A Steel Frame with the Main Girder Plane Arranged Diagonally Stable Design

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Abstract. Based on the SAP2000 finite element analysis software, the stability analysis of the steel frame structure with oblique arrangement in the main beam plane is carried out by three different stability design methods, namely the first-order elastic analysis, the second-order *P*-Δ elastic analysis and the direct analysis method, and the calculation results are compared and analyzed by combining the two different initial defect application Δmethods The error between the stress ratio obtained by the elastic analysis method and the stress ratio obtained by the first-order elastic analysis is small, and the stress ratio of some components is greater than that obtained by the second-order *P*-Δ elastic analysis method and the first-order elastic analysis when the elastic direct analysis method is used.

Keywords: Stable design method, SAP2000, Direct analysis method, Initial defects

1 Introduction

With the continuous development of structural analysis methods and structural calculation software, China has made several major revisions to the steel structure design specifications to address various issues that arise in the actual design and analysis process of steel structures. The steel structure design and stability analysis methods have different requirements in different versions [1-3].In recent years, a series of studies have been conducted by domestic and foreign researchers on the stability design methods for steel structures [4-6]. For the common irregular frame structure with diagonal intersections between the main beams, the column cannot be directly used for stability design due to the inability to determine which direction the column is constrained by. Therefore, there are still some difficulties in accurately analyzing the stability performance of the regular frame structure calculation length coefficient in the specifications. Therefore, this article is based on the structural arrangement of frame main beams that often occur in practical engineering, and adopts different stability design methods to study their stability performance.

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2 Project Overview

The structure is based on the outdoor corridor of 626 urban complex in Baiyintang Road, Gansu Province, and the structural system of the project is a steel frame-support structure. The structure is arranged in a fan-shaped, and the structural system is a steel frame structure, with 4 floors, a floor height of 3.6 meters, and a total height of 14.4 meters. The design seismic group is the first group, the fortification intensity is 8 degrees, the design basic seismic acceleration is 0.20g, the site category is Class II, the seismic grade of the steel frame is level 3, the characteristic period is 0.35, and the period reduction coefficient is 0.9. The basic wind pressure is 0.35kN/m^2, and the ground roughness is class B. During the structural analysis, the dead load and live load of the floor are 5kN/m^2 and 3kN/m^2 respectively. The three-dimensional structure diagram is shown in Figure 1, and the component parameters are shown in Table 1 below.

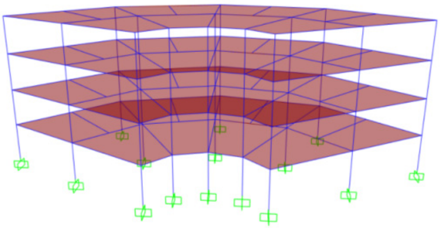


Fig. 1. Simplified structure 3D diagram

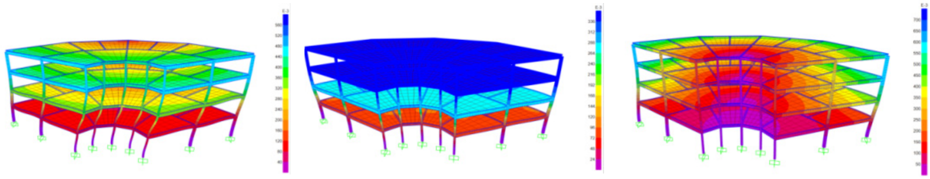
Table 1. Component Parameters

Section number	Cross-sectional dimensions（mm)	Elastic modulusE（MPa）	Moment of inertia Iy(mm4)	Moment of inertia Iz(mm4)
GL-1	H400×200×8×14	2.06×10^5	2.430×10^8	1.868×10^7
GL-2	H500×250×10×16	2.06×10^5	5.541×10^8	4.171×10^7
GL-3	H600×250×12×18	2.06×10^5	9.119×10^8	4.692×10^7
GL-4	H650×300×12×18	2.06×10^5	1.310×10^9	8.109×10^7
GL-5	H700×300×12×20	2.06×10^5	1.675×10^9	9.010×10^7
GZ-1	ϕ300×8	2.06×10^5	7.826×10^7	7.826×10^7
GZ-2	ϕ350×10	2.06×10^5	1.545×10^8	1.545×10^8
GZ-3	ϕ400×12	2.06×10^5	2.755×10^8	2.755×10^8
GZ-4	ϕ500×16	2.06×10^5	7.132×10^8	7.132×10^8
GZ-5	ϕ550×22	2.06×10^5	1.274×10^8	1.274×10^9

3 First-Order Elasticity Analysis

3.1 Eigenvalue Buckling Analysis

In this paper, SAP 2000 finite element software is used for structural analysis, and 1.0 dead load + 1.0 live load is selected as the static load case for linear buckling analysis, the first three modes are shown in Figure 2, and the first three critical load coefficients are shown in Table 2.



