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Hydraulic press design under different loading conditions using finite element analysis

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ABSTRACT

In this study, a suitable hydraulic press having four-column is designed and the stress distribution is calculated using both analytical and finite element methods under different loading conditions. Three different loading types, axial, eccentric and oblique, are considered in design process. Six different types of standard sections having the same cross-sectional area are used for the press columns. Three different models for the press head are designed to hold the hydraulic cylinder. Therefore, eighteen different design combinations for a hydraulic press are modeled under three different loading conditions. Their stress distributions are calculated using a computer-aided finite element analysis (FEA) tool and analytical formulas and the obtained results are compared. Two different types of finite elements, shell and beam, are used for the modeling processes. Based on the obtained results, the best model for the hydraulic press considering the head and body types is defined.

1. Introduction

The hydraulic press is one of the oldest basic machine tools working with oil pressure. Function of the press is to transfer one or more forces and movements to a tool or die with the purpose of forming or blanking a workpiece. Depending on intended application, the press is designed either to execute a specific process or for mainly universal use. Press design requires special experience and knowledge of the production process to be used. Hydraulic presses are operated based on principles of physics using and distributing hydrostatic pressure acting on a surface to produce hydraulic force [1]. Hydraulic presses provide much better performance and reliability than mechanical presses even though mechanical presses are used commonly in traditional applications.

Hydraulic presses are designed as single or double-acting presses according to their functions and body structures that can be open or closed. They are generally used for composite material manufacturing or sheet metal forming processes. The most critical part of a hydraulic press is the body since the type and magnitude of force acting on the body cannot be defined easily. Analytical calculations are made within three steps to simplify the theoretical design of the press body. First, the pattern of force acting in the press body is simplified and ignored the complexities. Second, high factor of safety is taken into account to design the press components under full cylinder loading acting on entire system. The last step includes calculating the overall dimensions of the press body [2]. Hence, designing of hydraulic press components is simplified considering these methods. An alternative design process is also the shaping or optimization technique using finite element method (FEM) utilized to verify the strength under the required operational conditions.

Available literature shows that a few studies have been carried out to analyze hydraulic presses and their structural bodies under different loading conditions. Lee and Box Y [3] studied development of the hydraulic press configurations under vertical preload. In order to reduce the memory capacity and computing time, Sinha and Murarka [4] focused on the analysis of a 918 kN capacity hydraulic press structure (welded frame) using FEA modeling. Neumann and Hahn [5] analyzed behavior of a single-point-drive eccentric press based on a rigid body dynamics using both experimental and computer aided simulations. Bai et al. [6] also proposed a design method to develop high capacity mechanical presses driven by multi-servomotors. Ou et al. [7] evaluated different structural configurations of the press frames and measured relatively small forces using triaxial force and moment transducers (Triax-FM). Du and Guo [8] presented a new metal forming press design including trajectory and velocity of the stroke. Fulland et al. [9] analyzed the fatigue crack growth in hydraulic press frame using crack simulation program, ADAPCRACK3D. Shanmei et al. [10] calculated stresses and displacements of upper cross beam of a 20MN forging hydraulic press subjected to nominal pressure using ANSYS program. Krušič et al. [11] determined the deflections of the workpiece-tool-press (WTP) system and tool loads to improve product accuracy in a multistage cold-

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forging process using both experimental and numerical approaches. Sumaila and Ibhadode [12] designed and manufactured a 30kN capacity hydraulic press and then tested its conformability and serviceability based on design objectives.

The purpose of this study is to design a hydraulic press body and head used commonly in industrial applications by numerical and analytical methods. The body consists of four-column having different cross-sections obtained using standard steel (beam) sections. The press head consists of different structural designs. The stress distribution of the press with different types of body and head designs is calculated under three different loading directions, axial, eccentric and oblique. Based on these circumstances, a suitable press design is modeled to provide benefits for machine tool industry.

2. Hydraulic Press Design

A combination of hydraulic press having different structural configurations is designed with a capacity of 250 kN. The schematic view of press is given in Figure 1. As seen from the figure, the press head is designed in different structural forms named as parallel (P), normal (N) and plus (T) using a steel plate having 15 mm thickness. The structural steel plates made of DIN 17100 St360-2 steel are connected to each other to form the three different heads and assembled on the columns of the press in order to hold the hydraulic cylinder.

