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Applications of hybrid string structures in large-span architectures

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Abstract
Along with rapid progress of large-span architectures in China, hybrid string structures which have excellent load-bearing performances as well as great ability to adapt innovative architectural forms, are being applied extensively in large-span architectures by engineers. In this paper, conceptual design, structural system and arrangement and optimization of hybrid string structures are discussed in several fine project cases, including theme pavilion of World Expo.2010, canopy of Fuzhou south railway station, Quanzhou Gym and Beijing University Gym, which hopes to provide references to similar projects.

Keywords: hybrid string structure, structural system, structural optimization, cable pretension force, support, ultimate bearing capacity

1. Introduction
Hybrid string structures(HSS) are being applied extensively in large-span architecture recently in China. From architectural expression, HSS can make a profound impression on people. The cables are light and form softly curving outlines. From structural behavior, HSS provides a clear load path, in which the material properties of structural members are used sufficiently. The cables improve structural efficiency, and actively control stresses and deformations of structural members. Some examples of HSS are presented in figure 1,.

This paper presents some structural applications of HSS in several large-span projects shown in figure1, in which all of projects except Olympic national gymnasium are designed by authors. Some structural design issues including conceptual design, structural system and arrangement, structural optimizations about cable pretension force, supports and so on, are discussed, which hopes to provide references to similar projects.

Serial Number	Buildings Name	Area (m^2)	Span (m)	Strcutural System
1	Theme pavilion of World Expo.2010	120000	126	Truss string strcuture
2	Canopy of Fuzhou south railway station	74000	62	Three-span continuous beam string struture
3	Quanzhou gymnasium	45000	94	Braced truss string shell
4	Olympic national gymnasium	81000	114	Two-way truss string structure
5	Beijing university gymnasiun	25000	80	Radiant-direction truss string strcuture
6	Anhui university gymnasium	12000	88	Suspendome

Figure 1: several HSS projects in China

2. Theme pavilion of World Expo.2010

2.1. Project overview

The theme pavilion of World Expo.2010 (hereinafter referred to as theme pavilion) will be preserved as the permanent architecture of Shanghai World Expo.2010[figure2], which is designed to show the theme of Shanghai 2010 World Expo-'Better City, Better Life'.

The theme pavilion is in a cube format with a plane dimension of 217.8m×288m and 26.3m high. Its total area is 120000m^2. According to architectural design, the theme pavilion includes west exhibition hall of one storey, middle hall and east exhibition hall of two storeys, and cornices in the north and south sides[figure3]. Especially to mention, the west exhibition hall which has a column-free space covering 126m×180m, will be built into one of the largest exhibition halls in China.

Figure 2: prespective view

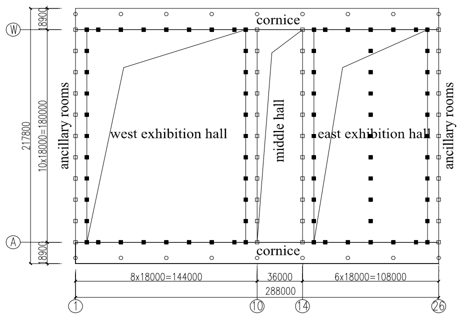


Figure 3: plam view

2.2. Structural system and arrangement

The choice of roof structural system is mainly based on the following considerations:

1) Architectural and structural morphology should be concordant and unified;
2) Structural morphology should be regular and elegant;
3) The roof structure should be transparent to release oppression of the interior space.

However, due to the interior clear height requirement, the structural height of 126m-span roof of west exhibition hall has to be limited in 11.5m. The rise-span ratio is less than 1/11. So it is a critical issue for structural engineering to choose a appropriate roof structural system of west exhibition hall.

