Influence of welding sequence on the mechanical properties of a latticed shell formed by orthogonal and oblique members

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Abstract. With the development of economy and the improvement of people's aesthetic level, large-span latticed shells are increasingly used. Such structures are commonly large in volume and huge in welding. In order to select an optimum welding sequence and avoid correcting complex welding deformation, a latticed shell formed by orthogonal and oblique members was taken as the research object in this paper. The finite element models of single and whole latticed shells were established respectively, and according to the equal deformation principle, the influence of different welding sequence on the deformation and internal force of the structure in each construction stage was quantitatively analyzed. The results show that in the welding and assembling stage of small assembling units in the single latticed shell, welding sequence has the greatest impact on the longitudinal deformation, and the change rate of the longitudinal deformation is up to 83.63%; whereas in the tension, sliding and closure stages of each piece of the latticed shell, the transverse deformation is most affected by welding sequence, and the change rate is 33.05%; in different construction stages, the axial stress of the latticed shell is less vulnerable to welding sequence. Furthermore, it is feasible to control the welding shrinkage deformation by selecting a reasonable welding sequence, and the symmetrical welding sequence from both ends to the middle should be adopted during construction.

1. Introduction

Welding is an essential process for machining and connecting steel stress system. However, the residual deformation caused by welding shrinkage will affect the installation accuracy and even mechanical properties of the structure. Large-span latticed shells have been widely used in important public buildings such as terminal, gymnasium and convention center for their beautiful shape, reasonable cost and large space [1]. Owing to the large and challenging welding work in such structures, complex welding deformation will be generated once an unreasonable welding sequence is selected. The subsequent correction will be limited by the conditions on the construction site to delay the schedule and increase the cost [2][3]. Therefore, in order to reduce the influence of welding shrinkage deformation, it is necessary to study the internal force and deformation of latticed shells under different welding sequences, master the law of their generation during the construction installation, and adopt effective means to control them in the design and construction scheme formulation stage.
Considering the calculation efficiency and time, it is impracticable to use numerical simulation to analyze the welding shrinkage deformation of the welded building structure with large volume and complex constraints. Previous studies on the influence of welding sequence on deformation and internal force focus on various types of welded joints [4][8], while for spatial structure systems such as latticed shells, most of them are based on the existing experience to put forward suggestions for construction [9][11], lack of quantitative analysis.

Regarding a latticed shell formed by orthogonal and oblique members as the research object, this paper will establish the finite element models of single and whole latticed shells respectively, and apply the equivalent temperature load to the welded joints of the latticed shells. On this basis, the influence of different welding sequence on the deformation and internal force in each construction stage will be quantitatively analyzed.

2. Finite element simulation

2.1. Finite element model

The roof of the south area in a conference center is selected as the calculation model, which is a latticed shell formed by orthogonal and oblique members with a plan dimension of 72m × 168m. There are four pieces of orthogonal latticed shells (AX~AU axis) with six prestressed cables of Ø110mm in size, and fourteen pieces of oblique latticed shells (AU~AH axis) with twenty-two prestressed cables of Ø95mm in size. The diagram of the single latticed shell is shown in Figure 1. Each piece of the single latticed shell is divided into seven assembly units along the span direction, which is composed of three or two main rods and the secondary rods between them. The layout plan of the roof small assembly unit is shown in Figure 2. The box section sizes of the steel roof member are mainly □700×200×18/20/25/30/35, □500×250×10/14, □500×200×10/16. The main material is Q345GJC, i.e. a high-rise building steel with yield strength of 345MPa and quality grade C. In ABAQUS software, the ideal elastic-plastic material with yield strength of 345MPa is used.

Figure 1. Diagram of the single latticed shell.

Figure 2. Layout plan of the roof small assembly unit.

The project adopts the construction scheme of block assembly and accumulative sliding. First, the small assembly units are hoisted to the operating platform for welding and assembling, forming a single latticed shell. Then, the single latticed shell is slid outward, and the prestressed cables are installed and tensioned in the first stage. Meanwhile, each piece of the latticed shell
is welded and assembled. After all the sliding sections are in place, the second stage tension of twenty-eight cables is completed from north to south in turn, and the construction of roof steel structure is finished.

