Analysis of the stability bearing capacity of biaxial bending cellular steel column with circular hole

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Abstract. In order to promote the application and promotion of the cellular steel columns in practical engineering. Considering the geometric initial defect, geometric nonlinearity, material nonlinearity and residual stress. Using ABAQUS to analyze the effect of parameters of axial pressure, hole spacing, member length, hole size and flange width-thickness ratio on the stability bearing capacity of the cellular steel column, and get the influence of various parameters. The results show that with the increase of the axial pressure, member length and hole size, the stability bearing capacity of the cellular steel column decreases. With the increase of the hole spacing and flange width-thickness ratio, the stability bearing capacity of the cellular steel column increases. It is found that axial pressure, member length and flange width-thickness ratio have a great influence on the stability bearing capacity of cellular steel columns.

1. Introduction
Steel structure buildings have many advantages and are widely used in daily life. While ensuring the safety and reasonableness of steel structure construction, the economic principle should be followed as far as possible. After expansion of the web, the cellular steel columns have greater stability bearing capacity than solid-web steel columns, so the cellular steel column is undoubtedly more steel-saving and more economical.

There are many researches on cellular structures. Some scholars[1-6] have studied the mechanical properties of cellular steel structures under axial compression or bending. In addition, some scholars[7-8] have studied the performance of cellular components at the web. The literature[9] analyzed the welding residual stress at the section of the cellular section through experiments and proposed the distribution model of welding residual stress. The literature[10] used ANSYS to simulate and analyze the section positive stress of cellular steel beam and improved the algorithm of positive stress. The literature[11] carried on the experimental research to the anti-seismic performance of cellular steel frame beam-column joints. However, there are few studies on biaxial bending cellular steel columns.

In this paper, under the condition of geometric initial defect, geometric nonlinearity, material nonlinearity and residual stress, the influence and regularity of axial pressure, hole spacing, member length, hole size and flange width-thickness ratio are analyzed by ABAQUS.

2. Finite Element Model

2.1. Establishment of Finite Element Model
Considering various factors, the S4R unit is very suitable for this paper. Using Q235 steel as an ideal
elastoplastic component. The yield strength is \( f_y = 235 \text{N/mm}^2 \), the elastic modulus is \( E = 2.06 \times 10^5 \text{N/mm}^2 \), Poisson's ratio is \( \mu = 0.3 \). The Mises yield criterion is adopted after considering the characteristics of various yield criteria.

The hole type of cellular steel column in this paper is circular. Various parameters are shown in figure 1: \( D \) is the hole height of the cellular steel column; \( S \) is the hole spacing; \( H \) is the height of section; \( B \) is the width of flange; \( t_f \) is the thickness of flange; \( h_w \) is the height of web.

![Figure 1. Geometric parameters of cellular steel columns.](image)

The density of mesh has a great influence on the precision and operation speed of the model. Therefore, the global dimension is set to 20mm. Figure 2 shows the mesh of cellular steel column.

![Figure 2. Meshing of finite element model.](image)

In this paper, the cellular steel column is subjected to biaxial bending. The bottom of the cellular steel column is rigid connection. The bottom of the cellular steel column is just connected by \( U_x = U_y = U_z = UR_x = UR_y = UR_z = 0 \). Because the upper end of the cellular steel column is subjected to biaxial horizontal load, the upper end is free and does not impose any constraints. The reference point RP-1 is set on the middle surface of the upper end of cellular steel column. The reference point is coupled to the top section of the steel column. First, the axial pressure is applied at the reference point, and then the biaxial horizontal load is gradually applied at the reference point in the X and Y directions in a ratio of 1:2.

Because the components will be deformed in the process of production, transportation, construction. This kind of deformation is called geometric initial defect, including initial bending, initial eccentricity and so on. According to the steel structure code\(^{[12]}\), the geometric initial defect is considered as a sinusoidal half-wave shape. In the middle of the cellular steel column, 1/1000 of the column length is taken as the peak value of the sine half-wave. In ABAQUS, the deformation of the cellular steel column after applying geometric initial defects is shown in Figure 3.
Figure 3. Initial geometrical defect of components.