The press base is obtained by connecting two C 50mm x 25mm channels and two L 50mm x 50mm x 5mm angles which are made of low carbon steel, DIN 17100 St490-2. The press workbench is obtained by bolting together two C 120mm x 55mm DIN 17100 St490-2 steel channels. The selection of nominal dimensions of C channel and L angle shapes is made considering Turkish Standards TS 912 [13] and TS EN 10056-1 [14], respectively. On the workbench, a steel plate is placed with a size of 340mm x 380mm x 25mm made of DIN 17100 St360-2 steel to be used as a jig for dies. C channels used to construct the workbench are connected to each other by workbench spindles with a diameter of 16 mm. The position of the press workbench is also adjustable by holders with a diameter of 17 mm on the columns. The spindle and holder made of DIN 17100 St490-2 steel are generally subjected to the shear stresses only during the operation of the press. Considering the safety factor as 3, when the allowable shear stress (τ_{em}) is taken into account for the pressing force of F=250 kN, the diameters of the workbench spindle (d_m) and workbench holder (d_t) can be calculated as follows:

$$d_m = d_t = \sqrt{\frac{4 \cdot F}{\pi \cdot \tau_{em}}} \tag{1}$$

Six different cross-sections are considered for the press columns made of DIN 17100 St490-2 steel as seen in Figure 2. The average cross-sectional area, A_a, and column length, l_c, for all section types are taken as 1200 mm^2 and 1430 mm, respectively. The parametric definitions of standard sections are made considering Turkish Standards (TS) [13, 15, 16, 17] and German Standards (DIN) [18, 19].

In order to determine normal stresses for the press types under axial loading, F_1, neglecting the head effects, columns are subjected exclusively to tensile stress, σ_t, in both xy- and yz-planes. Therefore, the normal stresses may be expressed as follows:

$$\sigma_{xy}, \sigma_{yz} = \sigma_t = \frac{F_1/2}{2 \cdot A_a} \tag{2}$$

Similarly, the stress components under eccentric load, F_2, exerted on the press can be calculated considering the press columns neglecting the head effects. Columns are subjected to both tensile, σ_t, and bending stresses, σ_b, in the xy-plane, and tensile stress, σ_t, in the yz-plane as follows:

$$\left.\begin{aligned} \sigma_{xy} &= \sigma_t + \sigma_{b,column} = \frac{F_2/2}{2 \cdot A_a} + \frac{(F_2/2 \cdot e) \cdot c_1}{2 \cdot I_{z,c}} \\ \sigma_{yz} &= \sigma_t = \frac{F_2/2}{2 \cdot A_a} \end{aligned}\right\} \tag{3}$$

