Influence on mechanical behaviors considering construction hosting process of large-scale steel structure

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Abstract. In the design of large-scale steel structure, the design calculation of the structure is usually based on the service state. But in the process of steel structure construction, the displacement and stress produced in the construction process cannot be completely consistent with that in the design state. With the progress of construction process, the deformation and stress caused by self-weight and construction load gradually accumulate until the structure is formed, which will produce construction error relative to the design state. In this paper, FEM method was used to simulate the construction process of the steel grid roof of the theater in the Beijing Sub Center Theater project, and the influence of the accumulated deformation and stress on the mechanical properties of the structure during the construction process was analyzed. The results show that the cumulative deformation and stress in the construction process have a great influence on the final deformation and stress distribution of the structure. The maximum vertical displacement in the actual construction state is 599.6% of that in the design state, and the maximum stress is 119.7% of that in the design state. This will lead to the difference between the construction-completed structure and the design structure, which makes the design result dangerous. The measures to optimize the construction process were also given in this paper, which provides guidance for the construction process of large-scale steel structure.

1. Introduction

The design calculation state of large-scale steel structure is the load combination design state at service stage based on the whole structure. When calculated according to this state, the whole steel structure is equivalent to once forming with rigid connection. The actual construction state refers to the corresponding state of the structure obtained according to the actual construction process and construction technology considering the actual boundary conditions. The design calculation state is the basis for the design at service stage, while the actual construction state is the response of the real stress state of the structure. After the construction is completed, the actual construction state of the structure should be as close to the design state as possible. If there is a big difference between them, the load combination calculation of the design state will become meaningless [1-4].

The construction process of large-scale special-shaped steel structure is often complex, and its construction process needs to go through fine design. In the construction process of the steel structure of the theater roof of Beijing Sub Center Theater project, the roof shape is unique, and the special-shaped steel beams are widely used in the grid structure. In the construction process, the multiple requirements of the shape and structure should be considered, and the reasonable construction method should be adopted.
In the construction process, due to the different construction conditions and methods, the load and boundary conditions of each component of the roof structure are different from that of the design state, resulting in the construction error of the component deformation and stress relative to the design state. At the same time, in addition to its own installation error, the post installed components are also affected by the stress redistribution caused by the previously installed components. With the progress of the construction process, the construction error is gradually accumulated, and the difference between the final actual structure and the design structure cannot be ignored.

Many experts and scholars have carried out research on the influence of construction process on the mechanical properties of steel structure. Qiao [5] studied the large-span arched steel pipe truss in the second phase reconstruction project of Harbin elevated station building, simulated the unloading process of the truss structure, and obtained the influence of different unloading construction methods on the unloading process and final state of arched truss structure; Guo [6] simulated the construction of the steel structure of Jinan Qingdao high speed railway station, analyzed the internal force and deformation of the steel structure under the construction condition, and studied the mechanical properties of the structure during the construction process; Liu [7] took Tianjin Airbus A330 spray painting hangar as an example, according to the construction scheme of the project, used the finite element software Midas Gen to carry out numerical simulation of the whole process of engineering installation and forming, and optimized the construction process and the constraint conditions in the construction process, so as to greatly reduce the structural stress after construction. Thus, for each different project, the construction method will have a greater impact on the mechanical properties of the structure. Therefore, it is necessary to analyze the construction process of large-scale steel structure separately.

In this paper, according to the construction process of the steel grid roof of the theater of Beijing Sub Center Theater project, the influence of cumulative deformation and stress on the mechanical properties of the structure during the construction process will be analyzed by using the finite element simulation method.

2. Project overview
The steel grid roof of the theater of Beijing Deputy Center Theater project is shown in Figure 1(a), and the structural support system is shown in the red part of Figure 1(b). The total amount of steel used in the project is 3171t, and the vertical steel column and lattice column are built above the concrete structure, and the cross sections are selected as □900×900×60×60, □900×900×35×35, □800×800×35×35. The steel structure roof above the steel column adopts hyperboloid grid roof, and the sections of the roof steel members are selected as follows: □1400×500×24×24, □950×300×30×35, □950×300×18×20, □800×400×16×45, □800×300×16×16/40, □790×400×16×35, □790×300×14×14/35, □700×400×20×22. A total of 31 permanent single independent supports and V-shaped supports are set under the roof. The schematic diagram of V-shaped support is shown in Figure 2, and the section is selected as Φ 500×25 and Φ 500 × 35 round pipe. The component materials are Q355 and Q345GJC.

Figure 1. (a) Schematic diagram of hyperboloid grid roof. (b) Diagram of roof support system.
3. Construction process (CP)
When the construction of the lower concrete structure is completed, the construction of the surrounding steel columns is carried out first. After the construction of the steel columns is completed, the installation of the grid roof is started. The grid roof first runs through the main ridge along the diagonal direction, and then the main (vertical to the main ridge direction) and secondary (parallel to the main ridge direction) members are assembled in blocks. The construction process of the steel structure of the theater is shown in Figure 3(a)-(g).