（a） First order （b） Second order （c） Third order

Fig. 2. The first three linear buckling modes

Table 2. 1.0 dead load + 1.0 live load coefficient

Buckling order	Critical load factor
1	39.163
2	39.889
3	51.520

As can be seen from the above, the lowest-order critical load coefficient of the improved structure is 39.163, and the second-order effect coefficient θ_i=0.0255≤0.1 is obtained. It should be noted that the first-order mode and the second-order mode of the general structure are usually translational, and the third-order mode is usually torsional, if the torsion occurs in the first two modes, it means that the torsional stiffness of the building is small, and the torsional effect of the structure will occur earlier than the translational of the structure, even if the periodic ratio meets the requirements of the code, the structure should be adjusted so that the first two modes of the structure are mainly translational.

3.2 Component Control Stress Ratio Calculations

SAP 2000 finite element calculation software is used to analyze the stress ratio of the structure, and the control stress ratio represents the envelope value of the strength stress ratio and the stable stress ratio. The results are shown in Table 3 when the maximum stress ratio of the frame column is 0.69, which is a two-layer frame column with member number GZ-1-3 and cross-section type of φ300×8, and the minimum stress ratio is 0.261, which is a four-layer frame column with member number GZ-1-1 and GZ-1-11 and cross-section type of φ300×8.

Table 3. Stress ratio of the component under the first-order elastic analysis method

Floor	Component Number	Component Section	Control Stress Ratio	Stress ratios due to different internal forces		
				Axial force	Spindle bending moment	Secondary shaft bending moment
2F	GZ-1-3	ϕ300×8	0.690	0.247	0.216	0.226
4F	GZ-1-1	ϕ300×8	0.261	0.096	0.192	0.311
	GZ-1-11	ϕ300×8	0.261	0.096	0.226	0.113

4 Second-Order *P-Δ* Elastic Method

The second-order *P-Δ* elastic analysis is theoretically more reasonable than the first-order elastic analysis method because it considers the second-order effect (i.e., the *P-*Δ effect) at the overall level of the structure and the influence of the initial geometric defects of the overall structure, and the structural analysis results are more accurate, but the operation is also more complicated[7].

4.1 The Way to Apply the Initial Defect of the Structure as a Whole

According to the description of the application methods for the initial geometric defects of the overall structure in the standard, the application methods are mainly divided into three types: the lowest order overall buckling mode method, the hypothetical horizontal force method, and the hypothetical displacement method. When using hypothetical horizontal forces, the initial defect representative value of the structure is calculated according to equation (1).

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

Δ_i —— represents the initial geometric defect representative value of the *i*-th floor ;

n_s——The total number of layers in the structure, when $\sqrt{0.2 + \frac{1}{n_s}} < \frac{2}{3}$, taking this radica as $\frac{2}{3}$; When $\sqrt{0.2 + \frac{1}{n_s}} > 1$, taking this radical value as 1.0;

h_i——The height of the *i*-th floor.

When applying the overall initial defect to the structure, it is necessary to define the P-Δ static analysis case, select nonlinear analysis type as nonlinear, select P-Delta as geometric nonlinearity, select 1.3 dead load + 1.5 live load as the load applied to the structure, and inherit the termination stiffness of the P-Δ nonlinear static analysis case for all other load cases.When the mode is adopted, it is first necessary to define the buckling load case, select 1.0 dead load + 1.0 live load as the buckling load of the structure, modify the undeformed geometry after analyzing the structure, select the modal scaling method, the overall initial defect of the structure is determined by the lowest-order global buckling mode of the structure, and the representative value of the overall initial geometric defect of the structure Δ0=H/250=0.0864 m.When using method 3, it is first necessary to define four hypothetical loads of NDX, NDY, NLX and NLY in the load mode (the hypothetical load refers to the standard value of the imaginary horizontal load applied to the top of each column), which represent the hypothetical load of the dead load in the X direction, the hypothetical load of the dead load in the Y direction, the hypothetical load of the live load in the X direction and the hypothetical load of the live load in the Y direction, respectively.

4.2 Component Control Stress Ratio Calculations

As can be seen from Table 4, the maximum control stress ratio of the component is 0.607, which is the column with the two-layer member number GZ-1-3 and the cross-section type of φ300×8, and the minimum control stress ratio is 0.209, which is the column with the four-layer member number GZ-1-3 and GZ-1-11 and the cross-section type of φ300×8. As can be seen from Table 5, the maximum control stress ratio of the component is 0.631, which is the column with the two-layer member number GZ-1-3 and the cross-section type of φ300×8, and the minimum control stress ratio is 0.210, which is the column with the four-layer member number GZ-1-1 and GZ-1-11, and the cross-section type is φ300×8.

