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Steel structure roof design of terminal T2 of Mianyang Nanjiao Airport

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Abstract

The construction project of T2 terminal building of Mianyang Nanjiao Airport is located in Mianyang City, Sichuan Province, China. The upper steel structure roof adopts an orthogonal square pyramid space grid structure. The shape of the lower surface of the space grid corresponds to the architectural modeling requirements and adopts free-form surface. Steel pipe columns in the landside passenger area adopt the pre-tensioned cable column with a large slenderness ratio, in order to meet the requirements of thin column, transparent building and artistic design. This paper introduces the basic principles of the inverse hanging method, and uses the numerical inverse hanging method to complete the form-finding design of the free-form surface of the lower surface of the space grid. Based on the direct analysis method, a large scale parametric analysis is carried out on the bearing capacity of pre-tensioned cable columns, and the effects of main parameters on the bearing capacity are summarized. Results from this study meet the architectural requirement well and can be used as a reference for similar projects.

Keywords: Space grid structure; numerical inverse hanging method; structural form-finding; pre-tensioned cable column

1. Introduction

Figure 1: Rendering of terminal T2 of Mianyang Nanjiao Airport

The construction project of T2 terminal building of Mianyang Nanjiao Airport (Fig. 1) is located in the East Airport Road, Fucheng District, Mianyang City, Sichuan Province. It is the only military, civilian and training airport in China and belongs to the domestic regional airport. The construction area is about 22,000 square meters, and the building height is 22.90m (the highest point of the building roof). The terminal has 2 floors above ground and 1 floor underground. The lower part of the terminal adopts reinforced concrete frame structure and the roof adopts free-form curved steel grid structure. The terminal is 149.5m long and 59.4 wide, with no structural gap.

The architectural design of this project has the following two distinct features: First, the upper surface of the roof is relatively gentle, with only a small drainage slope, and the lower surface adopts the image of the wave crest and trough to create a modern and simple architectural effect; Second, the roof covers the landside passenger area, and the four outdoor columns are required to be as slim as possible to create a transparent and light architectural effect (Fig. 2).

Figure 2: Landside perspective view of terminal building

The above two architectural characteristics are also the key and difficult points of this project design, and the following design strategies are adopted respectively according to their characteristics: In view of the architectural image of the wave crest and trough, the design adopts the numerical inverse hanging method to determine the surface shape of the grid frame and guide the correction of the architectural shape, so as to achieve the perfect unity of the rationality of the force and the aesthetics of the building; According to the building requirements of thin columns, the pre-tensioned cable column is used to meet the requirements of transparent and light building effects, and can provide a larger design bearing capacity.

This paper mainly introduces the application of numerical inverse hanging method in this project and the design method of the pre-tensioned cable column.

2. Numerical inverse hanging method

2.1. Basic principle of inverse hanging method

（a）The Sagrada Familia church

（b）Deitingen gas station

Figure 3: Typical engineering application of inverse hanging method

Physical inverse hanging method [1] generally refers to the use of flexible materials (rope can be used in one dimension, cloth can be used in two dimensions) under the load can only withstand the tension characteristics, first through the equal scale model, under the artificially given load and boundary conditions, make it in a zero bending moment, pure tension suspension state, and then curing the scale model. Zero bending moment and pure compression structure under given load and boundary condition can be obtained by scaling up after flipping. In the long development process of human history, wood, stone and brick have always been the main building materials, and these building materials have the characteristics of pressure resistance and weak tensile strength [2]. Therefore, historically, excellent building structural engineers designed a large number of construction projects (Fig. 3) with reasonable forces by using this method.

The concept of physical inverse hanging method is clear, but the experiment process is relatively complicated, and it is even difficult to realize in some cases. With the development of computer technology, the function of finite element analysis software is increasingly powerful, and the finite element analysis method is increasingly perfect. This creates the conditions for numerical simulation of physical inverse hanging method.

