Effect of residual stress in longitudinal and transverse weld on global stability of box section steel column

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Abstract. In order to study the influence of welding residual stress on the global stability of box section steel column, the simulation of the side effects from the welding process of Q345 box section steel column by ABAQUS thermal-structure coupling analysis was conducted. A temperature-displacement explicit analysis step was established, and the residual stress caused by the temperature difference of the welding specimen was simulated by applying the body heat flux directly to the solid element within the same thickness range of the weld seam and defining the load amplitude; The calculated welding residual stress was taken as the initial defect of the structure and the global stable bearing capacity of the box section steel column was solved by the arc length method. Considering the influence of thickness and welding residual stress on the global stability of box section steel column, the calculation results of 12 finite element models were compared. The results show that under the same body heat flux, the residual stress of steel columns with different thicknesses during welding is different, and the maximum value can reach 791MPa; Under the condition of the same residual stress, the global stability bearing capacity of the box section steel column will also change irregularly with the change of thickness, and the global stability bearing capacity can be reduced by 3.07% compared with that no residual stress.

1. Introduction
Steel structure has the advantages of high strength, light weight, uniform texture, isotropy, and short installation cycle [1], and has been widely used in engineering. With the continuous optimization of production technology and construction technology, as well as the improvement of research methods brought about by the development of science and technology, people begin to pay attention to the influence of residual deformation and residual stress caused by welding on the bearing capacity and safety of steel structures during the manufacturing process and the construction process of steel structures.

Beam-column is the most widely used structural form in steel structure, and its stability has an important impact on the bearing capacity and safety of the structure [2]. As a typical beam-column, it is significant to study the influence of welding residual stress on the stability of steel column.

Puliyaneth [3] and others have studied the interaction between welding residual stress and creep cyclic plasticity and creep fatigue damage of welded flange. They think that the existence of welding residual stress makes the stress distribution of flange change greatly. According to the magnitude and direction of welding residual stress, welding residual stress has adverse effect on the creep fatigue life of components, it also has favorable influence; Mohammadi [4]
and others implemented the improved algorithm into computer code in Matlab environment, and compared it with the finite element method. The local stability bearing capacity of stiffened aluminum plate affected by initial deflection and welding residual stress was studied in detail.

Gao [5] of Tsinghua University used ANSYS to study the influence of welding residual stress on the ultimate bearing capacity of Y-joints. The results show that welding residual stress reduces the ultimate bearing capacity of Y-joints; Lu [6] of Harbin Institute of Technology made a refined finite element analysis on the bearing capacity of spatial structure considering the influence of welding. The results show that the residual stress does not significantly affect the bearing capacity of the structure; Wang [7] of Chongqing University used ANSYS to simulate and analyze the welding process of KX joints, studied the influence of welding residual stress on the ultimate bearing capacity of spatial KX tubular joints, and considered that the existence of welding residual stress reduced the bearing capacity of the structure, and had a great correlation with the geometric parameters of the structure; Li et al. [8] of Hohai University studied the influence of initial bending and residual stress on the bearing capacity of steel box columns by using the finite element analysis method considering both geometric and material nonlinearity. It was considered that the ultimate bearing capacity of steel box columns decreased significantly when certain conditions were met.

In most cases, the ultimate bearing capacity of steel structure is not determined by the strength, but by the stability of the material before it reaches the ultimate strength. It is generally believed that the torsional stiffness and bending stiffness of box section steel column are larger than I-shaped steel column, and the stability of box section steel column is better. But the box section steel column in practical engineering is not ideal straight bar, and initial defects and welding residual stress will be produced in the welding process. These initial imperfections and stresses will reduce the torsional stiffness and flexural stiffness of the box section steel column and affect its stability. However, how much influence these factors have on the stability of box section steel columns is rarely studied in detail.

In order to simulate the working performance of the box section steel column under actual compression more accurately, the geometric nonlinearity of the model will be considered in this paper, and the ultimate bearing capacity of box section steel column under compression will also be explained by load-displacement curve.

2. Finite element model

The section height of steel column is 500mm, width is 500mm, thickness is varied (10-25) mm, length is 6000mm, as shown in Figure 1.

The ideal elastic constitutive model is adopted, Young's modulus $E = 2.06 \times 10^5$ N/mm$^2$, Poisson's ratio $\mu = 0.3$, yield strength $f_y = 345$MPa.

Three elements are evenly divided along the thickness of the steel column, three elements are also evenly divided along the width equal to the thickness, and one element is divided every 50mm in the weld length direction. The steel column model has 10752 elements and 14560 nodes in total.

![Figure 1. Geometric model.](image)

In the analysis, C3D8T element is selected, which is an eight-node thermal coupled hexahedral element with mechanical and thermal degrees of freedom, and can be used for the simulation analysis of mechanical thermal coupling problems; And the element is regular
hexahedron, which can effectively reduce the calculation cost and make the calculation results more convergent.

There are longitudinal and transverse welds in the model, in which the longitudinal weld is the junction position between the web and flange of the steel column along the length of the column, as shown in Figure 2. (a); The transverse weld is 1m from the column bottom and 10mm wide, as shown in Figure 2. (b).

Figure 2. Welds in different directions.

3. Welding residual stress calculation

In the calculation of welding residual stress, the thermal expansion coefficient, thermal conductivity coefficient and specific heat capacity of the material need to be defined. The values of each parameter in this paper are selected according to the European code EC3 [9], the thermal expansion coefficient is $1.2 \times 10^{-5} \text{m/(m\cdot{}^\circ{}C)}$, thermal conductivity coefficient is $54 \text{ W/(m\cdot{}^\circ{}C)}$, specific heat capacity is $425 \text{ J/(kg\cdot{}^\circ{}C)}$.

