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DIRECT ANALYSIS METHOD IN SELF-CLIMBING FORMING AND WORKING PLATFORM

Gao-Hong Ye [1], Zhi-Xiang Yu [1, *], Dong Liu [2], Huan He [1], Lin-Xu Liao [1] and Lei Zhao [1]

[1] *Southwest Jiaotong University, Chengdu, China*
[2] *HUASHI Engineering Technology (Shenzhen) Co, Ltd., Shenzhen, China*
* *(Corresponding author: E-mail: yzxzrq@home.swjtu.edu.cn)*

ABSTRACT

Due to the complex connection of components and significant initial defects in the formwork structure, the utilization of a direct analysis method to design the formwork structure can effectively address the shortcomings of traditional first-order linear design methods in formwork design standards. Taking a practical engineering project as an example, a direct analysis method for the construction of a SCP structure was proposed. Based on its design results, a comparative analysis with the traditional first-order linear design method was conducted to clarify the influence of considering initial defects and second-order effects on support reaction force, deformation, and stress ratio. This provided a reference basis for the design of SCP structures. Based on the results, cross-sectional optimization was carried out on the key components of the SCP structure. Following optimization, the stress ratio distribution of the structure was found to be more reasonable, and a 25.63% reduction in steel consumption was achieved, thus demonstrating the feasibility of the direct analysis method in the design and optimization of the SCP structure.

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1. Introduction

Because of their high efficiency, standardization, lightweight, and other attributes, various automated formwork systems are becoming more and more in demand in the construction of high-rise buildings, which is in line with the rapid development of these structures. Self-climbing forming and working platform (SCP) is a kind of integrated hydraulic jacking formwork for core-tube structure construction. It has the advantages of high load-bearing capacity, high space utilization rate, and high personnel comfort, which can significantly accelerate the construction speed of high-rise buildings [1-2]. Due to the low number of supports and high loads, the pursuit of a superior load-to-weight ratio while ensuring safety is one of the most important design goals of SCP.

In the Chinese standards [3-5] for formwork and scaffolding, their design is mainly based on the traditional first-order linear design method. SCP is a product of the development of construction technology, which has many forms of member connection, and it is complicated to determine the calculation length coefficient of members. Moreover, the number of members is large, and it is difficult to avoid overall defects and member defects in the process of production, transportation and repeated assembly of members. Therefore, it is difficult to guarantee the calculation accuracy of the traditional design method.

The Standard for design of steel structures GB50017-2017 implemented in China in 2018 [6] introduced the direct analysis method. Compared with the first-order linear design method based on the calculation length coefficient method, the direct analysis method introduces the initial defects of the overall structure and components, considering " P-Δ-δ" Nonlinear analysis and load-bearing capacity verification of second-order structural effects do not require the use of the calculated length coefficient method for component stability analysis. However, as a non-linear analysis, this method cannot directly stack different load combinations after they are calculated separately. It is necessary to combine the loads and apply them to the structure before analysis.

Regarding the application and research of direct analysis method in various structures, Chan Siulai. et al. used NIDA software to analyze steel frame structures and found that direct analysis method is more accurate and effective than first-order design method based on computational length coefficient method [7]. Shu Ganping et al. compared the calculation results with experiments, verifying the effectiveness and reliability of the direct analysis method for structural analysis of semi-rigid connected steel frames [8]. Wang Fawu et al. further developed a direct analysis and optimization method for semi-rigid frames[9]. In addition, Ding Zhixia et al. studied the continuous collapse of structures based on direct analysis method and compared it with traditional design methods [10]. Zhao Lei et al investigated the effect of initial geometric defects on the stabilizing capacity of spanning plane trusses [11]. Yu Zheng et al analyzed the design and optimization of cable structures [12]. In past studies, the direct analysis method has been successfully applied in a variety of structures.

As a typical steel frame structure, various types of construction formwork are often designed and analyzed based on their construction in existing research [2,13-14], but no direct analysis method has been applied in their structural design.

2. Overview of the SCP structure

The SCP used for the construction of the core tube of a high-rise building is shown in Fig. 1, including machine platforms, suspension platforms, the grid beam, the lattice column frame and support frames. The structure consists of 6 levels of operation platforms along the longitudinal direction, the height of the positive platform part is 9.8m, the height of the negative platform part is 9.5m, the total height of the structure is 19.3m, and the horizontal dimension is 8m×8m. The negative platform is mainly used as the maintenance platform, the 0-level platform is the operation platform for formwork, and the +1 and +2 platforms are used for concreting, reinforcement binding, and stacking of loads.