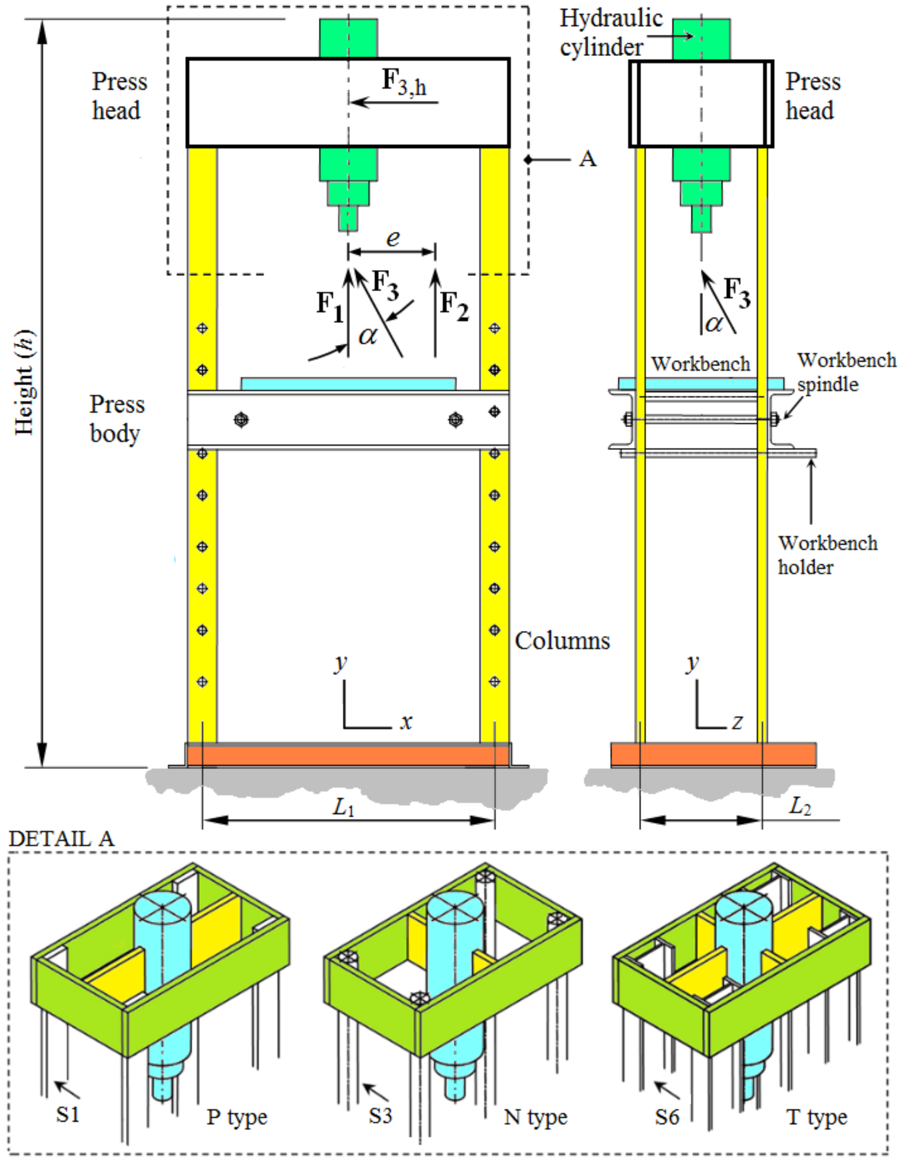

Figure 1. Hydraulic press design

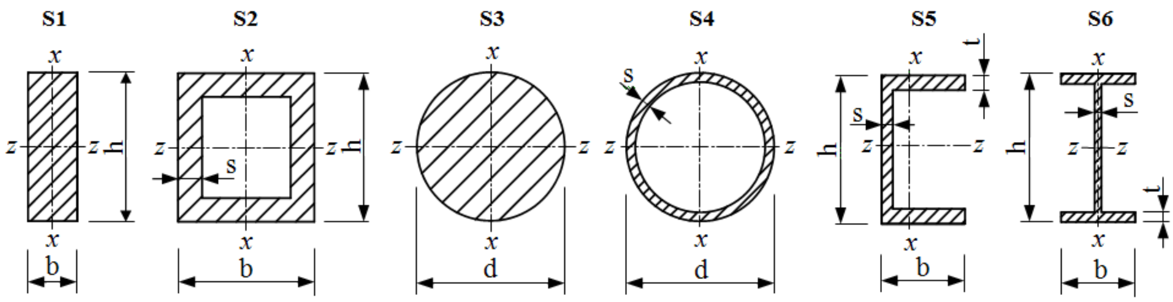

Figure 2. Different cross-sections used for the columns

The stresses under oblique load, $F_{3,xy}$, are obtained by resolving F_3 into both horizontal and vertical components, $F_{3,h}$ and $F_{3,v}$, in directions parallel to the x and y axes, respectively. Columns under the F_3 are subjected to tensile, σ_t, and bending, $\sigma_{b,column}$, stresses in the xy-plane, and tensile stress, σ_t, in the yz-plane. The $F_{3,h}$ also leads to bending stress, $\sigma_{b,head}$, in the heads. Accordingly, the combined stresses under static loading conditions can be calculated applying the rules of mechanics as follows:

$$\left.\begin{aligned} \sigma_{xy} &= \sigma_t + \sigma_{b,column} + \sigma_{b,head} = \frac{F_{3,v}/2}{2\cdot A_a} + \frac{(F_{3,h}\cdot L)\cdot c_1}{4\cdot I_{z,c}} + \frac{(F_{3,h}\cdot L_p)\cdot c_2}{I_{z,h}} \\ \sigma_{yz} &= \sigma_t = \frac{F_{3,v}/2}{2\cdot A_a} \end{aligned}\right\} \tag{4}$$

where $I_{z,c}$ and $I_{z,h}$ are the moments of inertia of the column section and the head plate section , respectively. The c_1 and c_2 are the outer distances from the neutral axis of the cross-sections. The L and L_p are distances from the $F_{3,h}$ applied point (head center) to the press base and hydraulic piston rod end, respectively. The stresses under oblique load, $F_{3,yz}$, can also be calculated in a similar way. When neglecting the shearing stress, the average value of the normal stress can be obtained from the following equation:

$$\sigma_{ave\_normal} = \frac{\sigma_{xy} + \sigma_{yz}}{2} \tag{5}$$

Piston diameter, d_i, can be calculated hydro-mechanically considering maximum operating pressure, P, and pressing force, F, as follows;

$$d_i = \sqrt{\frac{4\cdot F}{\pi\cdot P}} \tag{6}$$

Hydraulic cylinder tube thickness, S_o, can also be found using the thin walled-structure formulation as follows;

$$S_o = \sqrt{\frac{1.7\cdot d_i\cdot P\cdot S}{200\cdot \sigma_y}} \tag{7}$$

where σ_y is the yield strength. Consequently, hydraulic cylinder diameter, d_a, can be found as follows;

$$d_a = d_i + 2\cdot S_o \tag{8}$$

The minimum piston rod diameter, d_3, of a single acting spring return cylinder can also be calculated based on buckling (Euler's) formula as follows:

$$d_3 = 2\cdot \sqrt[4]{\frac{4\cdot F\cdot S\cdot S_k^2}{\pi^3\cdot E}} \tag{9}$$

where S_k is the piston rod length; S is the safety factor; E is modulus of elasticity.

