Analysis on accumulated deformation and stress of the steel roof of Beijing Opera House during construction

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Abstract. This paper aims to study the stress and deformation of large steel structure buildings in the actual construction process. Midas Gen finite element software is used to simulate and analyze the whole construction process of the curved reticulated shell roof, the peripheral steel columns and the permanent support. The stress and deformation results of the structure in the final construction state are compared with those in the design state under one-time loading. The results show that, in the final construction state, the maximum tensile stress and the maximum compressive stress are 1.9 times and 2.0 times of that in the design state under one-time loading respectively, which is very significant. When the design model is loaded with weight at one time, the maximum tensile stress and the maximum compressive stress of the structure both appear near the opening of the steel roof, while in the final construction state, the maximum tensile stress of the structure appears near the boundary frame beam, and the maximum compressive stress appears on the main ridge beam. The maximum vertical displacement of the structure in the final construction state is 2.0 times of that when the design model is loaded at one time. The maximum vertical displacement of the design state appears near the opening of the steel roof, while the maximum vertical displacement of the structure in the final construction state appears on the main ridge beam. In view of the above, the effective guidance for the construction of steel roof structure is provided in this paper to ensure the safety of the structure.

1. Introduction

Construction is a continuous process in which the structure is gradually formed and the load is gradually applied [1]. For the steel reticulated shell structure, because the whole structure has not yet formed during construction, the stress state of the structure or components is different from that in the design state. The stress and deformation of the structure in the final construction state are closely related to the construction process, and the ‘path’ and ‘time’ effects of the construction process directly affect the stress performance of the structure in the construction state and the service state [2]. Therefore, it is necessary to simulate and analyze the construction process of the structure, and compare the stress state of the structure in the final construction state and the design state.

In view of the mechanical analysis of the construction process of the steel reticulated shell structure, a lot of researches have been carried out by scholars. Zhang et al. [3] introduced the construction technology of large span hyperbolic space reticulated shell structure combing with the steel structure engineering of Shaanxi Olympic Sports Center Gymnasium Project, and used Midas Gen finite element analysis software to carry out modeling analysis and calculation of simulated construction conditions, which provides theoretical basis for the smooth implementation of the project. Zhang et al. [4-5] used
Midas gen to simulate the hoisting and jacking process of the reticulated shell in Tianshui Natatorium, and took the calculation results as the initial value of later unloading simulation, then used forced displacement method to simulate the unloading process of the reticulated shell. Wang et al. [6] analyzed the construction process of a large gymnasium steel structure project by using Midas Gen finite element software. The construction process includes pipe truss sliding construction, installation of the single layer reticulated shell roof at the top of the main hall, installation of the auxiliary hall and batch tensioning. The results showed that the calculation results of the structure under one-time loading state were significantly lower than that under the construction state. The maximum displacement of structure occurred in the process of sliding construction, and did not decrease with the increase of the force applied during batch tensioning. In the finite element analysis of a project construction process, Li et al. [7] used random defects to simulate the construction errors of the structure. On the basis of a feasible construction scheme, the influence of node setting error on the lower cable rod system was studied.

At present, there are few studies on the influence of construction process on the stress state of the final formed structure. This paper will use Midas Gen finite element software to conduct the analysis on the construction process of the steel reticulated shell roof of the Opera House in Beijing theatre project to study the influence of construction process on the stress state of the final formed structure.

2. The project profile

2.1. Overview of the engineering building
The Opera House project is a part of the Beijing Theater project in Beijing Urban Sub Central. The total construction area of the Beijing Theater project is 125350m². As shown in Figure 1, on the platform with 7.2m height, there are three buildings in the east-west direction, which are the Theatre, the Opera House and the Concert Hall. The steel structures of the three buildings are mainly distributed in the curved reticulated roofs and internal trusses of the buildings. Among them, the building area of the Opera House is about 430000 m², and the plan view dimensions is 117.6m long and 84m wide. The structural height is 48.5m, and the total steel weight is 6714t. No matter in geometrical dimension or steel weight, the Opera House is the largest of the three buildings. In addition, it is the only building with openings on the roof, so the construction of the curved reticulated shell roof is the most difficult. The steel roof construction of the Opera House mainly includes the construction of the curved reticulated shell roof, the peripheral steel columns and the permanent support. Q345GJC and Q355C are the main materials used in the main and secondary beam structure of the steel roof. The section dimensions are □1600×500×24×50, □1400×600×24×45, □1400×600×24×24, □1400×500×24×45 and □1400×500×24×24, etc.

