Second-order Effect Finite Element Analysis of Stainless Steel Frame Structure

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Abstract. Stainless steel has strong corrosion resistance and durability, which ensures the structural safety and durability, and has a good application prospect. Experiments on stainless steel have shown that the stress-strain nonlinearity of stainless steel is remarkable, which is different from that of ordinary steel. At present, the technical specifications for stainless steel structures do not specify the analysis of the internal force of stainless steel frames. By comparing the design specifications of steel structures and using finite element analysis method to analyze the internal forces of stainless steel frames, it is concluded that the approximate second-order analysis method in the design specifications of stainless steel frames can not be used, and the second-order analysis of internal forces of stainless steel frames should be carried out in consideration of material nonlinearity.

1. Introduction

The stainless steel structure has the advantages of beautiful appearance, good corrosion resistance, easy maintenance and low life cycle cost, which makes it have wide applicability in the building structure [1]. Different from ordinary steel, stainless steel is a typical nonlinear material, and its tangential elastic modulus will gradually decrease with the increase of stress, so its stability under axial pressure is quite different from that of ordinary steel. The current stainless steel structural technical specification CECS410-2015[2] does not clearly define the internal force analysis of the frame structure. Although it can be analyzed with reference to the steel structure design specification, the framework of the steel structure design specification GB50017-2003 [3] approximates the second-order analysis method. Mainly for steel materials with linear changes in stress-strain, whether it is suitable for internal force analysis of stainless steel frame structures remains to be verified.

In this paper, three typical stainless steel frame structures are established by using the finite element analysis method for first-order analysis and second-order analysis, compared with the results obtained by the second-order approximation analysis method provided in the steel structure design specification. It is verified whether the stainless steel frame structure design can follow the design method provided by the steel structure design specification, and provide ideas for the future design of the stainless steel frame structure.

2. Analysis Method in Steel Structure Design Specification

The first-order analysis is the equilibrium analysis in the undeformed state of the structure, and the analysis of the equilibrium of the structure in the deformed state is called the second-order analysis. The second-order analysis that only considers geometric nonlinearity is called second-order elastic analysis. The steel structure design specification GB50017-2003[3] frame structure internal force
analysis The first article stipulates that "frame structure can adopt first-order elastic analysis". For steel frames that satisfy the formula (1), a second-order analysis should be used.

\[ \sum \frac{N \cdot \Delta u}{H \cdot h} > 0.1 \]  

Where, \( \Sigma N \) — the sum of the design values of the axial pressure on each column of the calculated floor; 
\( \Delta u \) — the inter-story lateral displacement of the calculated floor obtained by first-order elastic analysis; 
\( \Sigma H \) — the sum of the horizontal forces on the calculated floor and the above layers for the generation of the lateral displacement \( \Delta u \); 
\( h \) — The height of the calculated floor.

Precise second order analysis of the framework can be done by numerical methods, such as beam-column method, finite element method, virtual load method, etc. However, accurate nonlinear analysis methods are time consuming and general engineering designs are not suitable for use. When accurate calculations are not required, it is easier to consider second-order effects using an approximate second-order analysis method. Therefore, GB50017 \cite{3} proposes an approximate second-order analysis method for the internal force analysis, which stipulates that when performing the second-order elastic-plastic analysis. Regardless of whether it is exact or approximate calculations, whether or not there are supporting structures, it is necessary to consider the imaginary horizontal force \( H_{ni} \) at the top of each column to take into account the influence of various defects of the structure and components (such as the initial tilt of the column, initial eccentricity, and residual stress) to match the accuracy of the calculation on the frame, and use Equation (2) for calculation.

\[ H_{ni} = \frac{\alpha_i Q_i}{250} \sqrt{0.2 + \frac{1}{n_i}} \]

Where, \( Q_i \) — The total gravity load design value of the i-th floor; 
\( n_i \) — The total number of layers of the frame, and \( \sqrt{0.2 + \frac{1}{n_i}} > 1 \) take this root number value as 1.0; 
\( \alpha_y \) — The influence factor of steel strength is 1.0 for Q235 steel, 1.1 for Q345 steel, 1.2 for Q390 steel, and 1.25 for Q420 steel.