Therefore, the combined stresses can be calculated considering the Eqs. (2) to (5). The press force was taken as F=250 kN, and the average cross sections of the columns were taken as A_a= 1200 mm^2. The values of the moment of inertia, $I_{z,c}$ and $I_{z,h}$, were calculated considering the section types and its geometrical parameters given in Figures 1 and 2. The distances of L_1 and L_2 parameters (see Figure 1), were specified as 600 mm and 250 mm, respectively. The effects of the bending moment due to oblique force (F_3) applied to head center are calculated considering the distances of L and L_P from the $F_{3,h}$ applied point (transferred to head center) to the press base and hydraulic piston rod end, respectively (see Figure 1). Considering some assumptions such as no affects of press workbench stiffness to simplify the analytical computations, the maximum and minimum combined stresses of the entire press model are calculated and given in Table 1.

Table 1. The maximum and minimum combined stresses of the hydraulic press

	Head type	Axial load, F_1	Eccentric load, F_2	Oblique load, F_3 xy-plane	Oblique load, F_3 yz-plane
Maximum Combined Stress, σ_{total} (MPa)	P	58.57 (S6)	298.96 (S3)	749.13 (S3)	1662.55 (S1)
	N	58.57 (S6)	298.96 (S3)	1265.34 (S3)	1164.39 (S1)
	T	58.57 (S6)	298.96 (S3)	745.63 (S6)	1143.24 (S6)
Minimum Combined Stress, σ_{total} (MPa)	P	49.76 (S3)	103.89 (S6)	188.74 (S6)	767.62 (S4)
	N	49.76 (S3)	103.89 (S6)	704.95 (S6)	269.46 (S4)
	T	49.76 (S3)	103.89 (S6)	185.24 (S6)	248.3 (S4)

3. Hydraulic Press Modeling

Finite element-based computer code, ANSYS, was employed for the simulations of the hydraulic press design. In order to simplify the structure of the press design without affecting the accuracy of prediction, two different types of finite elements, beam and plane, are selected to generate the finite element models as given in Figure 3. Both finite elements are joined to each other by nodes at junction of head and body with the absence of contact.

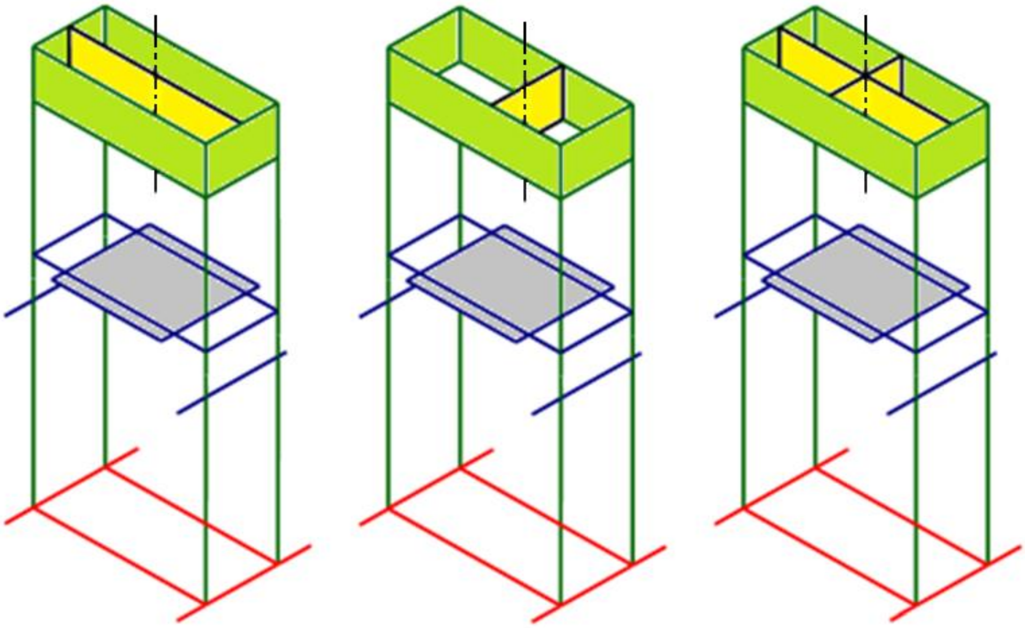

Figure 3. Finite element model of the hydraulic press

The BEAM189 and SHELL63 finite elements are used to generate the beam and plane models, respectively, to simulate the structure of the press. The BEAM189 is a quadratic 3D beam element based on Timoshenko beam theory and suitable for 1D structural analysis. This element has six degrees of freedom at each node [20]. The BEAM 189 element is used to model the press body including base, columns, workbench, and hydraulic cylinder. The SHELL63 is a shell element defined by four-node at which six degrees of freedom [20]. The SHELL63 element is used to model the press head structures and workbench plate. Real constants for the SHELL63 are defined as 15 mm for the press head modeling and 25 mm for the workbench plate modeling. In addition, the element size is taken as 10 mm to generate an appropriate finite element mesh in the modeling process. The mesh densities were obtained different based on press models having different head and column types but the densities were generated roughly close to each other. For instance, 6629 elements and 8131 nodes were obtained with P type head and S1 column. Similarly, 5981 elements and 8027 nodes were obtained with N type head and S6 column. The press model with T type head and S3 column was also divided into 7097 elements having 8587 nodes. The mechanical properties of structural steels DIN 17100 St360-2 and DIN 17100 St490-2 used in the simulations of the press design are given in Table 2.