![Figure 1. Beijing Theater project rendering in Beijing Urban Sub Central.](image)

2.2. Construction scheme of the curved reticulated shell roof
The roof of this project is a large-span single-ridge hyperbolic steel reticulated shell structure, which is in the shape of inverted arch surface. The elevation of the four corners of the roof is different, resulting in different radians of each component of the roof and complex space location relationships. According to the characteristics of the reticulated shell roof, high altitude in-situ segment installation combined with high altitude in-situ block installation is chosen as the construction scheme. During the block
hoisting process, the two main beam segments and the secondary beams between them should be welded into blocks on the ground, and then they should be hoisted to the location in situ for welding installation. The segment hoisting is to directly hoist the main beam segment to the location in situ for welding installation. When hoisting, temporary supports should be set at the butt weld joints of the main ridge beam and the main beam. In order to ensure the bearing capacity of the concrete structure at the bottom of the temporary supports, temporary supports should be set above beams or columns and avoid setting temporary supports on the concrete slab directly.

2.2.1. The construction sequence. (1) When the construction of the lower concrete structure is completed, as shown in Figure 2(a), the peripheral steel columns and the internal single permanent supports are installed firstly. The peripheral steel columns include steel frame columns and single steel columns. The internal single permanent supports are in two forms which consists of round steel pipes and square steel pipes.

(2) After the installation of the peripheral steel columns and the internal single permanent supports, as shown in Figure 2(b), the reticulated shell roof is installed. First, the peripheral steel beams and the main beams at the internal opening of the reticulated shell roof are installed, and then the main ridge beams are installed. When the main ridge beams are installed, the temporary supports are set at the segmental butt joints of the main ridge beams, and then the hoisting and installation are gradually carried out from the corners of both ends along the diagonal direction to the center of the roof, until the main spine is closed.

(3) After the installation of the main ridge beam is closed, as shown in Figure 2(c), the main beam blocks and the secondary beams of the reticulated shell roof are hoisted and installed from the corners of both ends of the main ridge beam to the center of the roof. Then high altitude in-situ segment installation combined with high altitude in-situ block installation is chosen as the construction scheme. The block hoisting method shall be adopted as far as possible within the scope of meeting the requirements of the tower crane. The temporary supports are set at the section butt joints of some main beams, and then the hoisting and installation are carried out from the corners of both ends of the main ridge beam to the center of the roof in segments or blocks. When hoisting, in order to ensure that the truss structure can be constructed at the same time, a rectangular hole should be reserved, as shown in Figure 2(d).

(4) After the reticulated shell roof structure with the reserved opening and the construction of the truss structure are completed, the components located at the reserved rectangular opening should be installed, and the installation should be carried out in the sequence of block hoisting first, and then the secondary beams between the main beams. After the reserved rectangular opening is patched, the curtain wall beam on the reticulated shell roof is installed. As shown in Figure 2(e).

(5) After the reticulated shell roof construction is completed, the temporary supports need to be removed, and the removal process is a step-by-step unloading process. In each unloading process, the height of the top of the temporary support is reduced by 10 mm, and the temporary support is unloaded step by step until the top of the temporary support is completely separated from the reticulated shell roof, and then the temporary supports that have been separated from the reticulated shell roof are removed. As shown in Figure 2(f).

(6) The temporary supports are removed and the reticulated shell roof structure construction is completed.
2.2.2. Advantages of the construction scheme. The temporary supports need to be installed on the lower concrete floor according to the construction scheme, which avoids cross operation of the reticulated shell roof construction with the lower concrete construction. And because of the small temporary support height and good stability, it is also conducive to ensure the safety. The high altitude in-situ segment hoisting requires less hoisting load of the machinery. In this way, the temporary supports required are fewer and the segmented span is large, which is conducive to improving efficiency and shortening the overall construction period.