Thermal-structure coupling analysis is a kind of analysis to solve the influence of temperature field on the physical quantities such as stress and strain in the structure. In ABAQUS, the "temperature-displacement, explicit" analysis step is selected. Apply $1.5 \times 10^{11} \text{ W/m}^2$ body heat flux load to the solid element at the weld, define the amplitudes of 0, - 0.5, - 1, to calculate different welding residual stress values, and output the calculated welding residual stress by editing the keyword "* node file" of the model.

Figure 3. Residual stress output path.

In ABAQUS, two node sets are defined as the output path of welds in two directions, as shown in Figure 3. Figure 3 (a) is used to output the residual stress value within 500mm
perpendicular to the longitudinal weld and figure 3 (b) is used to output the residual stress value within 400mm perpendicular to the transverse weld. When the body heat flux is taken as the load, and the stress result after calculation is output, which is the residual stress of steel column in the welding process, as shown in Figure 4. The vertical axis in Figure 4 represents the residual stress generated during welding and the abscissa represents the distance from the central axis of the selected path. As can be seen from the Figure 4, due to the relationship between temperature gradient and mechanical constraints, residual tensile stress is generated near the weld; The residual compressive stress is produced far away from the weld.

In order to investigate the influence of initial residual stress on the stable bearing capacity of box section steel column, the influence of steel column thickness and other factors was also considered. During the analysis and calculation, the components with different welding residual stresses and different thicknesses are numbered. The component numbers and corresponding parameters are shown in Table 1. The calculated values of different welding residual stresses are shown in Figure 4. Where, \( t \) is the thickness of the plate, \( b_0 \) is the width of the section, and \( l \) is the height of the steel column.

| Component number | \( l/\text{mm} \) | \( b_0/\text{mm} \) | \( t/\text{mm} \) |
|------------------|------------------|------------------|------------------|
| B10-RS0          | 6000             | 500              | 10               |
| B10-RS1          | 6000             | 500              | 10               |
| B10-RS2          | 6000             | 500              | 10               |
| B15-RS0          | 6000             | 500              | 15               |
| B15-RS1          | 6000             | 500              | 15               |
| B15-RS2          | 6000             | 500              | 15               |
| B20-RS0          | 6000             | 500              | 20               |
| B20-RS1          | 6000             | 500              | 20               |
| B20-RS2          | 6000             | 500              | 20               |
| B25-RS0          | 6000             | 500              | 25               |
| B25-RS1          | 6000             | 500              | 25               |
| B25-RS2          | 6000             | 500              | 25               |
4. Influence of residual stress on stability of box section steel column

As a nonlinear iterative control method, the arc length method has great advantages in tracking the loading path of the structure because it can solve the problem of generating the variable increment value when the load and displacement increment are uncertain. Therefore, the arc length method is used to solve the global stability bearing capacity of the box section steel column with welding residual stress.

In ABAQUS, select the "Riks" analysis step, input the welding residual stress calculated above by editing the keyword "imperfection" of the model, and control the same value of residual stress in the same control group by adjusting the "scaling factor". A concentrated load of 700kN is applied on the top of the steel column, and the ultimate bearing capacity of the steel column is obtained by the arc length method.

Figure 5 shows the influence of different sections and welding residual stresses on the stable bearing capacity of box section steel column. In the Figure 5, the ordinate represents the stability bearing capacity of the component, and the abscissa represents the axial displacement of the component.
Table 2 statistics the stability bearing capacity of different components calculated by ABAQUS. As can be seen from the table, when the residual stress is the same, the greater the thickness of the component, the greater the stability bearing capacity; When the section size of the component is the same, the larger the residual stress is, the smaller the stable bearing capacity of the component is. The reduction coefficient $\beta$ is the ratio of the stability bearing capacity of the steel column affected by residual stress to that not affected by residual stress.

| Component number | Stability bearing capacity / kN | Reduction factor $\beta$ |
|-------------------|--------------------------------|--------------------------|
| B10-RS0           | 6707                           | /                        |
| B10-RS1           | 6626                           | 0.988                    |
| B10-RS2           | 6584                           | 0.982                    |
| B15-RS0           | 9964                           | /                        |
| B15-RS1           | 9828                           | 0.986                    |
| B15-RS2           | 9718                           | 0.975                    |
| B20-RS0           | 13145                          | /                        |
| B20-RS1           | 12830                          | 0.976                    |
| B20-RS2           | 12742                          | 0.969                    |
| B25-RS0           | 16255                          | /                        |
| B25-RS1           | 16136                          | 0.993                    |
| B25-RS2           | 15828                          | 0.974                    |

5. Conclusion
Based on the finite element method, the welding residual stress of Q345 box section steel column is obtained by the given body heat flux. On this basis, the stable bearing capacity of box section steel column is solved, and the following conclusions are obtained:

(1) The de global stability bearing capacity of steel columns decreases with the increase of residual stress, and the reduction coefficient is more than 0.965; Compared with the zero residual stress state, the decrease of the global stability bearing capacity of steel columns is less than 5%.

(2) When the thickness of the steel column is 10mm, the same body heat flux and amplitude are defined, the maximum residual stress obtained by finite element calculation can reach about 800MPa; And the input body heat flux is reduced by half, the residual stress is not reduced by half. It shows that the magnitude of welding residual stress is not only determined by the amount of energy input during welding, but also closely related to the thickness of components.; And the relationship between body heat flux and welding residual stress is not linear.

(3) When the thickness of steel column is 20mm, the residual stress has the greatest influence on the global stability of steel column, up to 3.1%. It shows that with the increase of steel column thickness, the influence of residual stress on its global stability may be reduced.
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