Numerical inverse hanging method [1] is a form creation process of physical inverse hanging method through numerical simulation, that is, according to the modeling requirements, boundary supporting conditions and load distribution characteristics provided by the architectural profession, the numerical inverse hanging experiment is simulated by adjusting the elastic modulus and using nonlinear finite element technology. The specific steps are as follows (Fig. 4):

1) Establish the initial position finite element model according to the architect requirements, and specify the boundary conditions and load distribution.

2) The initial elastic modulus of the finite element model is assigned.

3) The geometric nonlinear finite element solution was carried out to obtain the equilibrium state of the structure under the elastic modulus.

4) Judging whether the structural form meets the requirements under the balanced state according to the architectural requirements.

5) If the modeling requirements are met, the coordinates are updated according to the deformation state, and the shape creation is completed after the inversion.

6) If the modeling requirements are not met, the elastic modulus can be adjusted according to the relationship between the modeling and deformation of the control point, and the above process can be repeated several times to obtain the structural shape that meets the architectural requirements.

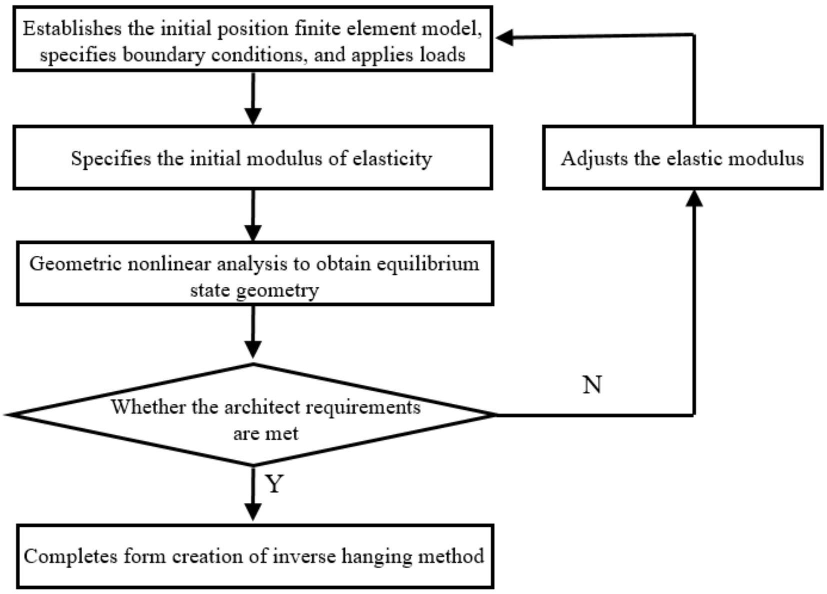


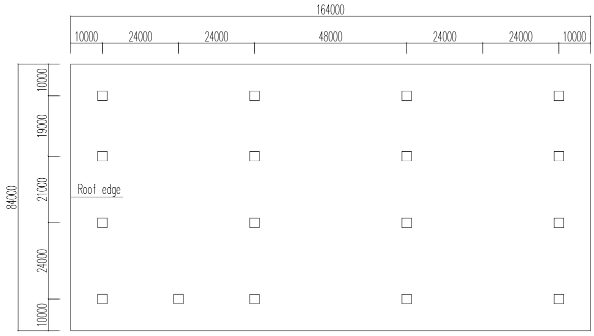
Figure 4: Numerical inverse hanging method flow chart

It should be noted that due to the complexity and variation of the actual force of the project, the form creation can only be carried out according to the main load during the inverse hanging method. Therefore, it is of no engineering significance to excessively pursue the coincidence between the inverse hanging method results obtained by the main load and the architectural modeling.