Figure 2. Construction sequence of the reticulated shell roof structure.
3. Finite element simulation of construction process
The construction process simulation is different from the traditional engineering design calculation, and the main differences are as follows. On the one hand, in the design of the structure, the structure is subjected to the service load, while in the construction, the structure is subjected to the construction load. In the simulation of the construction process, the self weight is considered only as the construction load. On the other hand, in the design, the load and boundary conditions are directly imposed on the complete structure, while in the construction, the structure, the load and the boundary conditions are constantly changing, so the stress state of the structure in the construction process changes with time.

In this paper, the construction stage analysis module of the finite element software Midas Gen is used to simulate the construction process, and the beam element is used to simulate the main ridge beams, main beams, secondary beams and other steel components in the reticulated shell roof. The beam element is a line element defined by two nodes, which has six degrees of freedom. During element division, the default setting of the software is retained, that is, the structure is divided into one beam element per meter. The simulation of each construction stage is realized by defining the application and release of load at any time, the generation and disappearance of elements and the change of boundary conditions. Different construction stages are defined by defining different load groups, structural groups and construction groups. In this paper, the main ridge beams, main beams and secondary beams of the reticulated shell roof are divided into several structural groups according to the construction sequence. When defining the construction stage, the loads, elements and boundary conditions of the model are simulated according to the changes of the structure during the actual construction. In the specific analysis of a construction stage, all the construction stages before the construction stage are in the active state and participate in the structural construction analysis. The construction stages after the construction stage are in the passive state and do not participate in the construction analysis of the construction stage. The stress and deformation of each construction stage affect the next construction stage. Due to the changes of load, structure and boundary conditions in this construction stage, the stress and deformation of the structure in each construction stage are cumulative results. Only in this way, can the whole construction process be simulated and analyzed.

In the actual construction, when the main ridge beams and the main beams are hoisted by segments and blocks, as shown in Figure 3, the ear plates at the end should be used to lap on the completed structure, and then the construction of the connection between the hoisting structure and the completed construction structure should be completed. In this process, the constraint conditions of hoisting components are different from those in design. The constraint conditions of the hoisting components are fewer when lapping, which will cause greater irreversible deformation of hoisting components, resulting in obvious redistribution of internal forces of the overall structure. In order to simulate this process, as shown in Figure 4, when simulating the hoisting components, the hinged state of the lapping joint can be simulated by releasing the rotation constraints of the beam ends.

![Figure 3. Schematic diagram of the component construction lap.](image-url)
4. Finite element analysis results of construction process
According to the construction sequence in section 2.2.1, the whole process of construction simulation analysis is carried out in the Midas Gen finite element software, and the design model is analyzed in the one-time loading condition. The stress and vertical displacement results of the last construction stage are compared with that of the design model loaded at one time.

4.1. Cumulative stress analysis
The structural stress results of the roof model in the last construction stage and the design model loaded at one time are shown in Figure 5.

(a) The stress calculation result of the roof model in the last construction stage
The stress calculation result of the one-time loading roof design model

Figure 5. The stress calculation result comparison of the roof model in the last construction stage and the one-time loading roof design model.

It can be obtained from Figure 5 that the maximum tensile stress of the roof model in the last construction stage is 79.7 MPa, which is located at the rectangular mark in Figure 5(a). The maximum compressive stress is -98.1 MPa, which is located at the circular mark in Figure 5(a). The maximum tensile stress of the one-time loading roof design model is 41.4 MPa, which is located at the rectangular mark in Figure 5(b). The maximum compressive stress is -48.4 MPa, which is located at the circular mark in Figure 5(b). The maximum tensile stress and maximum compressive stress of the roof model in the last construction stage are respectively 1.9 times and 2.0 times of that when the design model is loaded at one time. Notably, this difference is very huge. The maximum tensile stress of the design model appears on the main beam of the opening, and the maximum stress appears near the opening. The maximum tensile stress of the roof model in the last construction stage is near the peripheral steel beams, and the maximum compressive stress appears on the main ridge beam. The locations of the maximum tensile stress and the maximum compressive stress in the last construction stage (shown in Figure 5(a)) is far from the that of the one-time loading roof design model (shown in Figure 5(b)). This indicates that the internal force distribution of steel roof structure has changed during the construction process, and the internal force distribution of the structure is different from the design structure when the construction is completed. Therefore, the stress of each component are different from that in the design state, which leads to the potential safety hazards in the construction and service process.