The roof of west exhibition hall is carried by nine truss string structures (TSS), each sitting on two columns with a span of 126m center-to-center[figure4]. Each TSS includes two components. One is rigid elements on the top of TSS. The structural form of rigid elements is spatial truss, which section is equilateral triangle with a height of 3m and a width of 3m. The other is cable-strut system. Compared with many other long-span hybrid string structures, the roof structure in the theme pavilion has special characters as following. Firstly, rigid elements of conventional TSS are reverse triangular truss, e.g. the roof of Guangzhou International Expo center. However, in the roof design of theme pavilion, the rigid element is equilateral triangular truss. Thus, one end of roof purlin can be supported by the top chord of equilateral triangular truss, and the other end can be supported by the bottom chord. This structural solution is easy to form architectural folded plate shape of roof design. Secondly, the cable-strut system adopts special V-shaped struts. Compared with conventional multi-struts system of TSS, V-shaped struts laid in the middle span of TSS can optimize internal force distribution and decrease stress intensity of bending and compressive of rigid elements. At the same time, V-shaped struts of cable-strut system give people a new architectural vision.

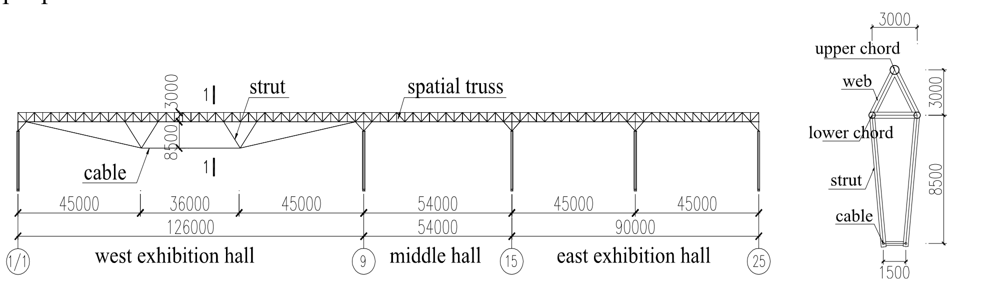


Figure 4: profile of roof structure

2.3. Structural Optimization

2.3.1. Cable pretension force

Cable pretension force of TSS of the theme pavilion is mainly based on the following considerations:

1) Active control of structural deformations. Comprehensive consideration of roof structural vertical deformation and horizontal deformation of support, under the two extreme load cases including dead & live load case and dead & wind load case, Cable pretension force should make the difference between undeformed and deformed structure minimum. The purpose of active deformation control is to make structure having appropriate geometrical configuration and necessary shape stability, and to decrease the roof structural eccentric load action to supporting column, which lighten the P-Δ effect of the columns and improve their ultimate bearing capacity.
2) Active control of internal force of structural members. In TSS, cable pretension force makes struts compression, which realizes unloading action to the top rigid elements and results in the decrease of bending or compressive stress of rigid elements.
3) Avoiding slack of cable under extreme case (mainly wind load). If cable repeatedly appears slack-tension phenomena under frequent wind action, the joints connecting cable and other members will be inclined to fatigue failure. Besides, slack will make cable lose its nonlinear effect, which maybe causes the whole cable-strut system into out of plane instability.
4) Integrating with construction scheme and improving construction efficiency. In China, most of construction schemes of long-span roof structure are assembling structure on scaffold. As for TSS, if the construction of rigid elements adopts assembling structure on scaffold scheme, the cable pretension force should make sure TSS detaching from scaffold after cable-tension stage.

Comprehensive considering the influencing factors of cable pretension force as mentioned above, in the design of theme pavilion, the cable pretension force of TSS is 2225kN. In order to review the cable pretension force effect, nonlinear staged construction analysis is used in the SAP2000 model. After cable-tension stage, the mid-span of TSS uplifts 49.5mm, so the whole TSS realizes detach from scaffold. Under the dead & live load case, vertical deformation of mid-span of TSS is -274mm and horizontal deformation of the top of supporting column is -37.5mm. While under the dead & wind load case, the vertical deformation is 101mm and the horizontal deformation is 37.2mm. The above analysis indicates the whole TSS can satisfy shape stability. Under the extreme wind action, the minimum internal force in cable is 1230kN, which indicates the cable will not appear slack.