Table 2. Mechanical properties of structural steels DIN 17100 St360-2 and DIN 17100 St490-2

Material	DIN 17100 St360-2	DIN 17100 St490-2
Modulus of elasticity, E (MPa)	2.07 x10^5	2.1x10^5
Poisson's ratio, ν	0.3	0.3
Yield strength, σ_y (MPa)	240	290
Ultimate tensile strength, σ_u (MPa)	370	500
Density, ρ (kg/m^3)	7850	7850

Considering the press operational conditions, all nodes located at the bottom surface of the press base are restricted to the translational and rotational displacements in x, y and z directions. Three different types of loads, axial (F_1), eccentric (F_2) and oblique (F_3), are considered in the simulations as given in Figure 1. As seen, the axial load is applied to the centre of the piston rod. The eccentric load is applied at a point located on the x axis at a distance (e) of 50 mm from the centre of the workbench plate. The oblique force is also applied with an angle of 6° to the axis of piston rod in different directions considering both xy- and yz-planes. These loads are instantaneously applied to the press body to represent the maximum loading condition.

4. Results and Discussion

Several configurations of the hydraulic press are designed to evaluate the stresses using both analytical calculations and finite element analysis under different loading conditions. The maximum equivalent stress (σ_{max}) and displacement (δ_{max}) values from numerical calculations are obtained for different types of presses as given in Table 3. As it can be seen from the table, the maximum stresses and displacements under the axial and eccentric loadings are obtained higher in the P type heads than others. The maximum stress and displacement for the oblique loading in xy-plane are obtained higher in the N type heads than others.

Table 3. The maximum equivalent stress and displacement values of hydraulic presses

Loading Types	Cross section type	Equivalent stress, σ_{max} (MPa)			Displacement, δ_{max} (mm)		
		P type	N type	T type	P type	N type	T type
Axial	S1	569.11	299.58	211.66	1.42	0.94	0.75
	S2	568.18	299.43	212.58	1.45	0.98	0.78
	S3	569.45	309.53	221.98	1.40	0.97	0.76
	S4	567.29	299.35	205.48	1.42	0.92	0.74
	S5	570.58	298.77	240.06	1.47	0.94	0.77
	S6	568.57	299.66	206.53	1.47	0.94	0.77
Eccentric	S1	555.33	299.89	207.44	1.43	0.95	0.76
	S2	554.42	299.75	211.50	1.46	0.99	0.80
	S3	555.68	302.48	217.65	1.41	0.98	0.77
	S4	553.52	299.65	207.98	1.44	0.93	0.76
	S5	556.83	299.15	272.17	1.48	0.96	0.78
	S6	554.80	299.96	222.73	1.49	0.95	0.80
Oblique (xy-plane)	S1	637.28	990.70	501.76	5.81	9.26	5.60
	S2	636.36	990.43	501.76	4.44	7.90	4.22
	S3	637.60	990.70	558.84	13.72	17.27	13.59
	S4	635.48	990.18	501.76	3.39	6.79	3.12
	S5	638.89	988.98	501.76	3.39	6.57	3.01
	S6	636.70	991.51	501.76	2.83	6.15	2.47

The stresses and displacements of the presses are found close to each other in the same types of the heads with different column cross-sections subjected to axial and eccentric loadings since the same cross-sectional area is used for the different column types. The FEA results of the hydraulic press obtained under the axial and eccentric loads indicate that the stresses and displacements depend basically on the type of the head, and thus the type of the head is more affective on the stresses and displacements than the column types. The stress values are also obtained about similar in the same type of heads having the different column cross-sections under the oblique loading in xy-plane. However, displacement values are obtained different depending on both head and column cross-section types. Therefore, it can be concluded from the results of finite element simulations, the displacements of the hydraulic presses are depending on not only head type but also column cross-section. In addition, the stress values of the P type heads are calculated similar using three different loading types, but the stresses in both N and T type heads under oblique load in the xy-plane are obtained significantly higher than the other loading conditions as seen in Table 3.

The stresses and displacements of the T type head under the axial and eccentric loads are obtained lower than the other head type that is important to achieve the desired stiffness. In other words, the use of the T type head considerably reduces the stresses. The displacements of the T type head are found approximately the same for six different columns. The stress values of the T type head under the oblique loading in the xy-plane are also calculated lower than the P and N type heads. The displacement values of the T type head are calculated variable depending on column cross-sections. Therefore, the press with the T type head and S6 column under the oblique loading condition in the xy-plane is identified as the best press type.