There are many kinds of residual stress modes. Cellular steel columns are made of hot rolled H steel. The residual stress in the web cannot be accurately simulated at the web, and the residual stress at the web has little effect on the stability bearing capacity of the cellular steel column. Therefore, only the residual stress at the flange is considered. The peak value of residual stress is set to $0.3f_y$.

2.2. Finite Element Model Verification

2.2.1 Model validation 1. According to the test data of components in document[13], two kinds of components are selected. Because each component is made of two, there are four components. The experimental data in the literature are compared with the value of ABAQUS simulation. $F_s$ is the simulated value; $F_e$ is the experimental value; $F_t$ is the theoretical value. The geometric size unit in Table 1 is mm and the unit of force is kN.

Table 1. Comparison of simulated values, experimental values and theoretical values.

| $b_f$ | $t_f$ | $H$ | $t_w$ | $p$ | $L$ | $F_s$ | $F_e$ | $F_s/F_e$ | $F_t$ | $F_s/F_t$ |
|------|------|-----|------|-----|-----|-------|-------|----------|-------|-----------|
| 30   | 4.2  | 38.4| 4     | 6   | 840 | 0.558 | 0.550 | 1.0145   | 0.540 | 1.0333    |
| 30   | 4.2  | 38.4| 4     | 6   | 840 | 0.558 | 0.525 | 1.0629   | 0.540 | 1.0333    |
| 30   | 4.2  | 38.4| 4     | 10  | 680 | 0.687 | 0.700 | 0.9814   | 0.645 | 1.0651    |
| 30   | 4.2  | 38.4| 4     | 10  | 680 | 0.687 | 0.650 | 1.0569   | 0.645 | 1.0651    |

According to Table 1, the range of error between simulated value and experimental value is -1.86%~6.29%. The error of simulated value and theoretical value is 3.33% and 6.51%.

2.2.2 Model validation 2. According to the data of finite element analysis in document[14]. Selecting nine components for simulation analysis with ABAQUS. As shown in table 2. $F_1$ is the simulated value of this article; $F_2$ is the value of the literature. The geometric size unit in table 2 is mm and the unit of force is kN.

Table 2. Comparison of simulated value and literature value.

| $b_f$ | $t_f$ | $H$ | $t_w$ | $\lambda$ | $D/h_w$ | $S/h_w$ | $e_t$ | $F_1$ | $F_2$ | $F_1/F_2$ |
|------|------|-----|------|----------|---------|---------|-------|-------|-------|-----------|
| 200  | 12   | 300 | 8     | 60       | 0.6     | 0.3     | 0.5   | 819.2 | 804.8 | 1.0179    |
| 200  | 12   | 300 | 8     | 80       | 0.6     | 0.3     | 0.5   | 757.6 | 737.4 | 1.0274    |
| 200  | 12   | 300 | 8     | 100      | 0.6     | 0.3     | 0.5   | 684.6 | 651.1 | 1.0515    |
| 200  | 12   | 300 | 8     | 100      | 0.7     | 0.3     | 0.5   | 670.3 | 640.6 | 1.0464    |
| 200  | 12   | 300 | 8     | 100      | 0.8     | 0.3     | 0.5   | 656.2 | 630.7 | 1.0404    |
| 200  | 12   | 300 | 8     | 140      | 0.6     | 0.1     | 1.0   | 405.0 | 409.0 | 0.9902    |
| 200  | 12   | 300 | 8     | 140      | 0.6     | 0.3     | 1.0   | 406.4 | 409.8 | 0.9917    |
| 200  | 12   | 300 | 8     | 140      | 0.6     | 0.5     | 1.0   | 407.1 | 410.7 | 0.9912    |
| 200  | 12   | 300 | 8     | 160      | 0.6     | 0.3     | 1.0   | 368.4 | 349.1 | 1.0553    |
As shown in Table 2, the range of error between the value of finite element simulation and the value of the literature is -1.21%~5.53%. The finite element verification of the two documents found that the errors were within a reasonable range, so it is feasible to use ABAQUS to establish models for the numerical analysis of the stability bending stability of cellular steel columns.

