Plastic Effect Analysis of High Strength Steel Frame Structure

Peixu Chen¹*, Zheng Zhang¹ and Rensheng Liao¹

¹School of Civil Engineering, Fujian University of Technology, Fuzhou City, Fujian Province, 350118, China
*cpx13055748461@163.com

Abstract. High strength steel structure is more and more widely used in the field of building structure because of its advantages in mechanical properties. The design of high-strength steel frame often refers to steel structure. For the high-strength steel with no yield platform of stress-strain curve, the influence of plastic strain before the nominal yield strength of its material on the results of the frame remains to be studied. In order to study the influence of plastic effect on high-strength steel frame, the second-order elastic-plastic analysis of typical frame is carried out and compared with the simplified design method of steel structure design standard. The results show that the plastic effect has no significant effect on the bending moment and lateral displacement of high-strength steel frame in most cases. Base on the analysis results, the design suggestions of high-strength steel frame structure are put forward.

1. Introduction
High strength steel has the advantages of high strength, reducing the cross-section of members and effectively reducing the self-weight of the structure. High strength steel structure has strong advantages in mechanical properties, economy and social benefits, and it has great engineering application potential[1]. The analysis and design of high-strength steel frame structure refer to the national standard steel structure design standard[2] (hereinafter referred to as the "steel standard"), because the frame analysis method proposed in the steel standard is mainly for ordinary steel with linear stress-strain change, it needs to be verified whether the high-strength steel with plastic effect before the nominal yield strength $f_{0.2}$ is applicable.

In order to investigate the mechanical properties of high-strength steel under plastic effect, the numerical models of single-layer single span, two-layer single span and two-layer two span typical high-strength steel frame structure are established in this paper. The precise second-order elastic analysis and the precise second-order elastic-plastic analysis are carried out to study whether the plastic effect will have an adverse effect on the design of high-strength steel frame structure, so as to obtain the results that can be used for reference in practical engineering design.

2. Design method
The second-order effect coefficient $\theta_{i}^{*\text{max}}$ is used to consider the influence of the second-order effect in the steel standard. The second-order effect coefficient is calculated as follows:

$$\theta_{i}^{*\text{max}} = \frac{\sum N_i \Delta h_i}{\sum H_i \Delta h_i}$$

(1)
Where, $\Sigma N_i$ is the sum of the design values of the axial forces of the columns in the calculation floor; $\Sigma H_k$ is the sum of the horizontal forces in the calculation floor and above; $h_i$ is the storey height; $\Delta u_i$ is the first-order analysis and calculation of the storey lateral displacement.

The initial defects of the frame include the overall structural defects and the component defects. The imaginary horizontal force and the equivalent uniform load are used to simplify the two initial defects. The simplified calculation model is shown in Figure 1.

![Frame calculation model](image)

**Figure 1. Frame calculation model.**

The calculation method of the overall initial defect of the frame structure is as follows:

$$A_i = \frac{h_i}{250} \sqrt{0.2 + \frac{1}{n_s}}$$

(2)

$$H_{k,i} = \frac{G_i}{250} \sqrt{0.2 + \frac{1}{n_s}}$$

(3)

Calculation method of initial defects of components:

$$q_0 = 8N_k e_0 l^2$$

(4)

Where, $A_i$ is the representative value of the initial defect, $n_s$ is the total number of floors of the structure, when $\sqrt{0.2 + 1/n_s} < 2/3$, take $2/3$; when $\sqrt{0.2 + 1/n_s} < 1$, take 1.0. $h_i$ is the floor height, $G_i$ is the design value of gravity load, $e_0$ is the initial deformation value in the span, $l$ is the total length of the member, $q_0$ is the equivalent distributed load, $N_k$ is the standard value of axial force.

3. **Numerical simulation**

3.1 **Constitutive relationship**

The constitutive relationship of high-strength steel is different from ordinary carbon steel. Q550 and above-strength steels have no yield platform[3], and have a certain nonlinearity (See figure 2).

![Stress-strain curve](image)

**Figure 2. Stress-strain curve of Q550 and ideal elastoplastic body of steel.**

The stress-strain relationship of high-strength steel without yield platform under monotonic load proposed by literature[4] is as follows:

$$\varepsilon = \begin{cases} \frac{\sigma}{E_0} + 0.002 \left( \frac{\sigma}{f_{0.2}} \right)^6 & \sigma \leq f_{0.2} \\ \frac{\sigma - f_{0.2}}{E_{0.2}} + \left( \varepsilon_0 - \frac{\sigma - f_{0.2}}{E_{0.2}} \right) \left( \frac{\sigma - f_{0.2}}{f_{0.2} - E_{0.2}} \right)^{10} + \varepsilon_0 & f_{0.2} < \sigma \leq f_e \end{cases}$$

(5)
Where, \( n = \ln(20/\ln(f_{0.2}/f_{0.01})) \), \( E_{0.2} = E_0/(1+0.002n/e) \), \( e = f_{0.2}/E \), \( m = -24.647f_{0.2}/f_u + 25.202 \), \( m = 1+3.5f_{0.2}/f_u \).