In order to consider the stresses and displacements of the press in both xy- and yz-planes as seen in Figure 1, the oblique force (F_3) is applied in different directions considering these planes. In other words, the F_3 is applied considering both positive (+) and negative (-) directions of x and z axes to calculate the maximum equivalent stresses and the displacements based on different head types. The calculated stresses and displacements of several types of the presses are given in Table 4 to compare the FEA results obtained under oblique loading. The press types are also illustrated in the table, where the maximum stress and displacement values are obtained. As seen from the table, for example, the maximum equivalent stress and the displacement are calculated as 558.84 MPa and 13.59 mm on the press with T type head and S3 column considering the xy-plane, respectively. According to the calculated values in this table, applying the F_3 in different directions of both planes are resulted similar outcomes considering both equivalent stresses and displacements occurred on the press types. The press head type is further playing an important role on the total displacement due to different head strength and stiffness.

Table 4. Application of oblique force in different directions

Maximum values	Head type	Cross section type	xy-plane		yz-plane	
			x-direction (-)	x-direction (+)	z-direction (-)	z-direction (+)
Equivalent Stress, σ_{max} (MPa)	P	S5	638.89	638.89	1374	1374
	N	S6	991.51	991.51	1070	1070
	T	S3	558.84	558.84	1156	1156
Displacement, δ_{max} (mm)	P	S3	13.72	13.72	50.69	50.69
	N	S3	17.27	17.27	36.76	36.76
	T	S3	13.59	13.59	32.51	32.51

The equivalent stress distributions of the hydraulic press with T type head for three different loading cases are given in Figure 4. The maximum equivalent stresses are obtained at junctions of the heads and columns since the effect of pressing force is transferred from the hydraulic cylinder to the columns. Additionally, the maximum displacements in horizontal (δ_y) and vertical (δ_y) directions are also calculated under the described loading conditions. The deformations of the hydraulic press with N type head under F=250 kN loading are shown in Figure 5. As seen, the deformation values of the presses under both axial and eccentric loads are obtained similar but under oblique loading are calculated higher.

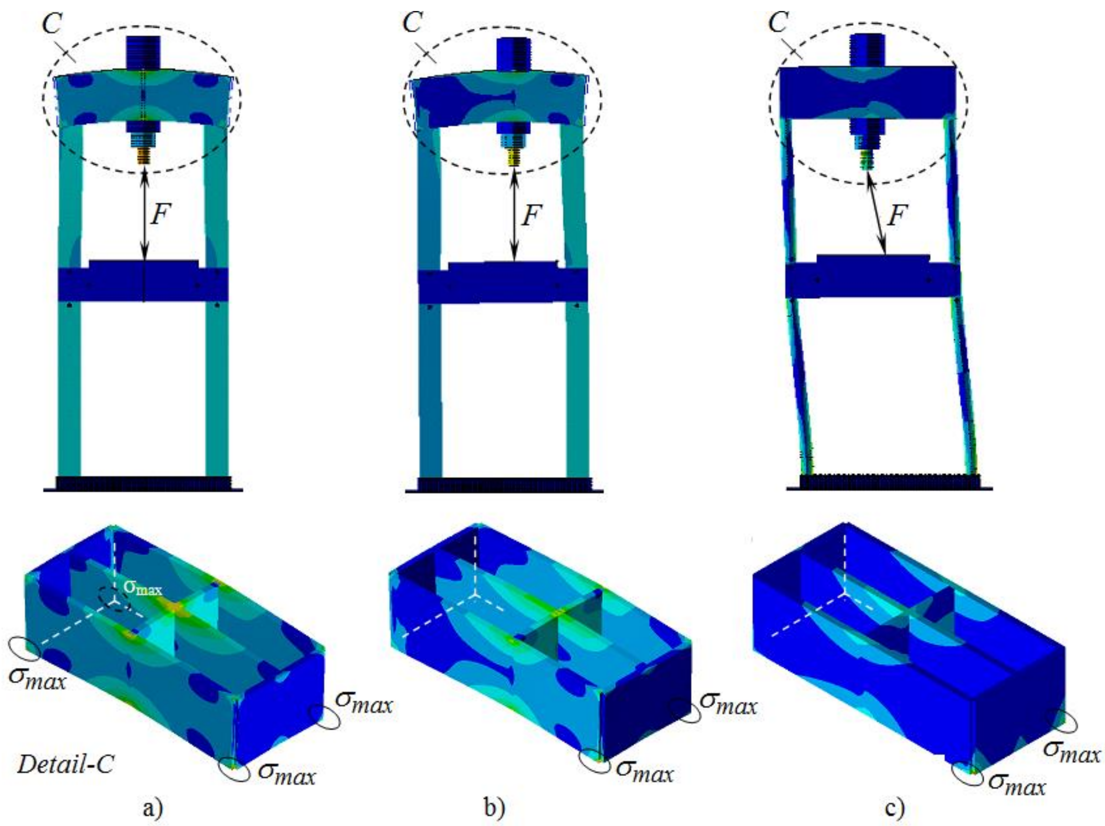

Figure 4. Equivalent stress distributions of hydraulic presses with T type head and S5 column under a) axial, b) eccentric, and T type head and S3 column under c) oblique loading in the xy-plane conditions

