Stability Analysis of Fan-shaped Hyperboloid Spiral Pipe Truss Under Different Construction Conditions

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Abstract: The analysis of the stability of fan-shaped hyperbolic spiral tube trusses is still inadequate in China. In this paper, through numerical simulation analysis of structures with different column spacings, the stability bearing capacity of such structures under different column spacings is obtained, and the optimal column spacing is obtained. At the same time, the influence of factors such as section type, pipe truss section size and wall thickness on the structural stability performance is obtained, and the general law is obtained, which provides very important guiding significance for construction.

1. Introduction

With the development of the construction industry and construction technology, the requirements for building forms are becoming higher and higher. Pipe trusses in steel structures are stable, economical, easy to install and manufacture, large in rigidity, good in integrity, and in complex curved shapes due to their stable forces. The structure has more advantages than the grid structure. At present, it has been widely used in many large-span or super-span structures in stadium buildings, such as theaters, convention centers, large stadiums or other large public buildings. The fan-shaped double-curved spiral pipe truss usually adopts a trapezoidal section, and its mechanical performance is more stable. It is often used for complex curved shape structures. At present, it has been applied to more and more buildings.

This article will make a detailed analysis from the middle truss of the whole grid. The support column is set under the middle truss, and its stability analysis has very important guiding significance for construction. In addition, the research on the stability of fan-shaped hyperbolic spiral pipe trusses is almost blank in China, so the key factors such as the type of pipe truss cross section, pipe truss cross section size, wall thickness, column spacing, and other factors affecting the stability of such structures. It is of vital significance.

2. Stability theory and strength analysis

The stability analysis of tube trusses can be divided into linear stability analysis and nonlinear stability analysis. Nonlinear stability analysis needs to consider geometric nonlinearity, material nonlinearity and initial defect and other factors; Linear stability analysis is to obtain the buckling factor and then the buckling load, also known as the eigenvalue buckling analysis, by solving the eigenvalue equation. For
the ideal elastic structure, the theoretical solution of eigenvalue buckling stability is calculated by using the assumption of small deformation.

This calculation model: Truss elevation 7.320m~35.473m, radius R = 37.1m, Pipe truss size P219x10, Mass density 7800, Elastic Modulus 2x10^5 MPa, Poisson ratio 0.3

2.1. Linear buckling analysis
The linear buckling analysis of the structure is performed first to obtain the critical load and buckling mode of the structure. The upper limit of the reference load is provided for the nonlinear buckling analysis. The stable performance of the structure is initially understood, and its instability mode is known. It also provides theoretical reference for nonlinear buckling analysis

\[
\begin{bmatrix} K \\ S \end{bmatrix} \{\varphi\} + \lambda \begin{bmatrix} K & 0 \\ 0 & S \end{bmatrix} \{\varphi\} = 0
\]

\[
\begin{bmatrix} K \\ S \end{bmatrix} — Structural stiffness matrix
\begin{bmatrix} K & 0 \\ 0 & S \end{bmatrix} — Stress stiffness matrix
\{\varphi\} — Displacement eigenvalue vector
\lambda — Eigenvalue
\]

The value of \( \lambda \) can be obtained through finite element analysis, and the buckling load is equal to the eigenvalue \( \lambda \) times the applied load.

Without considering gravity: If the applied load is a unit load, the eigenvalues represent buckling loads.

From the analysis results, it can be concluded that the first three order buckling factors are 46.2e3 47.4e3 56.7e3. Since the unit load is 1N / m, the buckling load obtained by the eigenvalue buckling analysis is 46.2KN / m, 47.4KN / m, 56.7KN / m, taking the minimum buckling load worth 46.2KN / m. Critical load and buckling mode mean that when the input critical load is applied to the structure, the structure will yield in the same form as the buckling mode. It can be seen from the results that the eigenvalues of the first and second orders are very similar, indicating that the structure is sensitive to defects. Non-linear buckling should be solved using appropriate defects or perturbations.
2.2. Nonlinear buckling analysis
For a more accurate analysis of the stable bearing capacity of the truss structure, must consider factors geometrical nonlinearity structure, material nonlinearity and initial defects, and carry out nonlinear buckling analysis of the structure. For the initial defect, the method of applying the initial displacement defect is used to consider the effect of the initial defect on the structural bearing capacity. 《The Technical Specification for Space Grid Structures》 states that the lowest order buckling mode of the structure can be adopted for the initial defect distribution. One hundredth of the first-order mode and one-thousandth of the second-order mode in the linear buckling analysis results are taken as the initial defects of the model in the nonlinear buckling analysis.