2.3.2. Roof supporting design

Upon architectural function request, the whole roof structure from west to east cannot arrange temperature joints. Therefore, the roof length of the theme pavilion in the west-east direction is up to 270m, and the whole roof structure form a four-span continuous girder, which have a great impact on internal force of the supporting frame structure[figure4]. In the design of supporting joints of the theme pavilion, seismic spherical bearings have been utilized to connect roof structure with supporting frame structure. Except that the supporting joint at the axial line 9 adopted rotary bearings that only restrict all of 3-dimensional translations, the other bearings would be sliding to form a self-balanced system during cable-tension and installation work. After roof accessory such as skylights, trellis louvers and gutters had been installation, all of the sliding bearings were welded to the base plates to form the rotary bearings.

The purpose of changing sliding bearing to rotary bearing during the construction stage can be accounted for as following:

1) Releasing the thrust of roof continuous girders to the supporting frame due to thermal expansion, which will enormously decrease deflection and bending stresses to the supporting column. While in serviceability state, indoor temperature change is almost constant, so the temperature action is relatively mild.
2) Releasing the unfavorable horizontal tension to the supporting column during cable-tension of TSS.
3) Making sure the whole structure including roof structure and supporting frame structure to form an integral structure to counteract additional load, e.g. storm or earthquake action. It will go far towards decreasing unbracing length of supporting columns and improving their ultimate bearing capacity.

3. Canopy of Fuzhou south railway station

3.1. Project overview

The roof of canopy of Fuzhou south railway station was designed as a three-span continuous wave shape. In order to provide a big functional space, there is no platform column in Fuzhou south railway station. The plane dimension of plan of the canopy is 450m along the railway direction, and 163m vertical to the railway station. Its total area is 74000m^2, and it can accommodate fourteen trains at the same time. Considering the requests of railway route, along the railway direction, the span of side columns is 12m and the span of internal columns is 24m. Vertical to the railway direction, the spans of three-span continuous wave roof are 61.75m, 55m and 46.25m respectively.

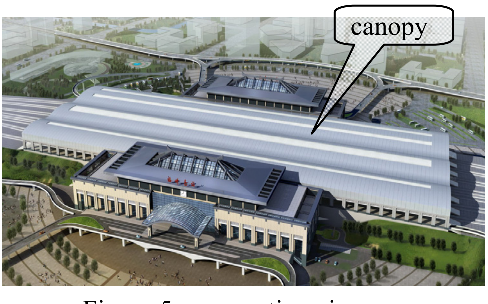


Figure 5: prespective view

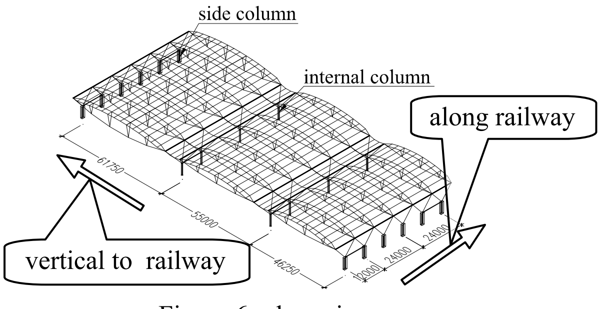


Figure 6: plam view

3.2. Structural system and arrangement

According to the architectural expression and structural efficiency, three-span continuous beam string structure (BSS) have been utilized in roof structural system. The top rigid elements of BSS are two parallel arch tubular beams with an arch rise of 3.5m height. The distance of the two parallel beams is 2.5m. The tension element of BSS is one cable and V-shape struts have been used to create a efficient and dramatic cable-strut system in this BSS design. The tension chords have a single cable, while the compression chords have double rigid elements. This reflects the relatively smaller allowable stresses in compressive members with consideration for the lateral stability. Actually, the three-span continuous BSS were designed like a huge three-span continuous beam with variable depth following the profile of the bending moment diagram under distributed loading, so the deflections of every cable of BSS is 4m, 1.5m, 1.7m, which are relative to the roof spans of 61.75m, 55m and 46.25m respectively.