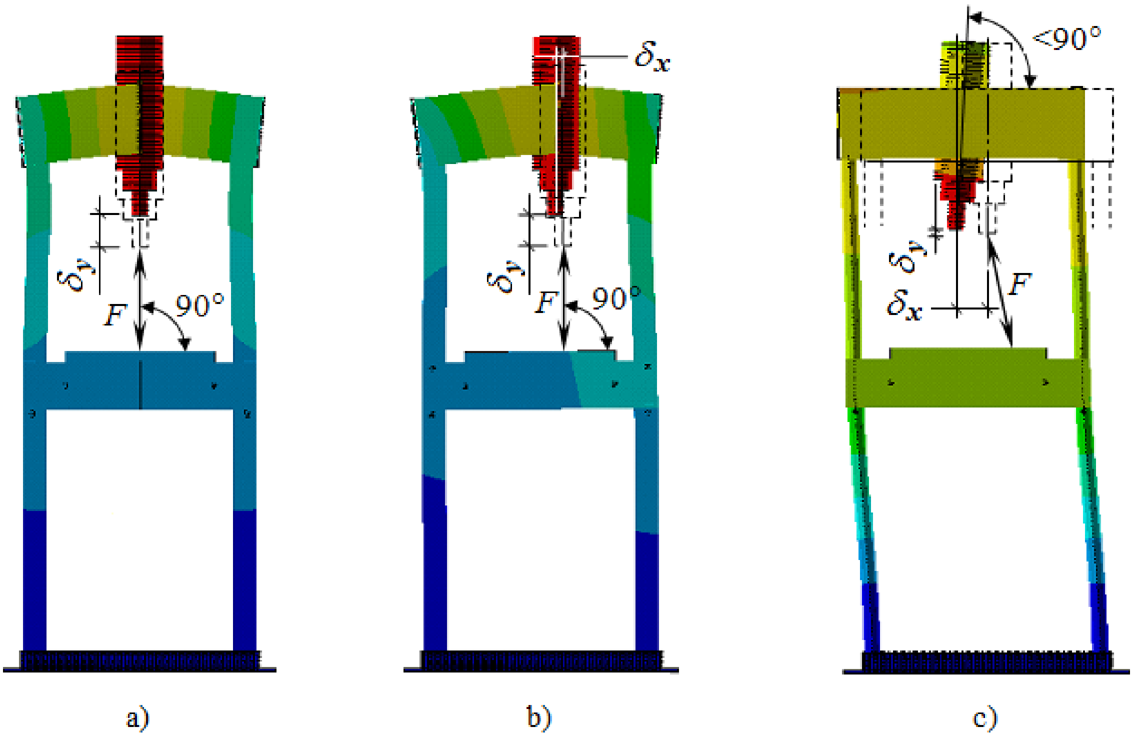

Figure 5. Vertical and horizontal displacements of the presses with N type head and S2 column under a) axial force, b) eccentric force, and N type head and S3 column under c) oblique force in the xy-plane

The maximum equivalent stress (σ_{smax}) and displacement (δ_{smax}) values of the columns are plotted as a function of column cross-section types illustrated in Figures 6, 7 and 8. As seen, the stress and displacement values are calculated varying depending on both head and column cross-section types. The stress and displacement values at the columns are obtained lesser than the heads. The equivalent stress value of the columns is calculated lesser than the yield stress of DIN 17100 St490-2 steel, so that the columns exhibit an elastic behavior under the static loading. The maximum stresses under the axial and eccentric loads are obtained at the S1 column with the N type head as seen from the FEA results given in Figures 6a and 7a. The maximum stresses are obtained at the S2 column under the oblique load in the xy-plane as given in Figure 8a. As it can be seen the FEA results illustrated in Figures 6b and 8b, the maximum displacements are obtained between the S2 columns with the N type head under both axial and oblique loads in the xy-plane. The total displacement from the FEA results under the eccentric load is plotted as a function of the column cross-section types shown in Figure 7b. The FEA results illustrated that the maximum displacement under the eccentric loading is calculated between the S6 columns with the P type head.

