Finite element analysis and optimization design of beam structure of forging press

Xin Ji¹,³, Shanmei Liao², Xiaoyan Zhang¹, Xiaoyong Gao¹ and Ruiyang Ma²

¹ Tianjin Tianduan Hydraulic Press Co., Ltd., Tianjin 300142, China
² Advanced Mechatronics Equipment Technology Tianjin Area Laboratory, Tianjin 300387, China
³ E-mail: abcjixin@sohu.com

Abstract. The structural optimization design of 20Mn forging hydraulic press was studied. Firstly, the structure and stress characteristics of the hydraulic press are analyzed, then according to the center load condition, the static structure of the frame is simulated by finite element method, so as to understand the stress and stress concentration of each part, and achieve the purpose of checking the strength and stiffness of each part. On the basis of the above analysis, the strength of the beam is optimized on the basis of reducing the overall stiffness. The simulation results show that the optimized design scheme can reduce the material consumption and save the cost.

1. Introduction
Forging press has been widely used in various fields of national economy, such as machinery, electronics, automobile, aerospace field. Especially with the increasing demand of large forgings, the nominal pressure of forging press is also increasing, this undoubtedly puts forward higher requirements for designers [1].

This paper, a certain type of 20Mn forging press is taken as the research object, through the analysis of the structure of the hydraulic press and the mechanical characteristics of each part, the solid model is established by using the three-dimensional modeling software Pro / E. The finite element analysis software ANSYS is used to analyze the static structure of the lower beam under the central load condition. On the basis of the static analysis, taking the quality of forging press as the optimization goal, the optimization design of the lower crossbeam is carried out under the premise of meeting the overall strength and stiffness. The simulation results show that the optimized design scheme achieves the purpose of reducing material consumption and saving cost.

2. Analysis model of forging press
2.1. Description of key parts of forging press
Taking 20Mn three beam four column forging press as the research object. Four column forging press is the most common and widely used structure in forging press. Its main feature is that its processing technology is simpler than other types of forging press [2].

Main engine body is composed of upper crossbeam, slider, lower crossbeam, column, mobile table, master cylinder, side cylinder and so on. The frame is a supporting frame which composed of upper crossbeam, lower crossbeam and four columns through the lock nut. So that, according to the
mechanical characteristics of frame, it is necessary to analyze the frame structure by finite element method.

2.2. Model preprocessing
Each part solid model of forging press is built through Pro/E, then the model is import into the ANSYS for analysis. In the modeling step, we should make appropriate simplification according to the characteristics of the model under the premise of fully reflecting the stress and strain of the frame. The principles followed in the modeling process are as follows [3-4]:

A. The material of forging press is considered as an elastic body composed of isotropic and continuous medium;
B. The parts that obviously do not affect the overall strength and stiffness of the frame should be simplified;
C. It is considered that the welding quality is reliable and each beam component is treated as a continuum;
D. According to the infinite stiffness of the foundation bolt, the elastic deformation of the parts outside the foundation and the frame is not considered;
E. The influence of gravity on the strength and stiffness of the structure is ignored, and the installation stress and temperature stress are not considered;

The lower beam solid model is shown in Figure 1.

![Figure 1. Lower beam model of forging press.](image)

Due to the symmetry of the structure and force of the lower crossbeam, this paper analyzes 1/4 model of forging press. The solid45 unit is selected as the unit type, the material properties are shown in Table 1.

| Material properties | Elastic modulus (MPa) | Poisson coefficient | Density (Kg/mm³) |
|---------------------|-----------------------|---------------------|------------------|
| ZG270-500           | 2E5                   | 0.3                 | 7.8E-6           |