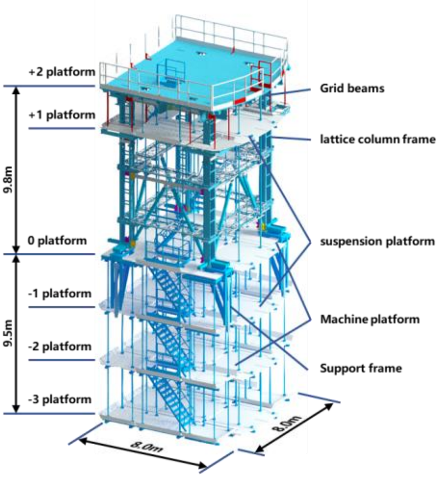

Fig. 1 SCP structure

The force transfer of the SCP structure is clear. As shown in Fig. 2, its force transmission path includes two parts. One is that each suspension platform transmits its load to the secondary beam of the +2 platform through the suspension rods, and then transmits the load to the support frame through the grid beam and the lattice column; another is each negative machine platform directly transmits the load to the 0-level machine platform through the suspension rod, and the zero-up machine platform is directly connected with the lattice column to transmit the load to the support frame in a downward direction. Ultimately, the support frame is anchored to the core-tube by pre-embedded anchors to transfer the loads to the core-tube.

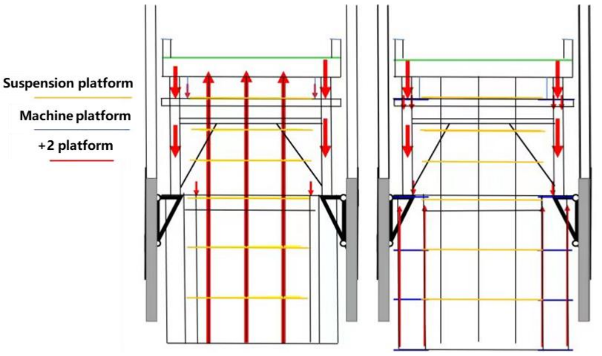

Fig. 2 Force transmission path

According to the force transmission characteristics of the structure, the lattice column frame, the grid beam and support frames are called the main frame (as shown in Fig. 3). Each platform is connected to the main frame, whose structural characteristics are shown in Fig. 4, including the main beam and secondary beam. The pivot point of the main beam is directly connected to the suspension rod or lattice column, and the secondary beam is supported on the main beam. In addition, the secondary beam of the +2 platform is responsible for transferring the load of the suspension rod and the +2 platform stacking load, and is supported on the grid beam.

Fig. 3 main frame

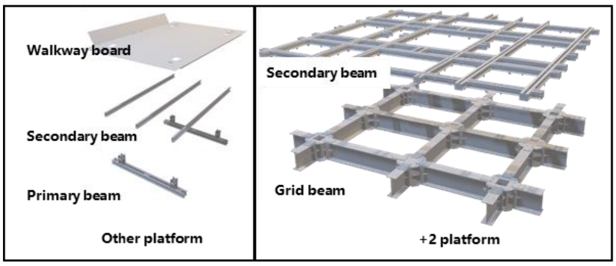

Fig. 4 Platform structure

3. Direct analysis method of SCP

3.1. Initial defects

The structural characteristics of the SCP cause its suspension platform stiffness to be very small, and its buckling mode is reflected as the lateral deformation of each suspension platform, and the consideration of the overall initial defect of the structure in accordance with the first order buckling mode is not in line with the purpose of the structural initial defects imposed. As a structure with regular shape and significant story separation, the overall initial defects can be added to the initial geometric defects representative value Δ_{ni} at the corresponding story height according to the Standard for design of steel structures (e.g., Eq. 1).

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

In the Eq. 1, h_i is the height of the calculated floor; Δ_{ni} is the total gravity load design value for the i-th floor; n_s is the total number of layers in the structure.

The initial defect of the member is shown in Fig. 4. Considering the influence of the initial deformation and residual stress of the member, it is determined by calculating the half-cycle sine curve as shown in Equation 2. e_0 is the initial deformation at the midpoint of the member, x is the distance from the end of the member, and l is the total length of the member.

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

Since the elastic-plastic development of the material is not considered, the initial deformation e_0 of the member is selected in accordance with the representative value of the integrated defects of the member in the Standard for design of steel structures.