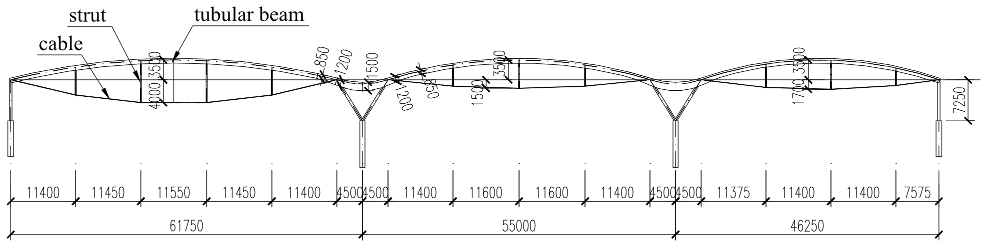


Figure 7: profile of roof structure

Because the three-span continuous BSS is mainly planar force system, cross braces are designed in the roof plane to resist the torsional-flexual buckling failure. But due to the great length of roof structure along the railway direction, while the cross braces improve the roof integral rigidity greatly, the temperature action of roof structure is also magnified. In order to reduce the temperature stress of structural members, temperature joints were designed in every 96m length of roof structure.

3.3. Structural Optimization

3.3.1. Cable pretension force

Cable pretension force of three-span continuous BSS should be satisfied the rules of single-span BSS as mentioned above. In addition, because the three BSS form a continuous beam, structural internal force and deformation of each BSS are not only impacted by its own cable pretension force, but also by the other BSS's cable pretension force. Especially when the spans of each BSS are different, the influences of cable pretension force will make the difference of each BSS mid-span deflections obviously. Meantime, it will bring a great stress concentration at the place of roof supports, which results in enormous deflection and bending stresses to the frames and causes an increasing structural budget.

According to the above principles, the cable pretension force of three-span continuous BSS is decided by the following state. Under the initial state (only including structural members' weight and cable pretension force) and the loading state (mainly including additional loads besides initial state), the mid-span deflections of each BSS is similar, so as for the cable internal forces. Based on trial-and-error method, under the initial state, the cable pretension forces of three-span continuous BSS are 390KN, 340KN, 320KN, which are relative to the roof spans of 61.75m, 55m and 46.25m respectively. And the deflections of each BSS is -2.5mm, 13.1mm, -17.6mm (negative value means reverse gravity direction). Under dead & live load case, the deflections is 51mm, 46mm, 50mm, and the cable internal forces are 1068KN, 960KN, 1016KN. The analysis indicates the differences of deflections of each BSS are insignificant, so as for the cable internal forces.

3.3.2. Roof wind-resistant design

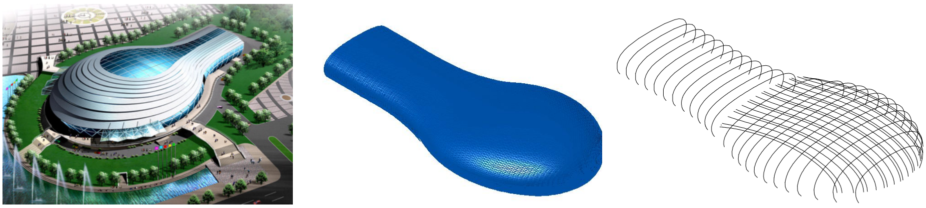
The site of canopy of Fuzhou south railway station is located at southeast coastal region in China, where the wind load is intensive. In the design of the roof structure, because of the long-span of each BSS and the roof wave shape, the wind uplift action is very obviously. However, the total weight of roof structure is so light, and the top rigid tubular beams of BSS is slender which can not provide the enough vertical stiffness, therefore the BSS will appear a great reverse deflection and the cable is slack.

In order to solve this problem, the method of increasing the cable pretension force does not work, because the top rigid beam has limited vertical stiffness. Therefore, the method of increasing the self-weight of BSS is adopted. Fine aggregate concrete is poured into the tubular beams. The analysis indicates that under the extreme wind action, the cable internal forces are 157kN, 302kN, 134kN, and the deflections are -20mm, 21mm, -30mm. The method brings about a desirable result.