(a) CP1: installation of peripheral steel frame column
(b) CP2: installation of main ridge line beam
(c) CP3-a: installation of grid roof in sequence
(d) CP3-b: installation of grid roof in sequence
(e) CP3-c: installation of grid roof in sequence
(f) CP4: installation of grid roof completed
In this paper, the general finite element software MIDAS is used to simulate the construction process of theater. In the actual construction process, the installation of the beam is often overlapped on the support or column, and the welding is completed with the progress of the construction. In the MIDAS simulation process, the components of each construction step are grouped separately according to the blocks of the construction process, and the construction phase module in the software is used to activate each group step by step to simulate the construction process. In MIDAS software, beam element is used to simulate all members.

The bottom end of the peripheral steel column is fixed. In order to consider the influence of boundary conditions in the calculation of roof installation process, during the simulation of beam installation process, the rotation constraint of beam end is released first to simulate the hinged state of lap joint, and the released constraint mark of beam end is shown as the green dot in Figure 4; When the subsequent structure is installed, the beam end constraint of the previous structure is passivated, and the joint is changed from hinged state to fixed state to simulate the completion of welding. The simulation of some sliding hinge supports in the construction process is also realized by releasing the beam end constraints in the corresponding direction. The load only considers the self-weight effect, and the self-weight load is applied in the initial construction stage.

In the static load condition setting, the load type of the self-weight is set as the load of the construction stage, and the stress and displacement results under the self-weight of each construction stage can be viewed in the post-processing module. In the construction stage analysis control data option, the analysis option is checked as accumulation model. At this time, the analysis of each step in the construction stage is accumulated on the stress and deformation state of the previous step. With the progress of the construction process, more units are activated in MIDAS construction stage, and the structure is installed in turn. The last step is the actual construction completion state after considering the accumulated deformation and stress in the construction process.
5. Analysis of influence of construction process on structural stress and displacement

The whole construction process of theater roof steel structure is simulated by the above method, and the stress and displacement results of each construction step can be obtained. However, the calculation in design state does not consider the actual boundary conditions and deformation accumulation in the construction process, and its stress and displacement state is equivalent to the whole structure installation.

This paper selects the final actual construction state and design state for comparative analysis.

5.1. Influence of construction cumulative deformation and stress on structural displacement

Considering the construction process, the vertical displacement nephogram of the structure at the construction completion stage is shown in Figure 5; The vertical displacement nephogram of the structure under the design state is shown in Figure 6.

As can be seen from Figure 5, considering the accumulated deformation and stress during construction, the maximum vertical displacement of the structure is located in the first span of the main ridge line beam, and the maximum vertical displacement is 70.64mm. The larger displacement is due to its larger span. Considering the actual boundary conditions in the installation process, the deflection caused by the beam weight is larger.

It can be seen from Figure 6 that the maximum vertical displacement of the structure in the design state appears at the weak support system of the grid roof, and the maximum vertical displacement is 11.78mm.

According to the above analysis, there is a significant difference between the actual construction state and the design state, and the maximum vertical displacement in the actual construction state is 599.6% of that in the design state. The large deflection of the actual construction state may cause problems in the structural modeling design, and will affect the stress and vertical displacement.
distribution of the structure during the load combination design in the service stage. The vertical
displacement value in the actual construction stage is much larger than that in the design stage, which
may lead to problems such as too large welding seam and deflection overrun in the construction process.

5.2. Influence of construction cumulative deformation and stress on structural stress
The stress nephogram of the structure at the construction completion stage considering the construction
process is shown in Figure 7; The stress nephogram of the structure in the design state is shown in Figure
7.

![Figure 7. Combined stress nephogram considering construction process.](image1)

It can be seen from Figure 7 that the maximum stress of the structure is 127.16MPa when considering
the cumulative deformation and stress during the construction process, which is located at the beam end
beside the permanent support of the main ridge beam. This is due to the large deflection of the beam
considering the actual boundary of the construction process, which leads to the large internal force at
the beam end.

![Figure 8. Combined stress nephogram in design state.](image2)

As can be seen from Figure 8, the maximum stress of the structure in the design state appears at the
end of a main beam connected with the main ridge line beam, and the maximum stress is 106.22MPa.

According to the above analysis, there is a significant difference between the actual construction
state and the design state, and the maximum stress value in the actual construction state is 119.7% of
that in the design state. The large deflection of the component itself in the actual construction state will
cause greater stress at the beam end of the component, which will require higher weld quality. In addition,
due to the larger stress, the design results based on the completed construction state will be quite
different from those based on the design state, which is dangerous.
6. Conclusions
Based on the analysis of the construction process of the theater roof steel structure of the Beijing Sub Center Theatre project, the following conclusions can be obtained:

(1) The results of structural displacement and stress considering cumulative deformation and stress during construction are quite different from that in the design state. Considering the influence of cumulative deformation and stress during construction, the larger vertical displacement often appears in the middle of the long-span members, and the larger stress appears in the beam end of these members. The larger displacement and stress in the design state appear in the weak position of the structural support system. The maximum vertical displacement in actual construction state is 599.6% of that in the design state, and the maximum stress is 119.7% of that in the design state. The cumulative effect of the construction process will have a significant impact on the location and value of the maximum deformation and stress of the structure.

(2) In practical engineering, the ideal state after the completion of construction should be as close as possible to the design state. Therefore, the boundary conditions and the arrangement of temporary support points should be controlled in each construction stage and component installation process, such as applying semi-rigid constraints at the beam end when installing beam members, setting temporary support in the mid span area when installing long-span beams, etc. To reduce the construction error caused by the cumulative effect of the construction process.

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