3. Finite Element Analysis of Stability Bearing Capacity of Biaxial Bending Cellular Steel Column

3.1. Axial Pressure

Table 3 shows the cellular component group with the axial pressure. The hole spacing, member length, hole size and flange width-thickness ratio remain unchanged. \( F_{ys} \) is the stability bearing capacity. When the axial pressure increases from 100kN to 200kN, \( F_{ys} \) is reduced from 12.776kN to 7.907kN. The decreasing amplitude is 38.11%. It means that the axial pressure has a great influence on the stability bearing capacity of cellular steel columns. When the other parameters remain unchanged, the stability bearing capacity of cellular steel columns decreases with the increase of the axial pressure.

### Table 3. Variation of axial pressure of components.

| Number | \( h_f \) | \( t_f \) | \( H \) | \( t_w \) | \( p \) | \( D/h_w \) | \( S/h_w \) | \( L \) | \( F_{ys} \) |
|--------|--------|--------|--------|--------|------|----------|----------|------|----------|
| A-1    | 200    | 10     | 260    | 8      | 100  | 0.5      | 0.3      | 4100 | 12.776   |
| A-2    | 200    | 10     | 260    | 8      | 110  | 0.5      | 0.3      | 4100 | 12.305   |
| A-3    | 200    | 10     | 260    | 8      | 120  | 0.5      | 0.3      | 4100 | 11.841   |
| A-4    | 200    | 10     | 260    | 8      | 130  | 0.5      | 0.3      | 4100 | 11.377   |
| A-5    | 200    | 10     | 260    | 8      | 140  | 0.5      | 0.3      | 4100 | 10.918   |
| A-6    | 200    | 10     | 260    | 8      | 150  | 0.5      | 0.3      | 4100 | 10.447   |
| A-7    | 200    | 10     | 260    | 8      | 160  | 0.5      | 0.3      | 4100 | 9.968    |
| A-8    | 200    | 10     | 260    | 8      | 170  | 0.5      | 0.3      | 4100 | 9.479    |
| A-9    | 200    | 10     | 260    | 8      | 180  | 0.5      | 0.3      | 4100 | 8.970    |
| A-10   | 200    | 10     | 260    | 8      | 190  | 0.5      | 0.3      | 4100 | 8.448    |
| A-11   | 200    | 10     | 260    | 8      | 200  | 0.5      | 0.3      | 4100 | 7.907    |

The load-displacement curves in X and Y directions of each component in Table 3 are drawn. As shown in Figure 4. When the components reach stability bearing capacity, the maximum displacement in Y direction shows a downward trend obviously. The maximum displacement is reduced from 30.260mm to 17.539mm. The decreasing amplitude is 42.04%.

![Figure 4. Variation of axial pressure of components.](image)

3.2. Hole Spacing

Table 4 shows the cellular component group with the hole spacing. The axial pressure, member length, hole size and flange width-thickness ratio are unchanged. \( F_{ys} \) is the stability bearing capacity. When the hole spacing is increased from 0.1\( h_w \) to 0.9\( h_w \), \( F_{ys} \) increases from 12.427kN to 12.481kN. The amplification is 0.43%. It means that the hole spacing has little effect on the stability bearing capacity.
of cellular steel columns. When other parameters remain unchanged, the stability bearing capacity of cellular steel columns increases with the increase of the hole spacing.

### Table 4. Variation of hole spacing of components.

| Number | $b_f$ | $t_f$ | $H$ | $t_w$ | $p$ | $D/h_w$ | $S/h_w$ | $L$ | $F_{ys}$ |
|--------|-------|-------|-----|-------|-----|---------|---------|-----|--------|
| B-1    | 200   | 10    | 260 | 8     | 120 | 0.5     | 0.1     | 4000| 12.427 |
| B-2    | 200   | 10    | 260 | 8     | 120 | 0.5     | 0.2     | 4000| 12.437 |
| B-3    | 200   | 10    | 260 | 8     | 120 | 0.5     | 0.3     | 4000| 12.447 |
| B-4    | 200   | 10    | 260 | 8     | 120 | 0.5     | 0.4     | 4000| 12.455 |
| B-5    | 200   | 10    | 260 | 8     | 120 | 0.5     | 0.5     | 4000| 12.463 |
| B-6    | 200   | 10    | 260 | 8     | 120 | 0.5     | 0.6     | 4000| 12.468 |
| B-7    | 200   | 10    | 260 | 8     | 120 | 0.5     | 0.7     | 4000| 12.472 |
| B-8    | 200   | 10    | 260 | 8     | 120 | 0.5     | 0.8     | 4000| 12.476 |
| B-9    | 200   | 10    | 260 | 8     | 120 | 0.5     | 0.9     | 4000| 12.481 |