Table 4. Stress ratio of the component under the elastic (modal) of the second-order P-Δ

Floor	Component Number	Component Section	Control Stress Ratio	Stress ratios due to different internal forces		
				Axial force	Spindle bending moment	Secondary shaft bending moment
2F	GZ-1-3	ϕ300×8	0.607	0.189	0.017	0.418
4F	GZ-1-1	ϕ300×8	0.209	0.046	0.135	0.092
	GZ-1-11	ϕ300×8	0.209	0.046	0.135	0.091

Table 5. Stress ratio of the component under the elastic (imaginary force) of the second-order P-Δ

Floor	Component Number	Component Section	Control Stress Ratio	Stress ratios due to different internal forces		
				Axial force	Spindle bending moment	Secondary shaft bending moment
2F	GZ-1-3	ϕ300×8	0.631	0.194	0.436	0.000
4F	GZ-1-1	ϕ300×8	0.210	0.046	0.136	0.091
	GZ-1-11	ϕ300×8	0.210	0.046	0.136	0.091

5 Direct Analysis

The direct analysis method is a second-order nonlinear analysis method, which can only consider the geometric nonlinearity of the structure and components, but does not involve the material nonlinearity, so as to carry out the second-order elastic analysis of the structural components, and can also consider the geometric nonlinearity and material nonlinearity at the same time. In this paper, the stability analysis and design of the structure are carried out by using the direct analysis method without considering the nonlinearity of the material.

5.1 Method for Applying Initial Defects to a Component

According to Article 5.2.3 of the Code for the Design of Steel Structures (GB 50017-2017) [3], there are two main ways to introduce initial defects into components. One is to consider the initial defect of the component through the representative value of the component defect, and the method uses a half-wave sinusoidal curve to determine the value of the defect value by equation (2), and this value method includes the influence of residual stress.

$$\delta_0 = e_0 \sin\frac{\pi x}{l} \tag{2}$$

For the SAP2000 finite element software, the finite element displacement method is used to consider the P-δ effect of the component. Through the automatic partitioning option, the software divides the beam column components into independent units, which are connected by nodes. The program captures the deflection of the components by capturing the displacement of the nodes, and then calculates the additional bending moment caused by the bending of the components[8].

5.2 Component Control Stress Ratio Calculations

As can be seen from Table 6, the maximum control stress ratio of the component is 0.747, which is the column with the two-layer member number GZ-1-2 and the cross-section type of φ300×8, and the minimum control stress ratio is 0.216, which is the column with the four-layer member number GZ-3-6 and the cross-section type is φ400×12. As can be seen from Table 7, the maximum control stress ratio of the component obtained by applying the initial defect of the structure according to the lowest order global buckling mode of the structure is 0.767, which is the column with the two-layer member number GZ-1-2 and the two-layer member number GZ-1-10 with a cross-section type of φ300×8, and the minimum control stress ratio is 0.218, which is the column with the four-layer member number GZ-3-6 and the cross-section type of φ400×12.

Table 6. Component stress ratios under direct analysis (modal).

Floor	Component Number	Component Section	Control Stress Ratio	Stress ratios due to different internal forces		
				Axial force	Spindle bending moment	Secondary shaft bending moment
2F	GZ-1-3	ϕ300×8	0.747	0.152	0.571	0.165
4F	GZ-3-6	ϕ400×12	0.216	0.104	0.112	0.003

Table 7. Stress ratio of the component under the direct analysis method (imaginary force).

Floor	Component Number	Component Section	Control Stress Ratio	Stress ratios due to different internal forces		
				Axial force	Spindle bending moment	Secondary shaft bending moment
2F	GZ-1-3	ϕ300×8	0.767	0.168	0.599	0.000
4F	GZ-3-6	ϕ400×12	0.218	0.104	0.114	0.000

6 Comparison of the Results of Different Stability Analysis Methods

For the sector structure in this paper, the stresses obtained by different stability analysis methods are shown in Figure 3 below.

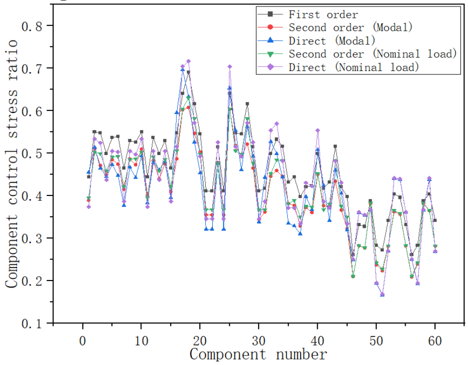


Fig. 3. Stress ratios obtained by different stability design methods

There is a certain gap in the control stress ratio of the components calculated by different stability design methods, which indicates that the three methods have differences in bearing capacity for the sector structure in this paper.

7 Conclusion

In this chapter, the stability of the sector steel frame model is analyzed by means of first-order elastic analysis, second-order *P*-Δ elastic analysis and direct analysis, and the consideration of the overall initial defects of different structures.

(1) For the fan-shaped structure in this paper, when different stability design methods are used to analyze and design the stability of the structure, there is a certain gap in the control stress ratio of the components obtained by different methods, among which the stress ratio obtained by the second-order P-Δ elastic analysis method is smaller than that obtained by the first-order elastic analysis, and the stress ratio of the component obtained by the direct analysis method is partially smaller than the control stress ratio of the component obtained by the first-order elastic analysis method, indi-

cating that there is a difference in the bearing capacity of the components between the three methods.

(2) The results obtained from considering the initial defects of the structure as a whole based on modal analysis and considering the initial defects of the structure as a whole based on hypothetical loads are similar, indicating that the two methods of applying initial defects to the structure as a whole are consistent.

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