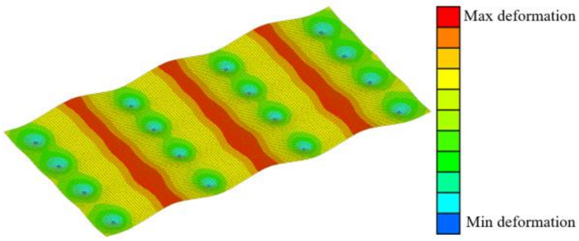
2.2. Engineering application of numerical inverse hanging method

In the early stage of the creation of the project, the structure major cooperated closely with the architecture major. According to the numerical inverse hanging method introduced in Section 2.1, the roof scheme with different column network arrangement was compared and selected for the shape requirements of the building image of the wave crest and trough, and the form design suggestions with reasonable force were put forward from the perspective of the structure major.

The column network layout scheme selected for the final project is shown in Fig. 5 (a). Four rows of columns are set in *x*-direction and *y*-direction. The column spacing in *x*-direction is 48m, and the column spacing in *y*-direction is 19m, 21m and 24m, respectively, with 10m overhangs around. The experimental results of the scheme inverse hanging are shown in Fig. 5 (b), and Fig. 5 (c). It can be seen that the column network is relatively uniform, and the wave crest and trough distribution are relatively uniform, which can realize the unification of beautiful architectural shape and reasonable structural stress.



（a）Column net

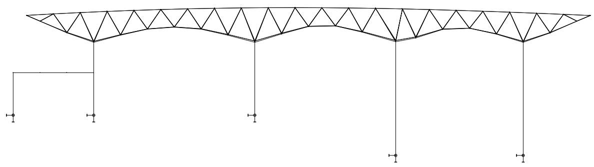


（b）Deformation cloud image

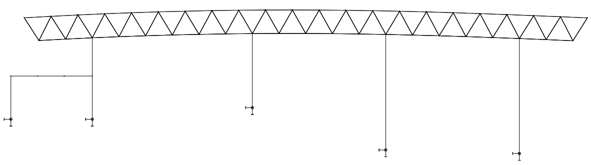
（c）X section view of column position

Figure 5: Project selection scheme

As shown in Fig. 6 (a), the grid scheme of the inverse hanging method is 1.7m thick at the middle span, and 5.2m thick at the top of the column. As shown in Fig. 6 (b) of the traditional slab grid scheme, the economic thickness of 3.45m and the minimum thickness of 1.7m at the middle span of the inverse hanging grid are selected as the thickness of the grid. The so-called economic thickness refers to the reasonable thickness of the grid that meets the requirements of the specification and has a certain degree of safety.



（a）Inverse hanging method scheme



（b）Traditional flat grid scheme

Figure 6: The comparison of the two grid schemes

The economic comparison of the three grid schemes is shown in Table 1. The grid with economic thickness of the overall steel use is about 11% higher than that of the inverse hanging grid, and the flat grid with the minimum thickness is about 52% higher than that of the inverse hanging grid.

Table 1: Economic analysis table of different schemes

Category	Amount of steel used （kg/m^2）			Entirety ratio
	Main structure	Ceiling decoration	Entirety	
Grid scheme of inverse hanging method	29.6	7.2	36.8	1.00
Economical thickness flat grid scheme	30.8	10.2	41.0	1.11
Midspan minimum thickness flat grid scheme	45.6	10.2	55.8	1.52

The inverse hanging grid scheme is compatible with the wave crest and trough building image, which not only realizes the perfect unity of the structural force rationality and the architectural modeling requirements, but also can significantly reduce the overall steel use of the structure and shorten the construction period. The comprehensive economic and technical index of the inverse hanging grid scheme is better than that of the traditional flat grid scheme.

3. Pre-tensioned cable column design

The axial compression bar is an important part of the engineering structure, under normal circumstances, its section size is determined according to the strength and stability requirements, and for the slender compression bar, the stability requirements are the control factors. By combining the cable with the compression member, elastic support is set in the middle of the member after the pre-tension is applied, the stable bearing capacity of the compression member can be significantly improved. The pre-tensioned cable column [3] can give play to the advantages of high strength of materials, save costs, and meet the architect's requirements for thin columns and transparent effects.