The load-displacement curves in the X and Y directions of each component in table 4 are drawn. As shown in Figure 5. According to the graph, the maximum displacement in X and Y directions is not obvious when the cellular steel columns reach stability bearing capacity.

![Load-displacement curves](image)

**Figure 5.** Variation of hole spacing of components.

### 3.3 Member Length

Table 5 shows the cellular component group with the member length. The axial pressure, hole spacing, hole size and flange width-thickness ratio are unchanged. $F_{ys}$ is the stability bearing capacity. When the member length is increased from 3400mm to 5200mm, $F_{ys}$ is reduced from 16.667kN to 6.661kN. The decreasing amplitude is 60.03%. It means that the member length has a great influence on the stability bearing capacity of cellular steel columns. When other parameters remain unchanged, the stability bearing capacity of cellular steel columns decreases with the increase of the member length.

### Table 5 Variation of member length of components.

| Number | $b_f$ | $t_f$ | $H$ | $t_w$ | $p$ | $D/h_w$ | $S/h_w$ | $L$ | $F_{ys}$ |
|--------|-------|-------|-----|-------|-----|---------|---------|-----|--------|
| C-1    | 200   | 10    | 260 | 8     | 120 | 0.5     | 0.25    | 3400| 16.667 |
| C-2    | 200   | 10    | 260 | 8     | 120 | 0.5     | 0.25    | 3600| 15.088 |
| C-3    | 200   | 10    | 260 | 8     | 120 | 0.5     | 0.25    | 3800| 13.706 |
| C-4    | 200   | 10    | 260 | 8     | 120 | 0.5     | 0.25    | 4000| 12.442 |
| C-5    | 200   | 10    | 260 | 8     | 120 | 0.5     | 0.25    | 4200| 11.274 |
| C-6    | 200   | 10    | 260 | 8     | 120 | 0.5     | 0.25    | 4400| 10.237 |
| C-7    | 200   | 10    | 260 | 8     | 120 | 0.5     | 0.25    | 4600| 9.252  |
| C-8    | 200   | 10    | 260 | 8     | 120 | 0.5     | 0.25    | 4800| 8.322  |
| C-9    | 200   | 10    | 260 | 8     | 120 | 0.5     | 0.25    | 5000| 7.471  |
| C-10   | 200   | 10    | 260 | 8     | 120 | 0.5     | 0.25    | 5200| 6.661  |
The load-displacement curves in the X and Y directions of each component in table 5 are drawn. As shown in Figure 6. The maximum displacement in X direction shows an obvious upward trend when the cellular steel columns reach the stability bearing capacity. The maximum displacement increases from 90.754mm to 151.730mm. The amplification is 67.19%.

![Figure 6. Variation of member length of components.](image)

### 3.4. Hole size

Table 6 shows the cellular component group with the hole size. The axial pressure, hole spacing, member length and flange width-thickness ratio are unchanged. $F_{ys}$ is the stability bearing capacity. When the hole size increases from $0.4h_w$ to $0.9h_w$, $F_{ys}$ is reduced from 12.946kN to 12.483kN. The decreasing amplitude is 3.57%. It means that the hole size has little influence on the stability bearing capacity of cellular steel columns. When other parameters remain unchanged, the stability bearing capacity of cellular steel columns decreases with the increase of the hole size.