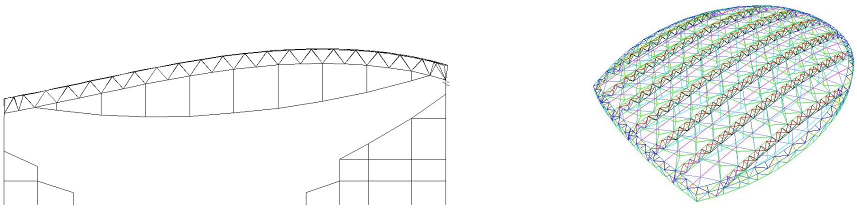
4 Quanzhou Gym

4.1 Project overview and Structural System

Quanzhou Gym, with the capacity of 8000 seats and total area of 45,000m^2, was designed to a elliptical sphere with the largest span of 94m. The first difficult problem is the architectural form design of the special roof, which cannot be represented by regular geometrical analytic surface because the curvature is changed a lot along the lengthways direction. However, architectural form design of the roof is the basis of structural system selection, structural members orientation, roof drainage system design and roof construction. Therefore, NURBS, i.e., Non-Uniform Rational B-Spline technology, is applied to the roof form design. NURBS method is accomplished in form design particularly for irregular special curves and surfaces. Firstly, the whole area of the roof is divided into several sub areas based on the control boundary lines. Secondly, the whole surface is produced through connecting and smoothing the sub surfaces which are created in each sub areas by NURBS method. Then, sectional lines are obtained for the upper chord orientation and the contour lines are applied to roof drainage system design. Thereby, architectural form design of the roof is transferred to structural system orientation and design successfully[figure8].



(a) Perspective View (b) Surface Created by NURBS (c) Section Lines



(d) Typical section of truss string structure (e) Braced truss string shell

Figure 8: Form Design and Structural Orientation of Quanzhou Gym

According to the architectural form and the boundary condition provided by the supporting structure, the braced truss string shell, a kind of new hybrid string structures, is selected as the roof structural system. At the parallel direction along the symmetry axis, seven spatial trusses with the section of inverse triangle are arranged with granularity of 12m. Pretension cables are placed under the spatial trusses with vertical masts as connection, which forms truss string structure(Figure8d). Bracing members are arranged between each two trusses, together with the outer spatial ring truss, to form the braced truss string shell(Fig.8e). The brace system and the outer ring truss could ensure the overall stiffness and integrity of the roof structure. The roof shell is connected upon the concrete ring beam of the supporting structure with one side of hinge bearings and the other of sliding bearings.

4.2 Structural Analysis

Considering that the concrete structure exerts an elastic supporting to the roof steel structure, the integral modeling is adopted, and the nonlinear method is used to conduct a static analysis: in the most disadvantaged load combinations, the maximum downward deformation of the structure is 137.7mm while the upward deformation of 69.2mm, and the vertical stiffness is rather good; the maximums of both the inward slip and the outward slip of the sliding support are controlled within 50mm; The largest tension force of the cables is 2000kN, which is ultimate load capacity; the fixed hinge support in the back end of the truss has a maximum lateral thrust force of 1200kN, which is resisted by the diagonal braces set in the lower supporting frame, while the front end and two sides of the truss eliminate the lateral thrust force by setting the sliding bearings to release displacement.

Ansys is applied in this roof for load bearing capacity. When the roof reaches the ultimate bearing, the plastic areas mostly concentrate on two parts: one is the upper chords of the spatial trusses and the bracing members in the center of the roof, where appears a notable bending deflection, and due to the great compression, the members in the roof plane bring plastic hinge foremost, thus dramatically reducing the vertical stiffness and the in-plane shearing stiffness of the roof. The other is the members in the cable connections and the bearing connections of the truss string structure, and the members in the bearing connections of the outer ring truss. In these areas, the members bring plastic hinge resulting from the greater axial force in each connection, thus continuously weakening the boundary restraint condition of the roof. Finally, the two causes mentioned above jointly bring the structure to the ultimate bearing, which belongs to strength failure by material yield. And at that moment, the load factor is 3.18, indicating that this new type of hybrid tension structure, when in normal service, has a sufficient safety stock.