3.1. Working principle of pre-tensioned cable column

The pre-tensioned cable column system is generally composed of three parts: center column, strut and cable (Fig. 7). The center column is the main force part of the cable column. The strut and the cable form the outer cable-rod system of the central column. After the pre-tension is applied, the strut is under pressure. The cable-rod system works together to provide elastic support for the central column, and then improve the overall compression stability capacity of the cable column. From the microscopic point of view, after applying the pretension, the outer cable-bar system plays an elastic supporting role on the central column and improves the boundary condition of the central column under pressure. From the macroscopic point of view, after applying the pretension, the center column, strut and cable cooperate to increase the overall flexural stiffness of the pre-tensioned cable column.

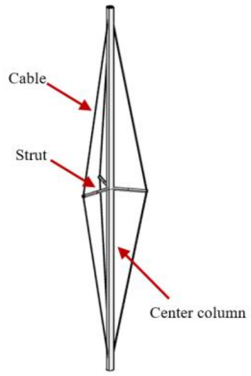


Figure 7: Structural drawing of cable column

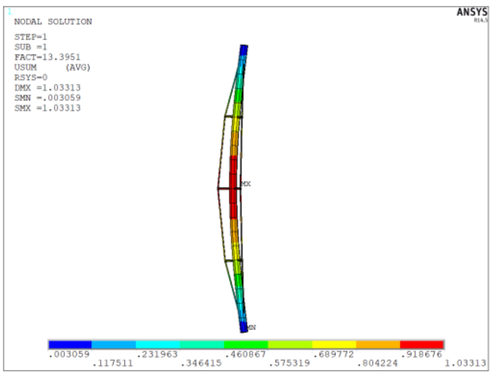


Figure 8: Overall buckling mode of cable column

3.2. Design method of pre-tensioned cable column

Compared with conventional structural columns, the composition of cable column is relatively complex, and there is no design specification for reference at present. This paper proposes a direct analysis method for the bearing capacity design of pre-tensioned cable column, and the specific process is as follows:

1) The overall model of the cable column is established based on software ANSYS. The center column, strut and cable are simulated by beam element BEAM188, rod element LINK180 and cable element LINK180 respectively, and the cable is set as only the pull element.

2) The initial defect of the cable column is determined by two factors: the displacement distribution mode and the maximum defect value. The displacement distribution mode takes the sinusoidal half-wave buckling mode of the overall buckling of the cable column, as shown in Fig. 8. The maximum defect value is $L/350$, where L is the overall length of the cable column [4].

3) The whole process of load-displacement analysis was carried out considering both geometric and material nonlinearity, and the stable bearing capacity of the cable column was determined according to the load-displacement curve.

3.3. Parameter analysis of stable bearing capacity of pre-tensioned cable column

According to the design method of the cable column proposed in Section 3.2, the main parameters affecting the bearing capacity of the cable column are analyzed, including the number of struts, the number of cables, the vector height of cables, and the pretension of cables.

The conditions for parametric analysis of the cable column are set as follows:

1) The height of the cable column is 17m.

2) Both upper and lower ends are set as ideal hinge supports.

3) The cable material is Zinc-5% aluminum-rare earth alloy coated steel strand wire.

4) Center column and strut material is Q355B.

5) The strut section is φ102x6, and the center column section is φ400x26.

The parametric analysis scheme of the pre-tensioned cable column is shown in Table 2.

Table 2: Parameter analysis table for bearing capacity of pre-tensioned cable column

Parameter categories	Parameter value
The number of poles (tracks)	1、2、3、4
The number of cables (tracks)	3、4、5
Cable vector height (m)	0.6、0.8、1.0、1.2
Pretension of cable (kN)	200、300、400、500、600

3.3.1. The number of struts

The models for the number of different struts are shown in Fig. 9, the number of cables is 4, the cable vector height is 0.6m, the cable pretension is 200kN, and the equivalent diameter of cables is 50mm.