3. Static analysis of lower crossbeam
The two bosses bear the working force transmitted by the lower cutting board, it is assumed that the working force is evenly distributed on the two boss surfaces under the central load, and the contact between the bottom of the lower crossbeam and the lock nut of the column bears upward tension. In the analysis, Symmetrical constraints are imposed on the sections of xoz and yoz planes, and full constraints are applied to the lower surface of the lower crossbeam.
The working pressure of three working cylinders is 20MN, and converted into surface force is 6.335MPa. The surface force is load on the upper surface of two bosses, and the direction is downward. With considering the preload, the extrusion load between lower surface of lower crossbeam and the lock nut of the column is 6.765MN, obtained from Equation (1), converted into area load is 94.34MPa, as shown in Figure 2(a), with upward direction. The working pressure on the contact between the upper surface of the lower beam and the column step is 1.37MPa, with downward direction.

\[
P_z = \frac{ZK_AA_2 + A_1P}{K_AA_2 + A_1}
\]

Through the finite element calculation, the stress and displacement of the lower beam joint can be obtained.

It could be seen from Figure 2(b), under the nominal pressure, the overall stress distribution is more uniform and most of the stress is very small, only the lower surface and the column lock nut contact point has the phenomenon of stress concentration. The maximum stress is 134.902MPa less than the allowable stress of ZG270-500, and meets the strength design requirements. Because the stress values in most places of lower crossbeam are very small, there is a large space for optimization.

It could be seen from Figure 2(c), the combined displacement of the lower crossbeam become smaller from the middle to both sides along the x-axis direction, which conforms to the structural characteristics of the bending moment of the lower crossbeam. The maximum relative deflection of lower crossbeam is 0.18E-3mm/m, far less than the allowable value. The stiffness of the lower crossbeam is good and has a lot margin, so the optimization should be carried out to improve the utilization of materials.
4. Structural optimizations of lower crossbeam

4.1. Optimization design method of ANSYS
This paper uses the first-order optimization method provided by ANSYS, suppose $F_{i-1}, X_{i-1}$ and $F_i, X_i$ are the $i$-1 iteration and $i$ th iteration of the target variable and the design variable, respectively. $F_0$ and $X_0$ is the optimal target variable value and the corresponding design variable value, and if any one of the following formulas is satisfied, it could be considered the iterative convergence.

$$\left\{ \begin{array}{l}
|F_i - F_{i-1}| < t \\
|F_i - F_0| < t \\
|X_i - X_{i-1}| < t \\
|X_i - X_0| < t
\end{array} \right. \quad (2)$$

Where, $t$ is the tolerance of design variables, the optimization design steps are shown in the Figure 3 [5].

4.2. Optimization analysis of lower crossbeam
In the optimal design of lower crossbeam, the mass of the following beams is the target variable, the thickness of the shell and inner rib plate of the beam is taken as the design variable, the allowable stress and maximum deflection of the material are taken as the state variables to constrain its strength and stiffness.
The shell, internal stiffeners and panels of the lower crossbeam are classified, as shown in Figure 4 there are 10 types steel plate ($B_1$ to $B_{10}$) according to thickness. The height of the 1st and 4th plate is $H_1$, the height of the 2nd, 3rd and 5th plate is $H_2$, the height of the 7th floors plate is $H_3$, and the height of the column hole is $H_4$. The design variable is

$$x = [B_1 \ \cdots \ B_{10} \ \ H_1 \ \cdots \ H_4]^T$$  \hspace{1cm} (3)$$

The process of solving the optimal mass value of the lower beam is actually the process of solving the minimum volume value. The objective function is

$$F(x) = \sum_i m_i$$  \hspace{1cm} (4)$$

Where, $n$ is number of all cells, $m$ is mass of unit $i$. The allowable stress of lower beam material ZG270-500 is 168.75MPa. The $Z_{max}$ could be calculate by maximum relative deflection, $Z_{max} = 0.8$mm. So that the state variables are $\delta_1 \leq 168.75$MPa, $\delta_2 \leq 0.8$mm.

The boundary conditions and loads is set up as follows, bottom beam DOF full restraint; the surface force applied on the upper surface of the boss is 6.335MPa; the surface force which applied on the ring surface where the upper surface of the lower beam is in contact with the column step is 1.37 MPa; the surface force which applied on the ring surface where the lower surface of the lower crossbeam is in contact with the locking nut is 6.335MPa.

The optimize variable settings are list in Table 2. When the difference between the objective function and the optimal value is 0.1, the iteration is stopped and the optimization times are 30.