![Figure 5. Equivalent stress diagram, Displacement diagram and load-displacement diagram](image)

The definition of buckling in engineering is that even small increments of force cause large displacements of the structure. The load in the load-displacement curve of the structure is converted to each rod, and the ultimate load of the structure is 3.7KN / m, which is about 8% of the ultimate load obtained by the eigenvalue buckling analysis of 46.2KN / m. The final stable bearing capacity of the structure is taken as the smaller value in the eigenvalue buckling analysis and nonlinear stability analysis of the structure, which is 3.7KN / m.

3. Effect of different column distances on structural stability
By adjusting the column spacing, the stable bearing capacity of the structure is obtained under different column spacings, and a reasonable column spacing that meets the economy and stability is found for the structure.
Number the trusses 1~66

![Figure 6. Truss numbering diagram](image)

3.1. Support pillars under pole 33

![Figure 7. Equivalent stress diagram, Displacement diagram and load-displacement diagram](image)
From the load-displacement curve of the structure, the ultimate load of the structure is 20.9KN / m

3.2. Support pillars under poles 16, 33, 49

![Figure 8. Equivalent stress diagram, Displacement diagram and load-displacement diagram](image)

From the load-displacement curve of the structure, the ultimate load of the structure is 66.2KN / m.

3.3. Truss Section two:

![Figure 9. Section two](image)

3.3.1. Articulated support only at both ends

The first three order buckling factor molecules are 55.9e3 57.5e3 59.0e3. Since the unit load is 1N / m, the buckling load obtained from the eigenvalue buckling analysis is 55.9KN / m, 57.5KN / m, 59.0KN / m. The minimum buckling load of the truss is 55.9KN / m.

Compared with the linear buckling load of section one, it is found that the buckling load can be increased by 21% by using the shape of section two, and the stability of the entire structure using section two is better under linear analysis.

Non-linear buckling analysis:

![Figure 10. Equivalent stress diagram, Displacement diagram and load-displacement diagram](image)

From the load-displacement curve of the structure, the ultimate load of the structure is 3.8KN / m

3.3.2. Support pillars under pole 33

![Figure 11. Equivalent stress diagram, Displacement diagram and load-displacement diagram](image)

From the load-displacement curve of the structure, the ultimate load of the structure is 38.0KN / m
3.3.3. Support pillars under poles 16 33 49

Figure 12. Equivalent stress diagram, Displacement diagram and load-displacement diagram

From the load-displacement curve of the structure, the ultimate load of the structure is 76.0KN / m

Table 1. Results comparison table

|                | Two support linear bearing | Two support non-linear carrying | Three support non-linear carrying | Five support non-linear carrying |
|----------------|---------------------------|--------------------------------|----------------------------------|---------------------------------|
| Section one    | 46.2KN/m                  | 3.7KN/m                        | 20.9KN/m                         | 66.2KN/m                        |
| Section two    | 55.9KN/m                  | 3.8KN/m                        | 38.0KN/m                         | 76.0KN/m                        |

According to the data in the above table, the stable bearing capacity of Section two is stronger. Now, we will study the stability performance of Section two under the load during construction.

3.4. Consideration of loads:

3.4.1. Gravity
The product of the dimensioned volume and the gravity density of the structural material is generally used.

3.4.2. Wind load
The wind load during the construction takes into account the wind pressure once every ten years as the calculation basis. This project is located in Shangqiu area, Henan province, where the basic wind pressure once every ten years is 0.2KN / ㎡.

Figure 13. Equivalent stress diagram, Displacement diagram

The wind load is applied to one side of the structure separately, and the equivalent stress cloud diagram and displacement cloud diagram of the whole structure are obtained. The maximum stress on the structure is 688.9pa, converted to 2N on the member, and the maximum displacement is 5.4x10^-8 m. From the results, it can be seen that the effect of wind load on the internal force of the structure is negligible.

Loads are applied to the overall structure, taking into account factors such as construction safety, and magnifying the structure accordingly. The result is shown below:
Figure 14. Equivalent stress diagram, Displacement diagram

It can be seen from the displacement cloud diagram that the maximum vertical displacement of the structure under load is 17.32mm <L / 500 = 22134/500 = 44.3mm (L is the column distance adjacent to the maximum point of displacement), which meets the requirements of the code.