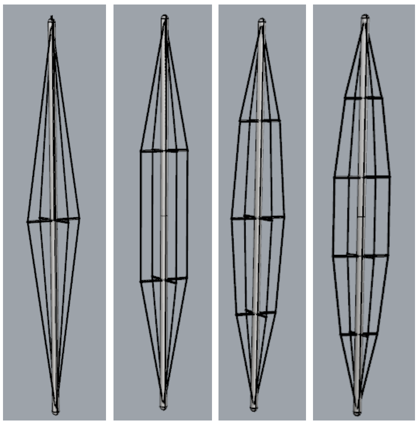


Figure 9: Cable column models with different number of struts

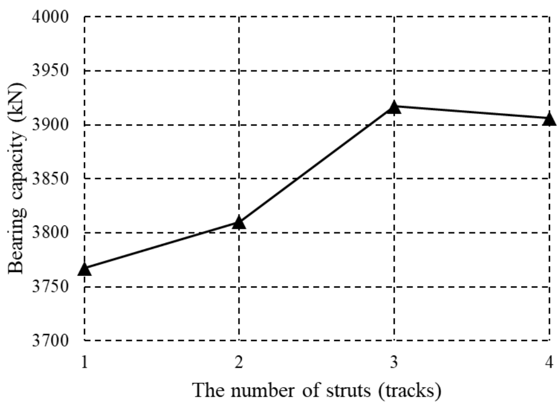


Figure 10: Effect of the number of struts on the bearing capacity

The influence of the number of struts on the bearing capacity of the pre-tensioned cable column is shown in Fig. 10. It can be seen that with the increase of the number of struts, the bearing capacity of the cable column first increases and then tends to be stable. After the initial geometric defect of sinusoidal half-wave is introduced, the middle area of the center column first enters the plastic stage with the increase of load, and the number of strut increases, which can provide more elastic supports for the center column, thus improving the overall bearing capacity of the cable column.

3.3.2. The number of cables

The models of different cable numbers are shown in Fig. 11, the number of struts is 3, the cable vector height is 0.6m, the cable pretension is 200kN, and the equivalent diameters of cables are 60mm, 50mm and 45mm successively. The equivalent diameters are different to ensure that the amount of cable materials is basically the same.

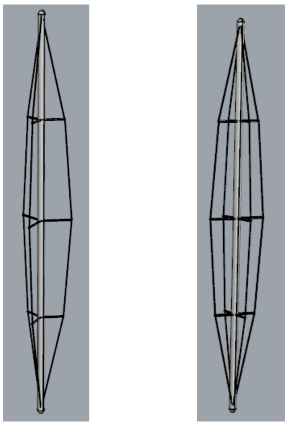


Figure 11: Cable column models with different number of cables

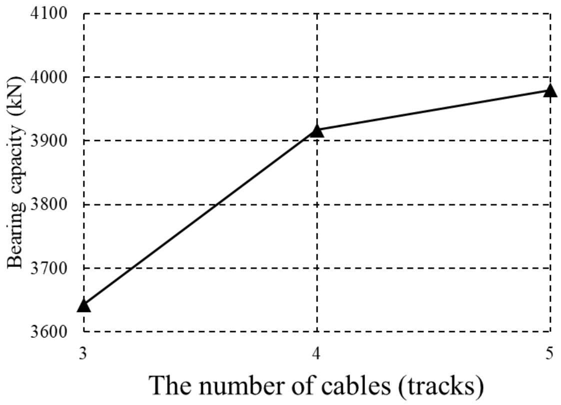


Figure 12: Effect of the number of cables on the bearing capacity

The influence of the number of cables on the bearing capacity of cable column is shown in Fig. 12. It can be seen that with the increase of the number of cables, the bearing capacity of cable column gradually increases, but the increase range gradually decreases. The increase in the number of cables can provide elastic supports for the center column from more directions, thereby increasing the bearing capacity of the cable column.