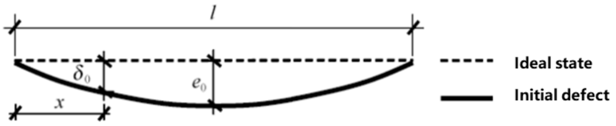

Fig. 5 Initial defect of member

3.2. Nonlinear analysis and verification

The nonlinear analysis is carried out after applying different combinations of loads to the structure. The internal forces in the members obtained from the analysis are substituted into Eq. (3) for verification.

$$\frac{N}{Af}+\frac{\mathrm{M}_{\mathrm{x}}^{\mathrm{ii}}}{M_{\mathrm{cx}}}+\frac{\mathrm{M}_{\mathrm{y}}^{\mathrm{ii}}}{M_{\mathrm{cy}}} \le 1.0 \tag{3}$$

N is the design value of axial force; A is the gross section area; f is the design value of strength of steel; $\mathrm{M}_{\mathrm{x}}^{\mathrm{ii}}$, $\mathrm{M}_{\mathrm{y}}^{\mathrm{ii}}$ are the design value of second-order bending moment around the x-axis and y-axis, respectively; M_{cx} and M_{cy} are the design value of bending capacity around the x-axis and y-axis, respectively.

3.3. Design process

The design process of the direct analysis method is clear and concise, and there is no need to determine the calculation length coefficient one by one for the complicated members. The direct analysis method can be used for the design of the top mold structure by referring to the steps of “simplification, modeling → applying load → load combination → applying initial defects → nonlinear analysis → member strength checking”.

4. Computational model

A wireframe model is established using 3D drawing software in accordance with the centerline of the members, and the primary and secondary beams are simplified from stacked to intersecting, but the loads are only applied to the secondary beams. The nodes are simplified as rigid or hinged with reference to the actual connections. The boundary conditions of the structure are shown in Fig. 5, all of which are hinged supports. The steel used in the model is Q235B.

In addition to the structure's self weight, the dead loads include those loads that can be considered permanent, such as sidewalks, handrails, stairs, formwork, and ancillary structures. The live loads refer to its working condition, which is determined by the working condition load planning of the SCP, and the live load cases are shown in Table 1. For the load combinations, the basic combination of “1.3×DL+1.5×LL” is used for the bearing capacity and bearing reaction, and the standard combination of “1.0×DL+1.0×LL” is used for the displacement calculation. These combinations are determined according to the standards.

Table 1
Working state load

Platform	Load/kN·m^{-2}
+2	5.00
+1	2.00
0	1.50
-1	0.75
-2	0.75
-3	0.75

5. Comparison between Direct Analysis and First Order Linear Analysis

NIDA has been used for direct analysis and first-order linear analysis.

5.1. Support reactions

The SCP in the example has four supports (Fig. 6), which are fixed to the core-tube, and their design is a key factor to ensure the construction safety and structural reliability, according to the basic combination of loads, the vertical support reaction force of each support is extracted as shown in Table 2.

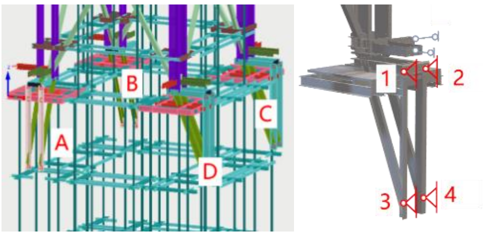

Fig. 6 Supports and its ID

Table 2
Support reaction force

ID	First-order linear analysis/kN	Direct analysis/kN	δ/%
A1	15.65	19.63	25.43
A2	25.44	25.51	0.28
A3	173.02	170.87	-1.24
A4	179.78	177.52	-1.26
B1	22.84	23.00	0.70
B2	16.89	20.69	22.50
B3	179.56	177.30	-1.26
B4	174.24	172.05	-1.26
C1	30.35	29.78	-1.88
C2	12.20	13.98	14.59
C3	184.41	183.57	-0.46
C4	176.44	176.56	0.07
D1	13.21	15.25	15.44
D2	28.25	27.73	-1.84
D3	178.76	178.66	-0.06
D4	184.70	183.63	-0.58
Total	1595.74	1595.74	0.00

Comparing the results of the first-order linear analysis and the direct analysis, the maximum support reaction force of both appeared in the D4 support, which was 184.7kN and 183.6kN, respectively, and the relative error of the two was only 0.58%; and the total support reaction forces were basically the same due to the same applied loads.

The maximum relative error was found in support A1, which reached 25%, but the absolute error was only 3.98kN, which is still small on the scale of the total support reaction force. This is the performance of the direct analysis method after considering the initial defects of the support frame members and the structure as a whole, which is the performance of the feedback to the support reaction force, and it can be seen that the use of the direct analysis method can give the design parameters of the reasonable support to the design of the support in this project.