4.3. Analysis of optimization results

The optimization process reaches the optimal value in 13 steps. After optimization, the mass of the lower crossbeam is reduced from 8722.32kg to 6963.77kg, the mass is reduced by 20.16%. The equivalent stress is reduced from 144.06MPa to 126.54MPa, and the strength is improved. The maximum displacement in Z direction is from 0.05mm to -0.34mm, the deflection increases, but it still has good stiffness, as shown in Figure 5. The optimized data are rounded and re-modeled for structural analysis. The optimized Z-direction displacement and equivalent stress are shown in figure below.

| Name | Unit | Symbol | Initial value | Lower limit | Upper limit | Optimal parameters | Round parameters |
|------|------|--------|---------------|-------------|-------------|-------------------|-----------------|
| Design variable | mm | | | | | |
| $B_1$ | | | 60 | 45 | 75 | 45.000 | 45 |
| $B_2$ | | | 60 | 45 | 75 | 60.369 | 61 |
| $B_3$ | | | 60 | 45 | 75 | 48.695 | 50 |
| $B_4$ | | | 60 | 45 | 75 | 45.000 | 45 |
| $B_5$ | | | 60 | 45 | 75 | 45.000 | 45 |
| $B_6$ | | | 80 | 70 | 90 | 72.738 | 73 |
| $B_7$ | | | 50 | 35 | 65 | 35.000 | 35 |
| $B_8$ | | | 85 | 70 | 95 | 72.374 | 73 |
| $B_9$ | | | 85 | 70 | 95 | 70.000 | 70 |
| $B_{10}$ | | | 90 | 75 | 105 | 75.059 | 76 |
| $H_1$ | | | 1445 | 1400 | 1500 | 1413.6 | 1414 |
| $H_2$ | | | 1080 | 1030 | 1130 | 1047.4 | 1048 |
| $H_3$ | | | 610 | 580 | 630 | 585.91 | 586 |
| $H_4$ | | | 861 | 800 | 900 | 897.34 | 898 |
| State variable | MPa | $\delta_1$ | 144.063 | — | 168.75 | 126.54 | 162.716 |
| | mm | $\delta_2$ | 0.0502 | — | 0.8 | -0.34413 | -0.339362 |
After re-modeling of lower crossbeam, the maximum deflection is 0.34mm, the maximum equivalent stress is 162.72MPa, as shown in Figure 6, the strength and stiffness meet the design requirements. And the distribution of stress and displacement are in accordance with the actual situation.

5. Conclusions
Under the central load, the lower crossbeam of forging press is analyzed. The simulation results show that the structure design of the lower crossbeam is reasonable, the strength and stiffness meet the design requirements, and it has good ability to resist eccentric load.

In the optimization design process of the lower crossbeam, the mass of the lower crossbeam is taken as the objective function of optimization, the thickness and height of each component of the lower crossbeam are taken as the design variables, and the maximum equivalent stress and maximum deflection are taken as the state variables.

In order to verify the reliability of the optimization, the structural analysis of the lower crossbeam is carried out with the optimized parameters.

Acknowledgement
This work was supported by the Key Technologies R & D Program of Tianjin (Grant No. 19YFZCGX00870).

References
[1] Liu H C and Huang Y 2015 Present situation and development analysis of automatic forging press in China Machinist Metal Forming (21) 18-19
[2] Li X J 2011 Finite Element Analysis of Frame in Heavy Four-column Damper Plate Cylinder-motion Hydraulic Press China Metal Forming Equipment Manufacturing Technology 46(01) 34-37
[3] Yin Z R, Li X C, Liu K L, et al. 2019 Finite element analysis on pre-tightened combination frame for100 MN hydraulic forging machine Forging and Stamping Technology 44(08) 106-111
[4] Liu G J 2006 Analysis and Optimization of the Structure of a Hydraulicup Setting Press Yanshan University
[5] Zhao W J and Zhang D K 2007 Structure optimal design for hydraulic press based on parameterization in ANSYS Mechanical design and manufacturing (12) 6-8