3.3.3. The vector height of cables

The cable vector height is 0.6m, 0.8m, 1.0m, 1.2m, the number of struts is 3, the number of cables is 4, the cable pretension is 200kN, and the equivalent diameter of cables is 50mm.The effect of cable vector height on the bearing capacity of cable column is shown in Fig. 13. It can be seen that with the increase of cable vector height, the bearing capacity of cable column basically increases linearly. This is because the larger the height of the cable, the larger the overall flexural stiffness of the cable column, and the higher the bearing capacity of the cable column.

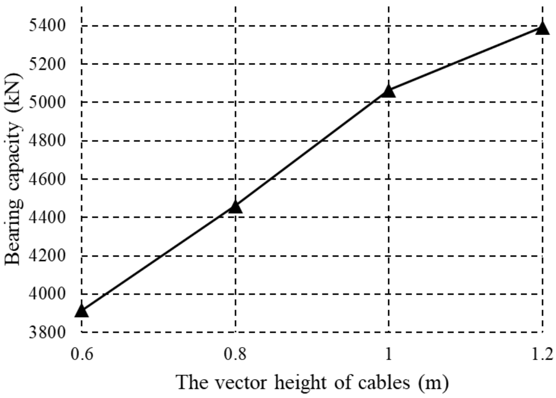


Figure 13: Effect of cable sagittal height on the bearing apacity

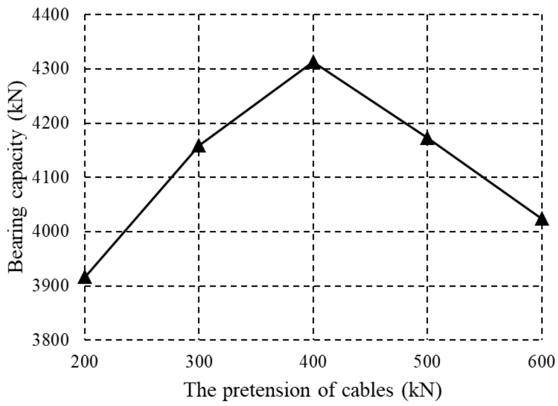


Figure 14: Effect of cable pretension on the bearing capacity

3.3.4. The pretension of cables

The pretension of cables is 200kN, 300kN, 400kN, 500kN, 600kN, the number of struts is 3, the number of cables is 4, the cable vector height is 0.6m, and the equivalent diameter of the cable is 50mm. The influence of cable pretension on the bearing capacity of cable column is shown in Fig. 14. It can be seen that with the increase of cable pretension, the bearing capacity of cable column increases linearly at first, and then decreases linearly.There is an optimal solution for cable pretension.

The influence of the cable pretension on the overall flexural stiffness of the cable column is reflected in two aspects. First, the cable pretension provides the geometric stiffness of the cable and increases the overall flexural stiffness of the cable column. Second, the pretension of the cable causes the compression of the center column, and the compressive stress reduces the overall flexural stiffness of the cable column.

3.4. Engineering application of pre-tensioned cable column

4 cable columns are set on the land side of the project. The height of the cable columns ranges from 16.700m to 17.400m. The cable columns become swing columns by setting the finished steel supports at the upper and lower ends, and the maximum design load is about 5950kN.