According to the above construction scheme, the whole construction process is divided into two stages: the welding and assembling stage of small assembling units in the single latticed shell; the tension, sliding and closure stages of each piece of the latticed shell. Among them, the first stage involves the welding of each small assembling unit in the single latticed shell, and the second stage involves the welding of each piece of the latticed shell.

In ABAQUS finite element analysis software, the single and whole latticed shell models are established, as shown in Figure 3. B31 and T3D2 elements are used to simulate the members and cables, respectively. The boundary condition of the latticed shell models is hinged, and the vertical displacements at the support points of the latticed shell models are limited considering the restraint of the assembling supports during the construction.

2.2. Simulation of welding shrinkage deformation

In the welding simulation calculation, it is time-consuming to consider the thermo-mechanical coupling effect for the whole structure. Therefore, in order to simplify the analysis process, this study draws into the equal deformation principle [13], that is to reduce the temperature at the welding joint, and ensure that the shrinkage of the joint is consistent with that of the corresponding welding seam during the cooling process. Based on this principle, the equivalent effect of welding seam shrinkage is introduced in the structure analysis.

The calculation formula of the cooling shrinkage of the butt weld and the member at the welding joint is as follows:

\[
B_1 = \frac{\kappa A}{d} \\
B_2 = \alpha L \Delta T
\]

Where: \(B_1\) is the shrinkage of butt weld; \(B_2\) is the shrinkage of the member at the welding joint; \(\kappa\) is the cross-section coefficient, which is related to the cross-section form of the member, and is 0.057 for the pipe section and 0.031 for the box section; \(A\) is the section area of the welding seam; \(d\) is the plate thickness; \(\alpha\) is the thermal expansion coefficient of steel; \(L\) is the length of the member; \(\Delta T\) is the cooling amplitude of the member.

It can be seen from the equal deformation principle that:

\[
B_1 = B_2
\]

Namely:

\[
\frac{\kappa A}{d} = \alpha L \Delta T
\]

By deforming equation (4), the calculation formula of cooling amplitude for each member can be determined as:

\[
\Delta T = \frac{\kappa A}{\alpha d L}
\]

Due to the difference in the size, length and section form of the members connected by welding joints, the corresponding cooling amplitude needs to be calculated one by one. The
member types and corresponding cooling amplitudes involved in this paper are shown in Table 1.

| Welding joint number | Length of member L/m | Thickness of pipe d/mm | Section area A/mm² | Cooling amplitude ΔT/℃ |
|----------------------|----------------------|------------------------|---------------------|------------------------|
| 1                    | 3.23                 | 10                     | 100                 | 7.998                  |
| 2                    | 3.40                 | 18                     | 324                 | 13.676                 |
| 3                    | 3.27                 | 25                     | 625                 | 19.750                 |
| 4                    | 3.41                 | 20                     | 400                 | 15.152                 |
| 5                    | 3.40                 | 16                     | 256                 | 12.157                 |
| 6                    | 3.00                 | 20                     | 400                 | 17.222                 |

2.3. Simulation of prestressed cable tension

The prestressed cable and the whole structure are taken as a whole for stress analysis. The temperature load is exerted on the prestressed cable (T3D2 element) to make it cool down and shrink, so as to simulate the prestressed effect of prestressed cable on the whole structure.

The cooling amplitude is calculated as follows:

\[
\Delta t = \frac{N}{\alpha EA} \tag{6}
\]

Where: \(\Delta t\) is the cooling amplitude to be exerted; \(A\) is the section area of the prestressed cable; \(\alpha\) is the thermal expansion coefficient of the prestressed cable; \(E\) is the elastic modulus of the prestressed cable; \(N\) is the prestressing force.