For unsupported frame structures, when using the second-order elastic analysis can use the equations (3) and (4) to calculate the bending moments at the rod end of each element.

\[ M_{ii} = M_{ib} + \alpha_{zi} M_{is} \]  

\[ \alpha_{zi} = \frac{1}{1 - \frac{\sum N \cdot \Delta u}{\sum H \cdot h}} \]

Where, \( M_{ib} \) — bending moment of each rod end obtained by first-order elastic analysis assuming that the frame is not laterally displaced; 
\( M_{is} \) — bending moment of each rod end obtained by first-order elastic analysis when each node of the frame moves sideways; 
\( \alpha_{zi} \) — the increscent coefficient of the lateral bending moment of considering the second-order effect i-th layer member.

3. Constitutive Relationship of Stainless Steel

Austenitic stainless steel S316 has a wide range of applications and is the most widely used steel grade after S304. The Article 4 is based on the austenitic stainless steel S31608, and the Ramberg-Osgood model is modified and fitted with the measured stress-strain curve. The modified Ramberg-Osgood model agrees well with the experimental curve. The formula (5) is as follows:
The calculation results show that the stress-strain curves of austenitic stainless steel S31608 and ordinary steel are as follows:

The material properties used in this paper are elastic modulus \( E = 2.03 \times 10^5 \) MPa, Poisson's ratio 0.3, austenitic stainless steel S31608 steel strength 375 MPa. The section properties of each study are shown in Table 1.

The frame is calculated by using the linear beam element B21\(^{[5]}\) in ABAQUS. Based on the Timoshenko beam theory, the influence of transverse shear deformation is considered in addition to the deformation such as axial, bending and torsion. It is suitable for structural analysis of large strain and large deformation. For the geometric nonlinearity, the large deformation switch is required to be opened in the analysis step. At the same time, the initial roll of the stainless steel frame is \( H/1000 \) (\( H \) is the total height of the frame) as the initial geometrical defect of the whole structure. The analysis did not take into account the semi-rigid, the column feet and nodes are set to rigid connection.

According to the provisions of the regulations, it used a precise second-order elasto-plastic analysis method and an approximate second-order elastic analysis method to make comparative calculations. The example (Figure 2) uses single-span single frame and single-span two-story frame.

Table 1. Section properties

| Example 1 | Section  | Section type | Cross section area/cm\(^2\) | Moment of inertia /cm\(^4\) | Modulus of section / cm\(^3\) |
|-----------|----------|--------------|-----------------------------|----------------------------|-------------------------------|
| Column    | HM300×200| 294×200×8×12 | 73.03                       | 11400                      |
| Beam      | HM400×200| 400×200×8×13 | 84.12                       | 23700                      |

| Example 2 | Section  | Section type | Cross section area/cm\(^2\) | Moment of inertia /cm\(^4\) | Modulus of section / cm\(^3\) |
|-----------|----------|--------------|-----------------------------|----------------------------|-------------------------------|
| Column    | HM400×300| 390×300×10×16| 136.7                       | 38900                      |
| Beam      | HM400×200| 400×200×8×13 | 84.12                       | 23700                      |

| Example 3 | Section  | Section type | Cross section area/cm\(^2\) | Moment of inertia /cm\(^4\) | Modulus of section / cm\(^3\) |
|-----------|----------|--------------|-----------------------------|----------------------------|-------------------------------|
| Column    | HM300×200| 294×200×8×12 | 73.03                       | 11400                      |
| Beam      | HM400×200| 400×200×8×13 | 84.12                       | 23700                      |

In addition, the calculation examples all meet the requirements of the deformation tolerance of the structures or members specified in GB50017, ie the beam disturbance is not greater than \( L/400 \) of the span \( L \), the relative displacement between the frames is not greater than \( L/400 \) of the layer height \( H \), and the column top displacement not more than \( L/500 \) of \( H \) of the total height of the frame structure.
4. Result Analysis And Comparison

Austenitic S316 stainless steel $\alpha_y$ is taken as 1.1. The horizontal lateral displacement of each frame calculated by finite element software ABAQUS is shown in Table 3. The data from Table 3 are substituted into Formula (1), Formula (2) and Formula (4) as shown in Table 2.