5.2. Deformation

Comparing the displacement calculation results of the two design methods, the maximum vertical displacements obtained by the first-order linear analysis and the direct analysis are 9.80 mm and 9.82 mm, respectively, and the maximum vertical displacements are located in the cantilevered position of a suspension platform, and the displacement calculation results of the two methods are verified by each other.

5.3 Stress ratio

Fig. 7 shows the comparison of the stress ratio results between the first order linear analysis and the direct analysis method in NIDA.

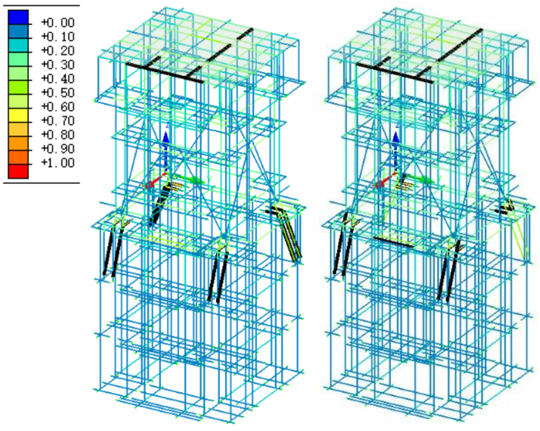

Fig. 7 Stress ratio

The maximum stress ratio for first-order linear analysis was 0.801, and the maximum stress ratio for direct analysis method was 0.799. In Fig. 7, the elements with a stress ratio greater than 0.5 were shown in black, and the elements with a greater stress ratio in both methods were the secondary beams of +2 beams, the secondary beams of 0 platform and the diagonal supports of the support frames.

The design results of direct analysis method and first-order linear analysis in NIDA were compared. After the difference between the two, the average difference in stress ratio was 0.0014. Overall, the results of the two were relatively close, with 91.1% of the unit stress ratios differing between -0.01 and 0.01. Statistics were conducted on elements with stress ratios exceeding 0.01, and a total of 119 elements with higher stress ratios were designed using the direct analysis method.

Statistics were conducted on units with stress ratios exceeding 0.01, and a total of 119 elements were found to have higher stress ratios using the direct analysis method. Among them, 64.7% were horizontal members, mainly bending members. There were a total of 52 elements with relatively low stress ratio using the direct analysis method, of which 73.1% were non-horizontal members, mainly axial and compression bending members. This is because the SCP structure is a typical vertical structural system, and the horizontal bending members increase in the increase of the initial defect design bending moment, resulting in an increase in the stress ratio. The vertically distributed members are mainly compression members, and the first-order linear analysis is more unfavorable than the actual situation due to the direct consideration according to the calculated length factor.

There were 16 elements with the difference of stress ratio greater than 0.1, as shown in Fig. 8, all of which were diagonal braces of the support frame. The diagonal bracing was divided into two elements, in which the lower, longer segments had smaller stress ratios under direct analysis, and the upper, shorter segments had larger stress ratios under direct analysis. This was due to the design value of bending moment in the compression bending member in the application of the initial defects increased significantly, the shorter element due to the compression bearing capacity verification coefficient was not significantly different, so the overall stress ratio increased, while the longer element although the design value of the bending moment increased, but due to the calculation of length coefficients were not taken into account, compression bearing capacity verification coefficient was significantly reduced, and the overall stress ratio was reduced.

In the actual situation as the same member, the stress ratio of the upper and lower elements in the results of the direct analysis method was closer and more in line with the actual situation.

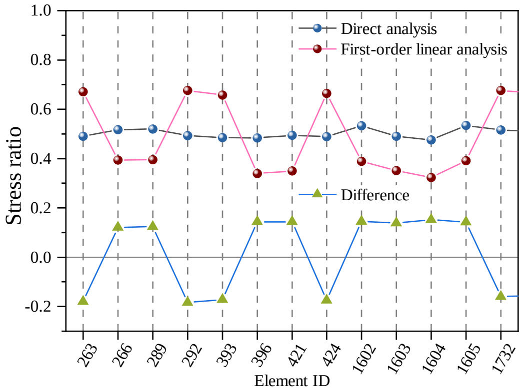

Fig. 8 Elements with stress ratio differences exceeding 0.1

6. Structural optimization

6.1. Optimization Schemes

In this example, the SCP structure has a large self-weight and most of the members have relatively low stress, so there is a large optimization space. This optimization was mainly based on cross-section optimization, and kept the cross-section type as much as possible to meet the original node connection mode, and for the convenience of assembly, the number of excessive cross-section was not increased, so as to realize the comprehensive optimization with the goal of high efficiency and light weight. By reducing the self-weight of the structure, the support reaction force can also be further reduced and the safety margin of the support anchorage point can be improved.

