm

Source: *original copyright*

Case	b_1	h_1	t_1	d_1	b_{2o}	h_2	t_2	d_2	a_{ws}	a_{wt}	M_p
1	15.000	40.00	1.476	0.500	20.000	70.00	1.139	0.684	0.300	0.473	1148.50
2	15.000	40.00	1.476	0.500	20.014	70.00	1.236	0.603	0.300	0.418	1103.93
3	15.000	40.00	1.476	0.500	20.000	70.00	1.292	0.558	0.300	0.373	1079.10

Case	b_1	h_1	t_1	d_1	b_{2o}	h_2	t_2	d_2	a_{ws}	a_{wt}	M_p
4	15.000	40.00	1.476	0.500	18.000	70.00	1.406	0.560	0.300	0.300	1077.97
5	15.001	40.00	1.475	0.500	16.000	70.00	1.548	0.558	0.300	0.376	1076.42
6	15.021	40.00	1.210	0.500	16.000	70.00	1.548	0.558	0.300	0.389	1038.62
7	22.180	40.00	0.600	0.500	16.000	70.00	1.547	0.559	0.300	0.360	991.75

Table 2. The optimal geometric parameters and optimal weight for the FDA algorithm
Source: *original copyright*

Case	b_1	h_1	t_1	d_1	b_{2o}	h_2	t_2	d_2	a_{ws}	a_{wt}	M_p
1	15.869	40.00	1.400	0.500	20.000	69.98	1.137	0.687	0.300	0.316	1149.46
2	15.000	40.00	1.476	0.500	20.126	70.00	1.228	0.605	0.300	0.320	1104.11
3	16.048	40.00	1.386	0.500	20.005	70.00	1.291	0.559	0.300	0.354	1079.83
4	15.004	40.00	1.476	0.500	18.000	70.00	1.407	0.560	0.300	0.306	1077.96
5	15.031	40.00	1.473	0.500	19.697	70.00	1.308	0.558	0.300	0.381	1078.94
6	15.041	40.00	1.208	0.500	16.332	70.00	1.521	0.560	0.300	0.300	1038.98
7	22.088	39.92	0.602	0.500	16.369	70.00	1.520	0.558	0.300	0.373	991.71

Table 3. Adopted values for optimal geometric parameters, weight and savings for the INFO algorithm
Source: *original copyright*

Case	$b_{1,op}$	$h_{1,op}$	$t_{1,op}$	$d_{1,op}$	$b_{2o,op}$	$h_{2,op}$	$t_{2,op}$	$d_{2,op}$	$a_{ws,op}$	$a_{wt,op}$	$M_{p,op}$	Savings (%)
1	15.0	40.0	1.5	0.5	20.0	70.0	1.2	0.7	0.3	0.5	1182.16	26.03
2	15.0	40.0	1.5	0.5	20.0	70.0	1.4	0.6	0.3	0.4	1147.36	28.20
3	15.0	40.0	1.5	0.5	20.0	70.0	1.4	0.6	0.3	0.4	1147.36	28.20
4	15.0	40.0	1.5	0.5	18.0	70.0	1.4	0.6	0.3	0.3	1115.23	30.21
5	15.0	40.0	1.5	0.5	16.0	70.0	1.6	0.6	0.3	0.4	1128.35	29.39
6	15.0	40.0	1.2	0.5	16.0	70.0	1.6	0.6	0.3	0.4	1085.49	32.07
7	22.2	40.0	0.6	0.5	16.0	70.0	1.6	0.6	0.3	0.4	1040.26	34.91

Table 4. Adopted values for optimal geometric parameters, weight and savings for the FDA algorithm
Source: *original copyright*

Case	$b_{1,op}$	$h_{1,op}$	$t_{1,op}$	$d_{1,op}$	$b_{2o,op}$	$h_{2,op}$	$t_{2,op}$	$d_{2,op}$	$a_{ws,op}$	$a_{wt,op}$	$M_{p,op}$	Savings (%)
1	15.9	40.0	1.4	0.5	20.0	70.0	1.2	0.7	0.3	0.4	1178.65	26.25
2	15.0	40.0	1.5	0.5	20.1	70.0	1.4	0.6	0.3	0.4	1148.93	28.11
3	16.1	40.0	1.4	0.5	20.0	70.0	1.4	0.6	0.3	0.4	1147.50	28.19
4	15.0	40.0	1.5	0.5	18.0	70.0	1.4	0.6	0.3	0.3	1115.23	30.21
5	15.0	40.0	1.5	0.5	19.7	70.0	1.4	0.6	0.3	0.4	1142.66	28.50
6	15.0	40.0	1.2	0.5	16.3	70.0	1.6	0.6	0.3	0.3	1090.80	31.79
7	22.1	39.9	0.6	0.5	16.4	70.0	1.6	0.6	0.3	0.4	1046.49	34.52

4. CONCLUSION

In this paper, the total weight (the objective function) of the press steel structure was optimized (minimized) according to Eurocode. The press structure is composed of two columns (I-girder) and a traverse beam (box girder). Ten geometric parameters were used as the variables in the optimization process. The maximum stresses at key points of the I and box profiles, the stability of plates of the press traverse, the maximum stress in the welded connections, and the maximum deflection of the press traverse were used as constraints. The optimization procedure was performed using two physics-inspired algorithms, the Flow Direction Algorithm (FDA) and the Weighted Mean of Vectors

(INFO) algorithm, in MATLAB software. One hydraulic press machine used in panel production served as the example for the optimization process.
The justification for using the proposed procedure and algorithms indicates significant material savings, ranging from 26.03% to 34.91% for the INFO algorithm (as shown in Table 3) and from 26.25% to 34.52% for the FDA algorithm (as shown in Table 4). Also, greater savings were achieved compared to the previous research [8]. Both algorithms were very successful in solving the presented optimization problem, which involved a large number of variables and constraints.

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