Parametric static analysis of a new type of fabricated plate grillard thin shell roof structure

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Abstract. The new fabricated slab ribbed shell roof structure is a new structure based on a large-span steel-concrete composite thin shell roof. An assembly unit composed of a thin-walled steel ribbed plate, a base plate, and concrete provided with bolt holes, and a plate-grid thin shell roof structure formed by the assembling and connecting assembly units. Considering the influence of the structure's rise span ratio, five groups of rise span ratios were used for finite element analysis and compared with single-layer cylindrical reticulated shells. The analysis shows that the mean value of the ultimate load of the new prefabricated panel latticed thin shell roof structure is increased by 5.3% on average compared with the single-layer cylindrical reticulated shell structure. When the rise span ratio is 1/5, the structure has the largest stiffness and the smallest deformation; when the rise span ratio exceeds 1/5, the growth trend in the ultimate load that the structure can withstand will become smoother, and the average maximum displacement will decrease by 4.3% compared with the single-layer cylindrical reticulated shell, which shows that the grid lattice structure has better stiffness.

Key words: Fabricated; Shell structure; Cylindrical latticed shell; Parametric static analysis;

1. Introduction

In recent years, the application of thin concrete shell structures had become less and less, the main reason is that the construction of thin concrete shells is difficult, and temporary formwork setting and formwork dismantling are required during construction. Domestic researchers had also conducted some researches and discussions on the construction method of thin concrete shells, aiming to eliminate the use of temporary formwork. However, the results were very limited in general. Medwadoski \cite{1} proposed a solution that is considered to be better, that is, in the form of an expanded film. In addition, Birini proposed the Binishell \cite{2} system, whose core technology is to use a pole-supporting membrane as a temporary support system for construction, which could eliminate the need for formwork and support. However, because the shape and thickness of the shell and the position of the reinforcing bars are difficult to control, it’s construction technology is demanding and difficult, and it is limited to the construction of curved roofs.
With the development and wide application of technology, the development of space structure systems such as grids and shells had made great progress. However, the weight of the bolts of the grid frame and the net shell structure accounts for a large proportion of the weight of the ball, and the overall deformation of the structure is difficult to control; the deviation of the geometric dimensions of the members and nodes and the deviation of the curved surface have a large impact on the internal force, overall stability and construction accuracy of the structure [3-4]. In view of the above problems, this paper proposes a new structure based on a large-span steel-concrete combined thin-shell roof. An assembly unit composed of a thin-walled steel ribbed plate, a base plate, and concrete provided with bolt holes, and a plate-grid thin shell roof structure formed by the assembling and connecting assembly units. Different from large-span steel-concrete combined thin-shell roofs, the connections between the base plate of the assembly units and the thin-wall rib are not directly welded to the edge of the lower rib, but a certain safety distance is set for the lower rib to set bolts to facilitate the assembly and connections of the assembly units; The base plate of the assembly unit is straight, and the curved surface of the overall structural space is achieved by changing the assembly angle of thin-walled ribs [5-6].

2. Structural form and theoretical calculation method

2.1. Construction type

A new type of fabricated plate grillard thin shell roof structure (hereinafter referred to as "slatted rib structure") is a new type of combined structure. An assembly unit composed of a thin-walled steel ribbed plate, a base plate, and concrete provided with bolt holes, and a plate-grid thin shell roof structure formed by assembling and connecting the assembly units. The assembly structural unit is not limited to a quadrangle, and can be applied to a triangle, a hexagon, and an octagon. The panel rib structure has the following characteristics: (a) As shown in Figure 1, the assembly units are produced in large quantities in the factory, and the shell of a certain span and curvature can be conveniently formed by simply setting the angle of the connection ribs of the assembly unit as designed body. (b) As shown in Figure 2, transportation and site construction are easy. The assembly units can be bolted to form a large curved arch, and then lifted and hoisted. The irregular shapes are constructed by loose spelling and other methods. (c) Reserve a certain distance from the lower edge of the rib plate, and make holes in the reserved positions of the upper and lower ribs to facilitate assembly. (d) Shorten the construction period and reduce the cost.