| Parameter values | Example1 | Example2 | Example3 |
|------------------|----------|----------|----------|
| $\sum N \cdot \Delta u / \left( \sum H \cdot h \right)$ | 0.133 | 0.109 | 0.073 | 0.126 | 0.120 |
| $\alpha_{2i}$ | 1.153 | 1.122 | 1.079 | 1.144 | 1.136 |
| $H_{mi}$ | 3.43 | 6.63 | 2.21 | 7.73 | 3.31 |

Through the data analysis in Table 2, it can be found that the horizontal displacement of the second-order elastoplastic horizontal phase is much larger than that of the first-order horizontal lateral displacement, and the problem of the second-order elastoplastic lateral displacement is not negligible in the frame design. Since frame 2 is considered as a whole, it can be clearly seen that the percentage of lateral displacement of frame 2 second-order elastoplastic horizontal displacement and first-order horizontal lateral displacement is much smaller than that of frame 3, which also verifies the model's Correctness.

The finite element first-order analysis results, the results of the approximate two analysis and the exact second-order elastoplastic analysis are shown in Table 4, Table 5 and Table 6. The nodes at both ends of the rod respectively indicate the bottom of the column with A and B indicates the top of the column.

Table 3. Comparison of horizontal displacement

| Parameter values | Example1 | Example2 | Example3 |
|------------------|----------|----------|----------|
| First order elastic $U_i$/mm. | First floor | First floor | Second floor |
| | 16.40 | 13.57 | 7.83 | 13.48 | 8.55 |
| Second order elastic-plastic | First floor | Second floor |
| | 31.87 | 17.08 | 10.46 | 26.34 | 20.67 |
\[ U''_{II}/\text{mm.} \]
\[ \left( \frac{U''_{II} - U_0}{U''_{II}} \right) \times 100 \% \]
\[ 48.5 \quad 20.6 \quad 25.1 \quad 48.8 \quad 58.6 \]

Table 4. Rod End Moment of Example 1

| Rod end number | First order elastic \( M_I / \text{kN} \cdot \text{m} \) | Approximate second order elastic \( M'_{II} / \text{kN} \cdot \text{m} \) | Second order elastic-plastic \( M''_{II} / \text{kN} \cdot \text{m} \) | \( \frac{(M_II - M_I)}{M_II} \times 100\% \) | \( \frac{(M''_{II} - M_I)}{M''_{II}} \times 100\% \) |
|----------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|---------------------------------------------|---------------------------------------------|
| 1-A            | -58.12                                        | -53.62                                        | -68.54                                        | 15.20                                       | 21.77                                       |
| 1-B            | 152.59                                        | 155.21                                        | 194.46                                        | 21.53                                       | 25.29                                       |
| 2-A            | -104.09                                       | -108.31                                       | -145.81                                       | 28.61                                       | 25.72                                       |
| 2-B            | 193.02                                        | 195.62                                        | 234.82                                        | 17.80                                       | 16.69                                       |

Table 5. Rod End Moment of Example 2

| Rod end number | First order elastic \( M_I / \text{kN} \cdot \text{m} \) | Approximate second order elastic \( M'_{II} / \text{kN} \cdot \text{m} \) | Second order elastic-plastic \( M''_{II} / \text{kN} \cdot \text{m} \) | \( \frac{(M_II - M_I)}{M_II} \times 100\% \) | \( \frac{(M''_{II} - M_I)}{M''_{II}} \times 100\% \) |
|----------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|---------------------------------------------|---------------------------------------------|
| 1-A            | -44.97                                        | -34.66                                        | -21.04                                        | -113.74                                     | 64.73                                       |
| 1-B            | 189.80                                        | 182.68                                        | 219.87                                        | 13.68                                       | 20.36                                       |
| 2-A            | -168.12                                       | -177.84                                       | -232.98                                       | 27.84                                       | 23.67                                       |
| 2-B            | 268.26                                        | 274.29                                        | 307.24                                        | 12.69                                       | 10.73                                       |
| 3-A            | -329.39                                       | -328.15                                       | -389.44                                       | 15.42                                       | 15.74                                       |
| 3-B            | 340.15                                        | 336.92                                        | 362.81                                        | 6.25                                        | 6.73                                        |
| 4-A            | -345.42                                       | -345.51                                       | -388.22                                       | 11.03                                       | 11.00                                       |
| 4-B            | 381.72                                        | 383.87                                        | 452.59                                        | 15.66                                       | 15.18                                       |