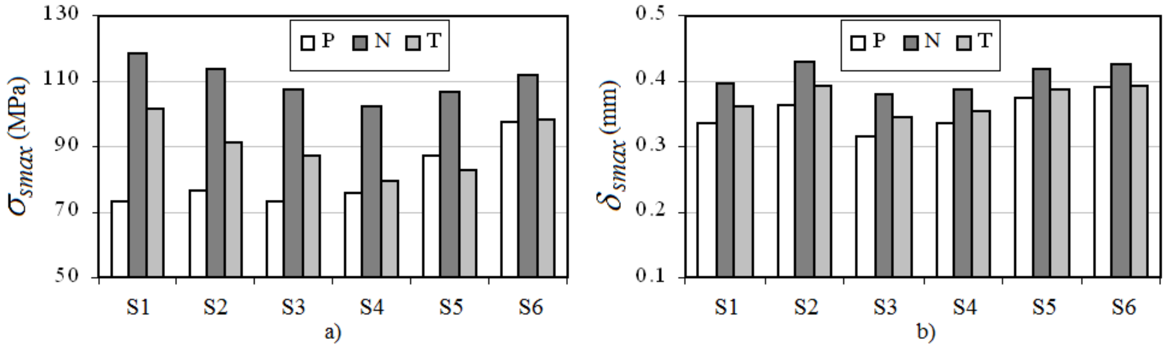

Figure 6. Stresses and displacements of columns (axial load)

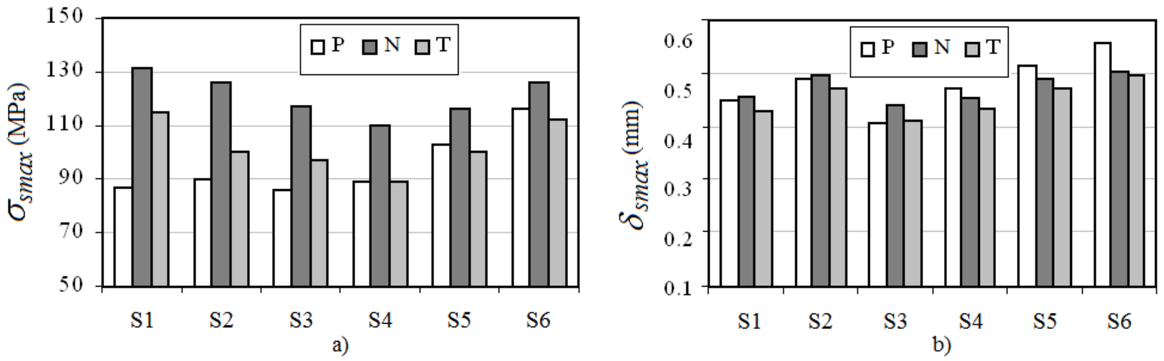

Figure 7. Stresses and displacements of columns (eccentric load)

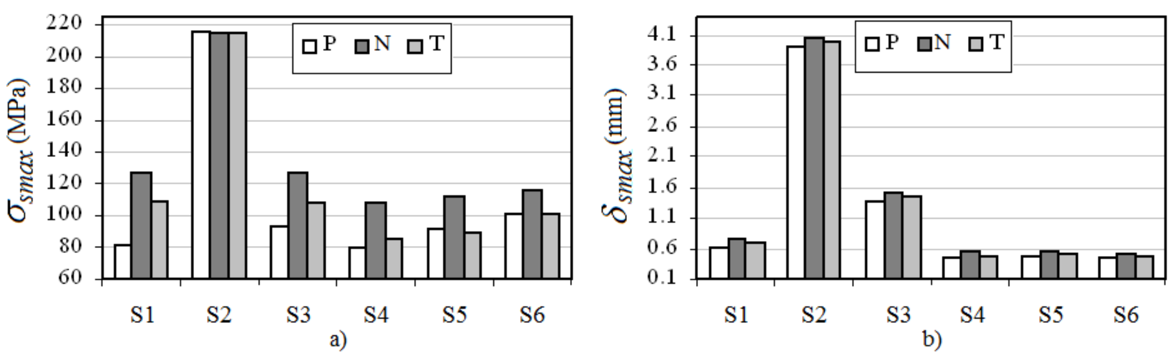

Figure 8. Stresses and displacements of columns (oblique load, xy-plane)

5. Conclusions

A hydraulic press with a capacity of 250 kN is designed with the different types of press columns and heads to minimize the stresses and displacements under different loading conditions. The stresses and displacements are calculated using both analytical and FEA method. In the numerical FEA calculations, finite element method is employed successfully along with both beam and plane elements in the models. Different types of loads are applied successfully in axial, eccentric, and oblique directions to the developed models. Appropriate boundary conditions are also applied to the models. The stresses and displacements of the hydraulic presses are calculated depending basically on the head types (see Table 3). The stresses and displacements on the press head are mostly obtained higher than the press columns. A good agreement is found between the analytical and FEA calculations considering the minimum stress values of the press models. Based on these calculations, the minimum stresses are calculated using press model having T type head and S4 or S6 columns (see Table 1 and Figures 4, 6, 7, and 8). Therefore, it is recommended to press manufacturers that the press with T type head and S4 column is the best design.

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