Figure 1. Assembly structural unit structure diagram.
Number: 1-Bolt for connection; 2-Concrete; 3-Bolt hole for connection; 4-Thin wall steel rib; 5-Thin wall steel base plate;

Figure 2. Schematic diagram of the overall panel rib structure.
2.2. Theoretical calculation method

The analysis methods of composite structures mainly include continuous pseudo-plate method and discretized finite element method. In this paper, Reissner [7] plate-shell theory method is used. Basic calculation assumptions are as follows:

- Suppose the deformation of the rib structure of the grid is small.
- Substitute the assembly structural unit of the plate lattice structure into the upper and lower layers of the plate shell, and the height of the pseudo plate is the actual height of the plate lattice structure.
- The calculation is limited to considering the symmetrical deformation of the panel rib structure.
- The straight line segment perpendicular to the middle plane before deformation, but still a straight line segment after deformation, but not necessarily perpendicular to the mid plane, that is, the displacement of the slab rib structure is three generalized displacements: $\theta_x$, $\theta_y$, $w$.

In this paper, Reissner plate and shell elements with three generalized displacements are used for analysis. As shown in Figure 3, the grid span is the x direction of the plate shell unit, the longitudinal direction is the y direction of the plate shell unit, and the grid thickness is the actual thickness direction of the plate grid rib, that is, the z direction of the plate shell unit.

![Figure 3. Schematic diagram of structural grid](image)

Under the assumption of small deformation, the bending problem of the plate and the plane problem will not couple. Therefore, the element stiffness matrix under combined deformation can be constructed based on the element's bending stiffness matrix and plane problem stiffness matrix. In order to consider the lateral effects of thin-walled steel ribs, the thin-wall steel ribs are separated into plate and shell units. In this paper, the static analysis of the structure is performed based on the finite element theory of plates and shells, and the optimal mesh size and the optimal assembly size are found through the parametric analysis of the rise span ratio.

3. Finite element analysis

3.1. Model parameters

This paper selects the structural dimensions in [8]. Take the length of slab rib structure span $L_1 = 20m$, the length of longitudinal length $L_2 = 30m$, and the structural sagittal height $f = 7.5m$, as shown in Figures 4 and 5. The span length of the assembly unit will change with the change of the structure's sagittal height. In this paper, it will be 1.3m, and the rib thickness is 6mm, as shown in Figure 6. The elastic modulus $E_c = 3.1\times10^8N/mm^2$, and the constitutive relationship is calculated according to the Hongnestad model [9]. Without considering the falling section, Poisson's ratio $\nu = 0.2$. The elastic modulus of steel material $E_s = 2.06\times10^6N/mm^2$, the stress-strain curve considers the ideal elastoplastic model [10], Poisson's ratio $\nu = 0.3$. The value of dead load is 3.5kN/m², the value of live load is 6.5kN/m², and the partial coefficients of load combination are 1.2 and 1.4, respectively.
3.2. Analysis result
Under the action of vertical load, the slab rib structure is deformed symmetrically across the longitudinal direction and the longitudinal direction. As shown in Figure 7, the displacement cloud diagram is deformed in a "strip shape", which indicates that the structure is subjected to unidirectional stress. As shown in Figure 8, when the load is before $7\text{kN/m}^2$, the displacement of the structure shows a uniform upward trend without a large inflection point of curvature, indicating that the material has not yet reached the yield point; when the load exceeds $7.28\text{kN/m}^2$, the curvature of the displacement curve appears larger. The inflection point indicates that the structural material enters yielding, and the displacement at this time is $69.94\text{mm}$, and the position occurs in the middle of the span, which accounts for about $1/285$ of the total span. Compared with the reference [8], the torsional span ratio is $1/272$ different from $4.9\%$, which indicates that the stiffness of the ribbed structure is greater. In order to reduce the error, the stiffness of the overall structure can be improved by increasing the rise span ratio and the thickness of the structure.