3.2 Parameter setting
In this paper, the high strength steel Q550 commonly used in engineering is selected for analysis. The elastic modulus \( E \) is 206 GPa, the nominal yield strength \( f_{0.2} \) is 550 MPa, and the Poisson’s ratio is 0.3. The large-scale general finite element analysis software ABAQUS is used for simulation, and the linear beam element B21[5] is selected as the element. Based on Timoshenko beam theory, the element can customize the section shape, and consider the influence of geometric nonlinearity and material nonlinearity.

3.3 Initial defect and model validation
The global initial geometric imperfection of the structure is set in the first-order buckling mode of the frame, and 1/250 of the total height of the structure is taken as the maximum value \( \Delta_0 \) of the representative value of the global initial geometric imperfection of the structure. The frame column is divided into 20 elements[6], and the form of sine half wave curve is applied to the model to consider the initial defect of the member. The maximum value of the initial defect \( e_0 \) of the member is 1/350 of the total length of the member.

| Frame type | Section | Section type | Section size | A/cm² | I/cm⁴ | W/cm³ |
|------------|---------|--------------|--------------|-------|-------|-------|
| A          | Column  | HW400×400    | 400×400×21×13 | 219.5 | 66900 | 3340  |
|            | Beam    | HM450×300    | 440×300×11×18 | 157.4 | 56100 | 2550  |
| B          | Column  | HW400×400    | 350×350×12×19 | 173.9 | 40300 | 2300  |
|            | Beam    | HM450×300    | 440×300×11×18 | 157.4 | 56100 | 2550  |
| C          | Column  | HW350×350    | 350×350×12×19 | 173.9 | 40300 | 2300  |
|            | Beam    | HM400×200    | 400×200×8×12  | 84.1  | 23700 | 1190  |

Table 2. Load arrangement.

| Example number | F₁/kN | F₂/kN | Q₁/kN-m | Q₂/kN-m |
|----------------|-------|-------|---------|---------|
| A              | 1     | 10    | 240     | /       |
| B              | 2     | 7     | 220     | 180     |
| C              | 3     | 10    | 260     | 80      |
| D              | 4     | 40    | 320     | 240     |
| E              | 5     | 10    | 320     | 95      |
| F              | 6     | 12    | 355     | 105     |
| G              | 7     | 10    | 340     | 270     |
| H              | 8     | 10    | 395     | 290     |
| I              | 9     | 10    | 365     | 110     |
| J              | 10    | 10    | 365     | 115     |
| K              | 11    | 10    | 380     | 305     |
| L              | 12    | 10    | 340     | 150     |

Table 1. Section parameter.

The boundary condition of the frame structure model is that the column base is fixed to the foundation, and the beam column joint is rigid. In the calculation process, the maximum stress of the control frame is under the nominal yield strength of high-strength steel. Table 1 shows the section parameters, table 2 shows the load layout, and figure 3 shows the calculation diagram of single-layer single span, two-layer single span and two-layer two span (respectively represented by frame types A, B and C).
The calculation results of the frame model in literature[7] (see figure 4) and literature[8] are simulated and compared. The comparison results are quite consistent, which shows the accuracy of the frame finite element model.

4. Computational analysis

The influence of plastic effect is determined by introducing plastic effect coefficient $\delta$, the formula is as follows:

$$\delta = \sigma_{max} / f_{0.2}$$  \hspace{1cm} (6)

In the formula, $\sigma_{max}$ is the maximum stress of the calculated frame, $f_{0.2}$ is the nominal yield strength of the metal material.

| Frame type | Node number | Bending moment and side shift | Second-order elastic $M_A/kN\cdot m$ | Second-order elastic-plastic $M_A/kN\cdot m$ | Second-order elastic $M_B/kN\cdot m$ | Second-order elastic-plastic $M_B/kN\cdot m$ | $(M_B-M_A)\times100\%$ | $(M_B-M_C)\times100\%$ |
|------------|-------------|-----------------------------|-------------------------------------|--------------------------------------|-------------------------------------|--------------------------------------|----------------|----------------|
| A          | 2           | $M_2$                       | 623.16                              | 737.57                               | 737.74                               | 0.00                                 | 0.02           | 0.02         |
|            | 4           | $M_4$                       | 767.71                              | 884.42                               | 884.59                               | 0.00                                 | 0.02           | 0.02         |
|            |             | $u/mm$                      | 11.42                               | 11.70                                | 11.70                                | 0.00                                 | 0.00           | 0.00         |
| B          | 2           | $M_3$                       | 545.51                              | 641.00                               | 641.01                               | 0.00                                 | 0.00           | 0.00         |
|            | 5           | $M_5$                       | -585.02                             | -680.79                              | -680.80                              | 0.00                                 | 0.00           | 0.00         |
|            |             | $u/mm$                      | 10.23                               | 11.14                                | 11.14                                | 0.00                                 | 0.00           | 0.00         |
| C          | 2           | $M_6$                       | -192.44                             | -234.73                              | -234.75                              | 0.00                                 | 0.01           | 0.00         |
|            | 9           | $M_9$                       | 205.88                              | 268.22                               | 268.23                               | 0.00                                 | 0.00           | 0.00         |
|            |             | $u/mm$                      | 6.62                                | 4.16                                 | 4.18                                 | 0.00                                 | 0.48           | 0.00         |