Table 6. Rod End Moment of Example 3

| Rod end number | First order elastic \( M_I / \text{kN} \cdot \text{m} \) | Approximate second order elastic \( M'_{II} / \text{kN} \cdot \text{m} \) | Second order elastic-plastic \( M''_{II} / \text{kN} \cdot \text{m} \) | \( \frac{(M_II - M_I)}{M_II} \times 100\% \) | \( \frac{(M''_{II} - M_I)}{M''_{II}} \times 100\% \) |
|----------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|---------------------------------------------|---------------------------------------------|
| 1-A            | -56.25                                        | -47.29                                        | -49.58                                        | -13.45                                      | 4.62                                        |
| 1-B            | 214.45                                        | 208.18                                        | 216.54                                        | 0.97                                        | 3.86                                        |
| 2-A            | -179.39                                       | -187.76                                       | -201.99                                       | 11.19                                       | 7.04                                        |
| 2-B            | 292.91                                        | 298.22                                        | 310.86                                        | 5.77                                        | 4.07                                        |
| 3-A            | -295.50                                       | -294.88                                       | -308.2                                        | 4.12                                        | 4.32                                        |
| 3-B            | 226.33                                        | 224.57                                        | 224.09                                        | -1.00                                       | -0.21                                       |
| 4-A            | -311.53                                       | -311.13                                       | -323                                          | 3.56                                        | 3.67                                        |
| 4-B            | 267.90                                        | 268.81                                        | 276.51                                        | 3.11                                        | 2.79                                        |

From Table 4, Table 5 and Table 6 analyses, in the case of stainless steel frame of \( \frac{\Sigma N \cdot u}{\Sigma H \cdot k} > 0.1 \), the approximate second-order analysis is quite different from the second-order elastoplastic analysis.
results, and the approximate second-order analysis is unsafe. For stainless steel frames of $\Sigma N \cdot u / \Sigma H \cdot h > 0.1$, accurate second-order elastoplastic analysis should be used. The stainless steel frame of $\Sigma N \cdot u / \Sigma H \cdot h < 0.1$, because its second-order effect is relatively small, it is found from the numerical results analysis that the stainless steel frame of $\Sigma N \cdot u / \Sigma H \cdot h < 0.1$ can be structurally designed according to the steel structure design specification method.

5. Conclusions
Through the analysis and comparison of the results in this paper, the following conclusions are drawn:

(1) From the data analysis in the table, it can be concluded that for the stainless steel frame of $\Sigma N \cdot u / \Sigma H \cdot h > 0.1$, the bending moment of the accurate second-order elastoplastic analysis is larger than the approximate bending moment obtained by the approximate second-order calculation in the steel structure design specification. Since the stress-strain curve of stainless steel is obviously nonlinear, and the stress-strain linear curve of ordinary steel material is linear, the difference in material properties is the main reason for the excessive error of the approximate second-order calculation method. For materials with a nonlinear change in stress-strain of the material, accurate second-order elastoplastic analysis is recommended.

(2) For stainless steel frame of $\Sigma N \cdot u / \Sigma H \cdot h \geq 0.1$, the first-order analysis results are close to the exact second-order elastic-plastic analysis results. For stainless steel frame of $\Sigma N \cdot u / \Sigma H \cdot h < 0.1$, the first-order analysis can be used to design the structure, which is consistent with the steel structure design code.

(3) In the second-order elastoplastic analysis, in addition to the increase of the bending moment value, the lateral displacement of the frame increases greatly, which is not negligible in the structural design. Due to the difficulty in the calculation of the precise second-order calculation method and the difficulty in practical engineering, it is very important to propose an approximate second-order analysis method for stainless steel. It is suggested that the bending moment expansion factor is also considered, and the problem of lateral displacement is also considered.

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