According to equation (6) and the first and second stage tension of the project, the cooling amplitudes are obtained as shown in Table 2.

| Prestressed cable number | The first stage tension /kN | The second stage tension /kN | The first stage cooling amplitude /℃ | The second stage cooling amplitude /℃ |
|--------------------------|-----------------------------|-----------------------------|--------------------------------------|--------------------------------------|
| 1                        | 1025                        | 2459                        | 43.63                                | 104.67                               |
| 2                        | 1065                        | 2352                        | 45.33                                | 100.12                               |
| 3                        | 1062                        | 2344                        | 45.21                                | 99.78                                |
| 4                        | 1081                        | 2310                        | 46.02                                | 98.33                                |
| 5                        | 1087                        | 2266                        | 46.27                                | 96.46                                |
| 6                        | 1043                        | 2212                        | 44.40                                | 94.16                                |
| 7                        | 1221                        | 1553                        | 69.68                                | 88.63                                |
| 8                        | 1215                        | 1567                        | 69.34                                | 89.43                                |
| 9                        | 1231                        | 1608                        | 70.25                                | 91.77                                |
| 10                       | 1064                        | 1358                        | 60.72                                | 77.50                                |
| 11                       | 1254                        | 1390                        | 71.57                                | 79.33                                |
| 12                       | 1042                        | 1160                        | 59.47                                | 66.20                                |
| 13                       | 1237                        | 1103                        | 70.60                                | 62.95                                |
| 14                       | 1546                        | 1633                        | 88.23                                | 93.20                                |
| 15                       | 791                         | 1615                        | 45.14                                | 92.17                                |
| 16                       | 1243                        | 1553                        | 70.94                                | 88.63                                |
| 17                       | 1234                        | 1586                        | 70.43                                | 90.51                                |
| 18                       | 1254                        | 1528                        | 71.57                                | 87.20                                |
| 19                       | 1260                        | 1556                        | 71.91                                | 88.80                                |
| 20                       | 1229                        | 1588                        | 70.14                                | 90.63                                |
| 21                       | 1215                        | 1602                        | 69.34                                | 91.43                                |
| 22                       | 1015                        | 1463                        | 57.93                                | 83.49                                |
| 23                       | 1036                        | 1496                        | 59.13                                | 85.38                                |
2.4. Welding sequence condition

(1) The welding and assembling stage of small assembling units in the single latticed shell.

For the single latticed shell model, three kinds of welding sequence are given:
(a) divergent welding from the middle to both ends;
(b) symmetrical welding from both ends to the middle;
(c) welding from one end to the other.

(2) The tension, sliding and closure stages of each piece of the latticed shell.

For the whole latticed shell model, two kinds of welding sequence are given:
(a) divergent welding from the middle to both ends;
(b) symmetrical welding from both ends to the middle.

3. Results and analysis

3.1. The welding and assembling stage of small assembling units in the single latticed shell.

Figures 4-7 plot the nephograms of axial stress and deformation in all directions of the single latticed shell model under different welding sequence. The transverse, longitudinal and vertical directions of the single latticed shell correspond to the X, Y and Z directions of finite element model.
Figure 4. Axial stress nephogram of the single latticed shell under different welding sequence.

(a) Sequence 1: divergent welding from the middle to both ends

(b) Sequence 2: symmetrical welding from both ends to the middle

(c) Sequence 3: welding from one end to the other

Figure 5. Transverse (X-direction) deformation nephogram of the single latticed shell under different welding sequence.
Figure 6. Longitudinal (Y-direction) deformation nephogram of the single latticed shell under different welding sequence.

(a) Sequence 1: divergent welding from the middle to both ends

(b) Sequence 2: symmetrical welding from both ends to the middle

(c) Sequence 3: welding from one end to the other
(c) Sequence 3: welding from one end to the other

Figure 7. Vertical (X-direction) deformation nephogram of the single latticed shell under different welding sequence.