4.2 Table3. Plastic effect.

| Frame type | Node number | Bending moment and side shift | Second-order elastic $M_A/kN\cdot m$ | Second-order elastic-plastic $M_A/kN\cdot m$ | Second-order elastic $M_B/kN\cdot m$ | Second-order elastic-plastic $M_B/kN\cdot m$ | $(M_B-M_A)\times100\%$ | $(M_B-M_C)\times100\%$ |
|------------|-------------|-----------------------------|-------------------------------------|--------------------------------------|-------------------------------------|--------------------------------------|----------------|----------------|
| A          | 2           | $M_2$                       | 851.83                              | 951.66                               | 967.24                               | 0.39                                 | 1.64           | 0.32         |
|            | 4           | $M_4$                       | 1001.05                             | 1103.03                              | 1118.21                              | 0.32                                 | 1.38           | 0.32         |
|            |             | $u/mm$                      | 11.97                               | 12.20                                | 12.20                                | 0.00                                 | 0.00           | 0.00         |
| B          | 2           | $M_3$                       | 734.56                              | 831.25                               | 832.08                               | 0.02                                 | 0.10           | 0.02         |
|            | 5           | $M_5$                       | -774.81                             | -872.74                              | -873.88                              | 0.01                                 | 0.13           | 0.01         |
|            |             | $u/mm$                      | 12.03                               | 13.05                                | 13.40                                | 0.42                                 | 2.68           | 0.42         |
| C          | 2           | $M_6$                       | -272.48                             | -305.68                              | -306.71                              | 0.07                                 | 0.33           | 0.07         |
|            | 9           | $M_9$                       | 316.17                              | 349.73                               | 350.49                               | 0.05                                 | 0.22           | 0.05         |
|            |             | $u/mm$                      | 4.49                                | 4.72                                 | 4.86                                 | 0.67                                 | 2.97           | 0.67         |
|            |             | $u/mm$                      | 7.65                                | 8.00                                 | 8.32                                 | 0.92                                 | 4.00           | 0.92         |
According to the data in Table 3, the plastic effect of high-strength steel frame increases with the increase of plastic effect coefficient $\delta$, but the increase is not obvious. Through the analysis of data, when $\delta \leq 0.9$, the maximum difference of bending moment and displacement is 0.33% and 4.00% respectively, the plastic effect has little influence on the bending moment and lateral displacement, so the plastic effect can be ignored within the scope of the plastic effect coefficient. When $\delta > 0.9$, the maximum difference of bending moment and displacement is 7.13% and 12.87% respectively, the internal force and deformation of the high-strength steel frame have a greater impact on the plastic effect, so the plastic effect should be considered in the design of the plastic effect coefficient range.

5. Conclusion
In this paper, the second-order $P-\Delta-\delta$ elastic analysis and the second-order $P-\Delta$-elastic-plastic analysis of the high-strength steel frame under different plastic effect coefficient are compared, and the following conclusions are drawn:

(1) Based on the data in this paper, when $\delta \leq 0.9$, the plastic effect is not obvious, the maximum increase of internal force is 1.88%, and the maximum increase of lateral displacement difference is 4.00%. When $\delta = 0.95$, the influence of plastic effect is obvious, the maximum increment of moment is 5.12%, and the maximum increment of lateral displacement is 7.43%. When $\delta = 0.98$, the plastic effect of frame is more significant. The maximum increase of bending moment of frame A, B and C is 7.13%, and the maximum increase of lateral displacement is 12.84%.

(2) The influence of the plastic effect on the moment and the lateral displacement of the high-strength steel frame structure is not significant most of the time before the stress reaches the nominal yield strength. When the plastic effect coefficient is $\delta=0.9$, the influence of plastic effect on the frame is obvious. When $\delta \leq 0.9$, the plastic effect has little effect on the bending moment and lateral displacement of the frame. The increase of bending moment and lateral displacement caused by plastic effect is only 1.88% and 4.00% respectively. Therefore, this paper suggests that when the plastic effect coefficient of high-strength steel is $\delta \leq 0.9$, the plastic effect of materials may not be considered in the structural design of high-strength steel frame.

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