| Number | $b_f$ | $t_f$ | $H$ | $t_w$ | $p$ | $D/h_w$ | $S/h_w$ | $L$ | $F_{ys}$ |
|--------|-------|-------|-----|-------|-----|----------|----------|-----|----------|
| D-1    | 200   | 10    | 260 | 8     | 110 | 0.4      | 0.2      | 4000| 12.946   |
| D-2    | 200   | 10    | 260 | 8     | 110 | 0.5      | 0.2      | 4000| 12.903   |
| D-3    | 200   | 10    | 260 | 8     | 110 | 0.6      | 0.2      | 4000| 12.807   |
| D-4    | 200   | 10    | 260 | 8     | 110 | 0.7      | 0.2      | 4000| 12.736   |
| D-5    | 200   | 10    | 260 | 8     | 110 | 0.8      | 0.2      | 4000| 12.646   |
| D-6    | 200   | 10    | 260 | 8     | 110 | 0.9      | 0.2      | 4000| 12.483   |

The load-displacement curves in X and Y directions of each component in table 6 are drawn. As shown in Figure 7. The maximum displacement in Y direction shows a certain upward trend when components reach the stability bearing capacity. The maximum displacement increases from 27.710mm to 33.056mm. The amplification is 19.29%.

![Figure 7. Variation of hole size of components.](image)

### 3.5. Flange Width-Thickness Ratio

Table 7 shows the cellular component group with the flange width-thickness ratio. The axial pressure;
hole spacing, member length and hole size are unchanged. $F_{ys}$ is the stability bearing capacity. When the flange width-thickness ratio is changed from 17 to 21, $F_{ys}$ increases from 7.745kN to 14.599kN. The amplification is 88.50%. It means that the flange width-thickness ratio has a great influence on the stability bearing capacity of components. When the other parameters remain unchanged, the stability bearing capacity of cellular steel columns increases with the increase of the flange width-thickness ratio.

**Table 7.** Variation of flange width-thickness ratio of components.

| Number | $b_f$ | $t_f$ | $H$ | $t_w$ | $p$ | $D/h_w$ | $S/h_w$ | $L$ | $F_{ys}$ |
|--------|-------|-------|-----|-------|-----|--------|--------|-----|---------|
| E-1    | 170   | 10    | 260 | 8     | 100 | 0.5    | 0.3    | 4100 | 7.745   |
| E-2    | 175   | 10    | 260 | 8     | 100 | 0.5    | 0.3    | 4100 | 8.287   |
| E-3    | 180   | 10    | 260 | 8     | 100 | 0.5    | 0.3    | 4100 | 9.212   |
| E-4    | 185   | 10    | 260 | 8     | 100 | 0.5    | 0.3    | 4100 | 10.046  |
| E-5    | 190   | 10    | 260 | 8     | 100 | 0.5    | 0.3    | 4100 | 11.005  |
| E-6    | 195   | 10    | 260 | 8     | 100 | 0.5    | 0.3    | 4100 | 11.899  |
| E-7    | 200   | 10    | 260 | 8     | 100 | 0.5    | 0.3    | 4100 | 12.776  |
| E-8    | 205   | 10    | 260 | 8     | 100 | 0.5    | 0.3    | 4100 | 13.729  |
| E-9    | 210   | 10    | 260 | 8     | 100 | 0.5    | 0.3    | 4100 | 14.599  |

The load-displacement curves in X and Y directions of each component in Table 7 are drawn. As shown in Figure 8. When the flange width-thickness ratio increases from 17 to 21, the maximum displacement in Y direction is obviously rising. The maximum displacement increases from 18.072mm to 35.370mm. The amplification is 95.72%.

**Figure 8.** Variation of flange width-thickness ratio of components.

### 4. Conclusion

1. The axial pressure has a great influence on the cellular steel column. Keeping other parameters unchanged, the stability bearing capacity of cellular steel columns decreases with the increase of axial pressure;

2. The hole spacing has little effect on the cellular steel column. Keeping other parameters unchanged, the stability bearing capacity of cellular steel columns increases with the increase of hole spacing;

3. The member length has a great influence on the cellular steel column. Keeping other parameters unchanged, the stability bearing capacity of cellular steel columns decreases with the increase of member length;

4. The hole size has a certain effect on the cellular steel column but not much. With other parameters unchanged, the stability bearing capacity of cellular steel columns decreases with the increase of hole size;

5. The flange width-thickness ratio has a great influence on the cellular steel column. Keeping other parameters unchanged, the stability bearing capacity of cellular steel columns increases with the increase of flange width-thickness ratio.
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