Table 3 lists the maximum deformations and axial stress of the single latticed shell under three welding sequences, which is visual to compare the influence of welding shrinkage on the deformation and axial stress of the single latticed shell under different welding sequences.

| Welding sequence | Transverse deformation (mm) | Longitudinal deformation (mm) | Vertical deformation (mm) | Axial stress (MPa) |
|------------------|-----------------------------|-----------------------------|--------------------------|------------------|
| Sequence 1       | -0.905                      | -1.783                      | 4.649×10^{-2}            | 5.561            |
| Sequence 2       | -0.884                      | -1.138                      | 4.133×10^{-2}            | 5.468            |
| Sequence 3       | -0.808                      | -6.953                      | 4.646×10^{-2}            | 5.534            |

It transpires from Figures 4-7 and Table 3 that, for the two symmetrical welding sequences, compared with welding sequence 1 (divergent welding from the middle to both ends), welding sequence 2 (symmetrical welding from both ends to the middle) makes the deformation of the single latticed shell smaller in all directions, and reduces the maximum deformation of transverse, longitudinal and vertical directions by 2.32%, 36.17% and 11.10%, respectively. Under the asymmetric welding sequence, i.e., welding sequence 3 (welding from one end to the other), the longitudinal deformation caused by welding seam cooling increases significantly, which increases by 289.96% and 510.98%, compared with sequences 1 and 2. Compared with welding sequences 1 and 3, the maximum axial stress under welding sequence 2 reduces by 1.67% and 1.19%. For the above three welding sequences, the influence of welding shrinkage on the longitudinal deformation is the most significant, while the influence on the transverse deformation and axial stress is less.

3.2. The tension, sliding and closure stages of each piece of the latticed shell

In the tension, sliding and closure stages of each piece of the latticed shell, the stress and deformation distributions of the whole latticed shell model under the two welding sequences are similar. Therefore, only the axial stress and deformation nephograms of the whole latticed shell model under divergent welding from the middle to both ends are given as shown in Figures 8-9. The transverse, longitudinal and vertical directions of the whole latticed shell correspond to the X, Y and Z directions of finite element model respectively.
Figure 8. Axial stress nephogram of the whole latticed shell.

(a) Transverse (X-direction) deformation nephogram of the whole latticed shell

(b) Longitudinal (Y-direction) deformation nephogram of the whole latticed shell
Figure 9. Deformation nephogram of the whole latticed shell in all directions.

Table 4 lists the maximum deformations and axial stress of the whole latticed shell under two welding sequences.

| Welding sequence | Transverse deformation (mm) | Longitudinal deformation (mm) | Vertical deformation (mm) | Axial stress (MPa) |
|------------------|-----------------------------|------------------------------|--------------------------|-------------------|
| Sequence 1       | -20.94                      | 7.215                        | -50.90                   | 107.4             |
| Sequence 2       | -14.02                      | 7.377                        | -47.63                   | 105.8             |

It is revealed from Figures 8-9 and Table 4 that, compared with welding sequence 1 (divergent welding from the middle to both ends), welding sequence 2 (symmetrical welding from both ends to the middle) makes the maximum transverse and vertical deformation of reticulated shell smaller, reducing by 33.05% and 6.42% respectively. The maximum axial stress under welding sequence 2 is 1.49% lower than that under welding sequence 1. Changing the welding sequence has the most significant effect on the transverse deformation of the latticed shell, but has little effect on the longitudinal deformation and axial stress.

4. Conclusion
In this paper, the calculation models of the single and whole latticed shell for a latticed shell formed by orthogonal and oblique members are established, and the influence of different welding sequence on the deformation and internal force of the structure in each construction stage is studied. The main conclusions are as follows:

(1) In the welding and assembling stage of small assembling units in the single latticed shell, welding sequence has the greatest effect on the longitudinal deformation, while has little effect on the transverse deformation and axial stress. In the tension, sliding and closure stages of each piece of the latticed shell, the influence of welding sequence on the transverse deformation is the most prominent. In contrast, the influence on the longitudinal deformation and axial stress is less.

(2) Based on the changes of axial stress and deformation under different welding sequence in each construction stage, it is suggested in the welding and assembling stage of small assembling units in the single latticed shell and the tension, sliding and closure stages of each piece of the latticed shell, the symmetrical welding from both ends to the middle should be both adopted for the single and whole latticed shell.

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