As shown in Figure 9, under the constraint of the longitudinal support structure, the plate unit and the solid unit both realize the overall force. The equivalent stress of the plate element is $340.8\text{MPa}$, which occurs near the support; the equivalent stress of the base plate of the structural assembly unit reaches $310.1\text{MPa}$; the concrete has the effect of preventing buckling of the ribs, and the equivalent stress of
the lateral rib is 221.6Mpa. As shown in Figure 10, the equivalent stress of the concrete solid element is 27.9Mpa, and the position occurs at the connection of the edge assembly unit, and the rest of the concrete just reaches the yield point. The supporting structure has a restraining effect on the overall structure, so that the upper panel rib structure material can reach the yield. While ensuring the structural safety, the stress at the supporting structure has not yet reached the yield point. The panel rib structure meets the requirements of the code and is relatively stable overall.

4. Parametric analysis
The rise span ratio is a sensitive parameter for the stability of the open-web reticulated shell structure, and different values directly affect the mechanical performance of the panel lattice structure. Take 5 kinds of rise span ratios $f/L = 1/3, 1/5, 1/6, 1/7, 1/8$ for finite element static analysis. As shown in Table 1, with the decrease of the rise span ratio, the ultimate load of the slab rib structure also decreases, which is the same as the change of the ultimate load of the single-layer cylindrical reticulated shell structure. The rise span ratio is $1/8 \sim 1/3$, and the average limit load of the ribbed structure is 6.99kN, which is an average increase of 5.3% compared with the single-layer cylindrical latticed shell structure (average limit load of 6.63kN). It shows that the new structure has high bearing capacity.

| Rise span ratio $f/L$ | 1/8  | 1/7  | 1/6  | 1/5  | 1/3  |
|----------------------|------|------|------|------|------|
| Slatted rib structure | 6.00 | 7.05 | 7.10 | 7.28 | 7.55 |
| Cylindrical latticed shell | 5.52 | 6.64 | 6.79 | 6.92 | 7.27 |
| Difference value     | 8.0% | 5.8% | 4.4% | 4.9% | 3.7% |

Under the same load, with the decrease of the rise span ratio, the structural displacement of the same span gradually changes gently. Within a certain range of the rise span ratio, the ultimate bearing capacity of the structure increases with the increase of the rise span ratio, and the displacement increases accordingly. However, when the rise span ratio exceeds 1/5, the ultimate load that the structure can withstand tends to stabilize, and the ultimate displacement will continue to increase with a significant increase. The average maximum displacement of the slab rib structure is 75.8mm, which is an average decrease of 4.3% compared with the single-layer cylindrical latticed shell structure (average maximum displacement 79.2mm). This shows that the grid lattice structure has better stiffness. The comparative analysis of the maximum displacement of different rise span ratios is shown in Table 2.

| Rise span ratio $f/L$ | 1/8  | 1/7  | 1/6  | 1/5  | 1/3  |
|----------------------|------|------|------|------|------|
| Slatted rib structure | 107.08 | 79.39 | 75.37 | 57.39 | 48.75 |
| Cylindrical latticed shell | 112.11 | 82.57 | 78.65 | 60.82 | 50.95 |
| Difference value     | 4.5% | 3.4% | 4.2% | 5.6% | 4.3% |
5. Conclusion

- Based on the parametric static analysis of the structure, an excessively small rise span ratio will increase the structural deflection, which is not conducive to the control of the stiffness and strength of the structure. It is recommended that the structure rise span ratio is not less than 1/5.
- Compared with the single-layer cylindrical reticulated shell structure, the average limit load of the plate-grid structure is an average increase of 5.3%, indicating that the new structure has a high bearing capacity.
- Compared with the single-layer cylindrical reticulated shell structure, the average maximum displacement of the plate-grid rib structure decreased by 4.3% on average, indicating that the plate-grid structure has greater stiffness than the single-layer cylindrical reticulated shell structure.
- Under the large load, except for the local component stress concentration, the overall stress distribution is more uniform, and the ribs have less stress than the base plate, indicating that the structure has a good constraint on the ribs in the bending state of the structure effect, effectively prevent the ribs from buckling and improve the bending stiffness of the ribs.

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