4.2. Cumulative deformation analysis
The vertical displacement results of the roof model in the last construction stage and the design model loaded at one time are shown in Figure 6.
It can be obtained from Figure 6 that the maximum vertical displacement of the roof model in the last construction stage is 69.8mm, which is located at the circular mark in Figure 6(a). The maximum vertical displacement of the one-time loading roof design model is 34.6mm, which is located at the circular mark in Figure 6(b). The maximum vertical displacement of the roof model in the last construction stage is up to 2.0 times of that when the design model is loaded at one time. When the design model is loaded at one time, the maximum vertical displacement appears on the main beam of the opening, while in the last construction stage, the maximum vertical displacement appears on the main ridge beam. The location of the maximum vertical displacement calculated according to the construction sequence (shown in Figure 6(a)) is far from that calculated according to the one-time loading state (shown in Figure 6(a)). This is because in the construction process, the roof structure has not been completed, the overall bearing capacity of the structure is lower than that of the design model. Large deformation will appear on the single component in the construction process, which is irreversible in the actual construction process. For a single component, the larger deformation makes its stress state in the construction process different from that in the design model. This change has uncertainty, which may lead to potential safety hazards in the construction and service state.
The calculation results in this paper have the same law as those in reference [5], and are consistent with the qualitative law obtained by using Ansys in reference [8]. According to the above calculation results, the maximum tensile stress, maximum compressive stress and maximum vertical displacement of the roof model in the last construction stage are all greater than those of the design model under one-time loading by comparison. The locations of maximum tensile stress, maximum compressive stress and maximum vertical displacement are also different in the two working conditions, which indicates that there is a certain difference between the stress state of the completed construction structure and the designed structure. The internal force redistribution of the completed construction structure occurs relative to the design structure during the construction process. The reason for this phenomenon is that during the construction process, larger deformation occurs under the action of self weight when the structure is not integrated, which is irreversible in the actual construction process. This kind of deformations leads to the redistribution of both internal force and deformation of the structure when the construction is completed. Scientific and detailed simulation analysis before actual construction can help ensure the safety of the structure in the process of construction and service. In order to ensure the safety of the structure in the service stage, corresponding measures should be taken to control the deformation of the structure in the process of construction, such as the pre-camber in the component processing plant and the pre-camber in the construction site, so as to minimize the influence of the construction process on the stress state.

5. Conclusion
In this paper, the whole construction process of the reticulated shell roof in the Opera House are analyzed by using the Midas Gen finite element software. The stress state and displacement of the roof model in the last construction stage and the one-time loading roof design model are compared, and the following conclusions are obtained.

1) In the last construction stage, the maximum tensile stress, the maximum compressive stress and maximum vertical displacement of the structure are all greater than that of the one-time loading roof design model. In the last construction stage, the maximum tensile stress, the maximum compressive stress and maximum vertical displacement of the structure are 1.9 times, 2.0 times and 2.0 times of that of the one-time loading roof design model. In calculation results of the roof model in the last construction stage and the one-time loading roof design model, the locations of the maximum tensile stress, the maximum compressive stress and the maximum vertical displacement are also different, and the internal force redistribution occurs.

2) There are some differences in the stress state between the completed construction structure and the design structure. It is necessary to carry out scientific and detailed finite element analysis before construction to ensure the safety of the construction process.

3) During the construction, certain measures should be taken to control the deformation of the structure that has not been completed in the construction process. Measures such as pre arching in the component processing plant and pre arching in the construction site can help to reduce the structural deformation in the construction process, so as to minimize the influence of the construction process on the stress state of the structure, which can ensure the safety of the structure in the construction process and service stage.

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