4. Explore the influence of member size on the stability of this type of pipe truss

For this type of pipe truss structure, there are many models to choose from. Now consider the effect of different combinations of pipe diameter and wall thickness on structural stability.

Scheme 1: Increase the overall pipe diameter by 14.8% to obtain the effect of the larger pipe diameter on the structural stability.

Scheme 2: Increasing the overall wall thickness by 50% gives the effect of an increased wall thickness on structural stability.

Scheme 3: Keep the upper chord unchanged, increase the wall thickness of the lower chord by 50%; reduce the wall thickness of the web by 60%. It is concluded that the wall thickness of the lower chord increases and the wall thickness decreases.

Figure 15. Load-displacement diagram

From the analysis of the figure, it is obtained that the diameter of all members of the structure is increased, and the stable bearing capacity of the structure is 95.7KN / m, which is increased compared with 76.0KN / m obtained by the previous analysis, and the wall thickness of all members of the structure is increased. The stable carrying capacity of the structure is 60.1KN / m, and the stability performance has decreased. The wall thickness of the lower chord of the structure is increased, and the wall thickness of the web is reduced. The stable bearing capacity of the structure is 106.1KN / m, and the stability performance is significantly enhanced.

5. Conclusions

(1) Considering the material's geometric nonlinearity and material nonlinearity, and introducing the linear analysis results of the first and second-order modes of the one-hundredth and one-thousandth of the defects, the analysis results obtained are more reliable and more in line with engineering practice.

(2) The analysis of the bearing capacity and load of the structure under different column distances shows that the effect of wind load on the structure can be ignored. Setting support columns at 1/2 and 1/4 of this type of pipe truss structure can meet the structural safety requirements and provide a value reference for the design of such structures.

(3) In the analysis of the bearing capacity of the structure of the combination of different pipe diameters and wall thicknesses, it can be seen that simply increasing the wall thickness of all members in the structure will reduce the stable bearing capacity of the structure, and the increase in wall thickness will cause the structure to bear the gravity load. As a result, the stable bearing capacity of the structure
is reduced. Increasing the diameter of all members will increase the stable bearing capacity of the structure, but it will make the economy poor. Therefore, the wall thickness of the lower chord and the wall thickness of the web can be increased. Therefore, the wall thickness of the chord under the structure can be increased, and the wall thickness of the web can be reduced to increase the structural stability bearing capacity and meet the economic requirements.

References
[1] Gu, J.M., Zhang, Q.L. Study on Introducing First-Order Buckling Mode as Initial Imperfection[C]// National Symposium on Modern Structural Engineering. 2005.
[2] Chen, F., Analysis of the characteristics of grid structure and space tube truss structure[J]. Chongqing Architecture, 2012(06):20-22.
[3] Guo, Y.L., Guo, Y.F., Du, C., et al. In-Plane Stability and Experimental Study of Quadrilateral Circular Arc Space Steel Pipe Truss Arch[J]. Journal of Building Structures, 2010(08):58-66.
[4] Ma, H.W., H.J., Ye, L., Research on the Global Stability of Spatial Inverted Triangular Pipe Truss[J]. Steel structure, 2017(2).
[5] Wu, Y.P., Han, Bo., Zeng, Q., et al. Research and Engineering Application of Structural Linear Buckling Analysis Algorithm [J]. Building Structure, 2017(18):110-114.
[6] Yong, Q.L., Research on Comprehensive Modal Buckling Theory [J]. Journal of Nanjing University of Aeronautics and Astronautics, 1992(01):102-106.
[7] Tan, Y.L., Wang, R.P., Qian, R.J., Research on buckling analysis of multi-parameter systems [C] // Research on Steel Structure Engineering (10) -Proceedings of the 14th (ISSF-2014) Academic Exchange Conference and Teaching Symposium of the Structural Stability and Fatigue Branch of China Steel Structure Association. 2014.
[8] Xu, L., Zhang, J., Study on the construction mechanical properties of long-span hyperboloid pipe truss steel structure roof [J]. Construction Technology, 2016, v.45;No.459(08):69-71.
[9] Huang, J., Analysis of bearing capacity and stability of long-span pipe trusses [D]. Hefei University of Technology. 2012.
[10] Zhou, P., Shen, H.S., Chen, T.Y. Buckling and Postbuckling of Stiffened Cylindrical Shells under External Pressure [J]. China Shipbuilding, 1991(2):38-44.