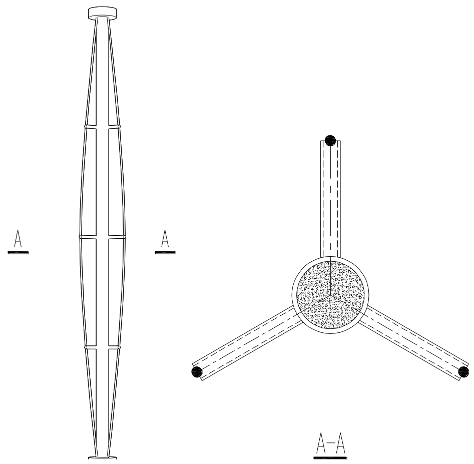


Figure 15: Drawing of pre-tensioned cable column of this project

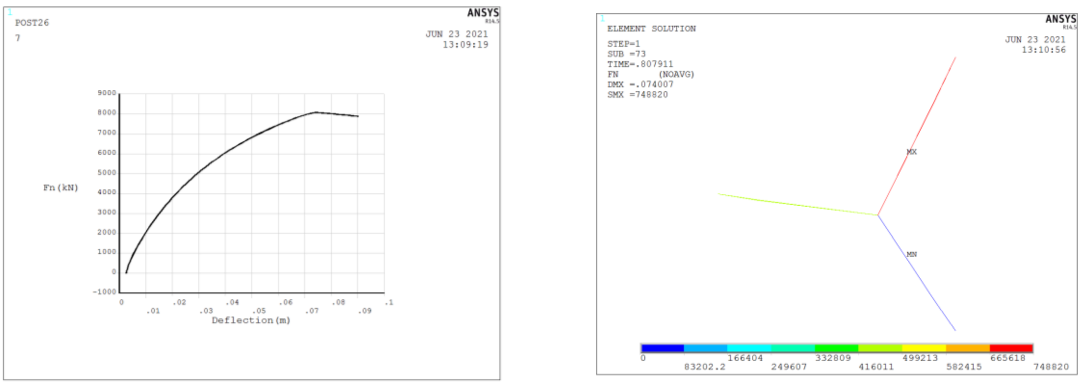
According to the conclusion of parametric analysis on the bearing capacity of Section 3.3 cable column, the design of cable column in T2 terminal building of Mianyang Nanjiao Airport is shown in Figure 15, and the design information is as follows:

1) The section of the center column is φ450x28 and the material is Q355B;

2) Three cables are set. The cable is made of Zinc-5% aluminum-rare earth alloy coated steel strand wire with tensile strength of 1670MPa and equivalent outer diameter of 65mm;

3) Three struts are set, the section of the struts is φ114x8, the material is Q355B, and the two ends of the struts are hinged;

4) The cable vector height is 900mm, and the initial pretension of the cable is 750kN.



(a) Load-displacement curve

(b) Internal force of cable in limit state

Figure 16: Full process analysis of load displacement

After the initial geometric defects are applied, the whole process of load-displacement analysis of the cable column is shown in Fig. 16. The bearing capacity of the cable column can reach 8000kN. In the limit state, the cable on the compression side relaxes and exits, and the internal force of the cable on the tension side is 749kN.

Take the height of the cable column 17m, when the action of the peripheral cable is not considered, according to the Chinese design standard, the design value of the axial compression capacity of the central column is 3822kN. The stable bearing capacity of the pre-tensioned cable column is 2.1 times that of the central column. It can be seen that the stable bearing capacity of the pre-tensioned cable column is significantly increased after the cable and strut system is set up.

4. Conclusion

Mianyang Nanjiao Airport T2 terminal project is a typical small and medium-sized regional airport terminal. In combination with the architectural modeling requirements of the wave crest and trough and the architectural effect requirements of transparent and light landside, this paper studies the application of numerical inverse hanging method in the creation of free-form surface of steel roof and the design method of pre-tensioned cable column. The main conclusions are as follows:

1) The numerical inverse hanging method has clear concept and simple operation, and is an effective method for the creation of free-form surface structure. The freeform surface obtained by the numerical inverse hanging method is beautiful and modern, which can realize the unity of the rationality of structural force and the beauty of architectural shape.

2) The constitution and basic principle of the pre-tensioned cable column are introduced in detail, and the direct analysis method which can be directly applied to the design of the cable column is put forward.

3) Based on the direct analysis method, the stability bearing capacity parameters of the pre-tensioned cable column are analyzed. The analysis shows that the three struts are relatively superior. The bearing capacity of the cable column increases with the increase of cable number and cable vector height, and increases first and then decreases with the increase of pretension.

4) The conclusion of parametric analysis of pre-tensioned cable column successfully guided the design of cable column in Mianyang Nanjiao Airport T2 terminal project, and well realized the architectural effect of thin column, transparent and light on the land side

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