The cross sections of some members were optimized, and the comparison of the cross sections before and after optimization is shown in Table 3. The total weight was reduced from 35.02 tons to 26.05 tons after optimization, which was about 25.63%.

Table 3
Cross-section optimization scheme

Component	Size/Model [a]		weight loss
	Before	After	
Machine platform beams	C 20B	C 20B	-
0.5 story platform beams	C 16B	C 16B	-
Platform secondary beam	C 10	HT 100×50×3.2/4.5	40.19
Platform primary beam	2C 10	2C 100×50×4	51.59
Suspension rods	F 50×5	F 50×4	37.33
Grid beams	HM 594×302×14/23	HN 600×200×10/15	45.76
+2 story secondary beam	2C 10	2C 14B	-67.85
lattice column	C 40B	C 40A	9.60
Support frame beam	C 14B	C 14B	-
Support frame column	L 200×125×16	L 200×125×16	-
Support frame diagonal supports	C 22B	C 22B	-
Main frame diagonal supports	J 160×130×8.5/9.6	J 160×130×6/6	31.77

[a]: C: U-steel; 2C: doble U-steel; F: square tube; H: H-steel; L: L-steel; J: rectangular tube.

6.2. Optimization results

The stress ratio cloud diagram after optimization is shown in Fig. 7. The overall distribution pattern was similar to that before optimization, and the elements with stress ratios greater than 0.5 were changed to 0-story and +1-story platform beams, which were not included in main frame elements. Compared to the pre-optimization, the stress ratios of the elements of the +2 platform, the machine platform, and the main frame diagonal supports have been reduced.

The stress ratio-number of elements distribution before and after optimization is shown in Fig. 9. After reducing the amount of steel used by 25.63%, there was no significant increase in the number of high stress ratio elements, and the percentage of elements with stress ratios greater than 0.4 increased by only 4% from 2.3%, retaining a large safety margin. Due to the high number of horizontal elements, the number of elements with stress ratios less than 0.1 was reduced after optimization.

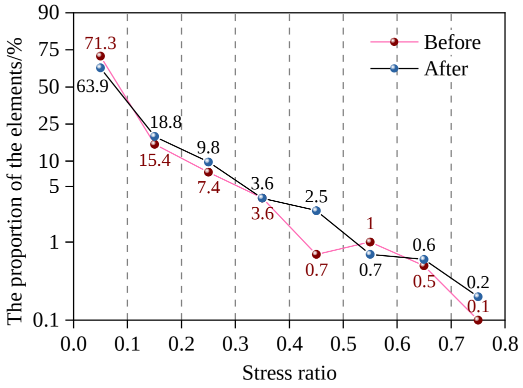

Fig. 9 Distribution of the number of elements with different stress ratios

The comparison of the main parameters before and after optimization is shown in Table 4. The stiffness decreased with the reduction of the cross section of some members, the maximum vertical displacement increased from 9.82mm to 11.74mm, and the maximum vertical displacement of the main frame increased from 3.55mm to 5.94mm, which still met the usage requirements. The vertical reaction force decreased from 1595.74kN to 1475.45kN due to the decrease in the self-weight of the structure, with a decrease of 7.54%. The maximum vertical reaction of the support still occurred at the D4 support and decreased from 183.63kN to 169.35kN, with a decrease of 7.78%. After optimization, the design value of the support load was reduced to a certain extent.

Table 4
Optimization result parameters

Parameters	Before	After
Maximum vertical displacement/mm	9.82	11.74
Maximum vertical displacement of the main frame/mm	3.55	5.94
Total vertical support reaction force/kN	1595.74	1475.45
Maximum support reaction force/kN	183.63	169.35
Maximum stress ratio	0.75	0.75

7. Conclusions

This paper introduces the direct analysis method of the top mold structure, compares it with the traditional first-order linear design method, and optimizes the structure based on this method. The following conclusions can be drawn from the data presented.

(1) The design and optimization of SCP using direct analysis method is simpler and more efficient than the first-order linear design method based on the calculation of length coefficients.
(2) The outcomes of the direct analysis are largely congruent with those of first-order linear analysis. The discrepancy is primarily attributable to the divergence in calculation methodologies between the two.
(3) In the example, by using the direct analysis method, 25.63% of the steel consumption was saved through cross-sectional optimization, while maintaining a high safety margin.

The direct analysis method is unable to fully consider the detailed construction of structural connection nodes. Consequently, it is planned to conduct node performance analysis in the future in order to obtain the semi-rigid parameters of each node. This will facilitate multi-scale optimization design.

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