4.3 Structural Optimization

It is critical to determine the initial tension of the cables in order to realize the roof form design and ensure the excellent bearing performance of hybrid tension structure. Generally speaking, two main aspects should be considered. Firstly, ensure the cables keeping a minimum amount of tension against slack under all load conditions including wind uplift and temperature action, so that the integral stiffness and the stable geometrical form could be maintained. Secondly, the deformation of the roof structure should be effectively controlled. Concretely, the cable force caused by pretension should bring advantaged upward deformation to counteract the downward deformation caused by self-weight so that the vertical stiffness of the roof could be enhanced. And the inward or outward deformation of the sliding bearings under the most disadvantage load combinations should be reduced so that the in-plane shearing stiffness of the whole roof structure could be improved.

Firstly, the pretension cable is brought to individually throw initial pretension of 700kN, 900kN, 1100kN, as three contrast models. In terms of the deformation, the sliding bearings of the model 1(700kN), under the vertical load and the rising temperature effect, appears an excessive outward slippage; while the support of the model 3(1100kN), owning to the wind load and the descending temperature effect, has an excessive inward slippage. As for the variation of the axial force of cables: the cable of the model 1, in the most unfavorable load combination, remains an excessively small tension, possibly arousing the slack phenomenon; while the model 3, as a result of its rather large initial prestress, not only brings a big bending moment and axial force to the rigid substructure, but also causes inconvenience to the construction. Consequently, through the optimal selection, the initial pretension of 900kN is the most reasonable.

5 Beijing University Gym

5.1 Project overview and Structural System

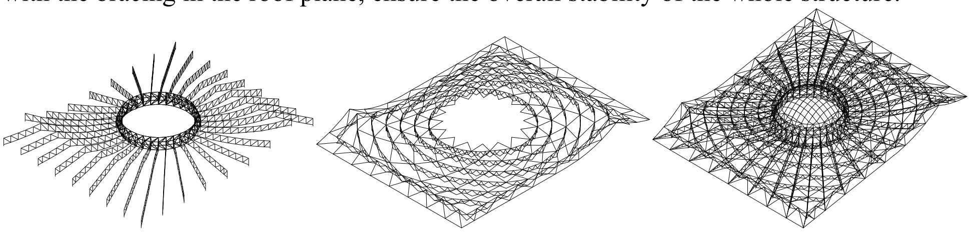
Beijing University Gym is designed especially for the Table Tennis Game of 2008 Olympic. The total floor area is about $2.5\times10^4 m^2$ with the capacity of 6,000 fixed seats and 2,000 temporary seats. The roof is composed of two spiral ridges, four curved eaves and the central transparent sphere shell, which symbolizes table tennis(figure9a).

Similar with Quanzhou University Gym, the architectural form for the roof is also a kind of complex curved surfaces(figure9b), and it is very difficult to finish the form-finding design because of the frequent changeable form and curvature. Again, NURBS method is successfully used to complete form-finding design for this roof(figure9c).

(a) Perspective View (b) Surface Created by NURBS (c) Typical section of BBS

Figure 9: Form Design and Structural Orientation of Beijing University Gym

Based on the study of architectural form and supporting frame structure, pre-stressed truss shell system, a new type of hybrid tension structure (Figure10) is selected as the roof structural system. The whole roof structure is composed of 32 2.5m-deep radial plane trusses with 32 cables connecting to the central tension ring truss, which is connected to the upper compression ring truss by 32 masts. The radial trusses are supported on the concrete frame columns through 28 sliding bearings and 4 fixed hinge bearings in the corners. For the out-of-plane stability of the radial trusses, vertical bracing members, which is situated at concentric circles and consist of trusses stabilizing the structure against buckling, together with the bracing in the roof plane, ensure the overall stability of the whole structure.



(a) radial trusses (b) brace system and outer truss (c) roof steel structure

Figure 10: Composing of Roof Structure

5.2 Structural Analysis

Through tensioning cables, the pretension force induces initial stress in the critical members so that their failure can be delayed. The tension effect of cables causes upward deformation, which counteracts the downward deformation caused by the self-weight of the roof. Furthermore, the horizontal displacement in the sliding bearings is reduced by the horizontal force of the cables, which improves the in-plane shearing stiffness of the roof structure. In a word, active control on the stress of members and the deformation of roof structure is realized in this hybrid tension structural system, so that load-bearing performance is enhanced and the structural efficiency is improved. Therefore, in all load cases, the maximum deflection of the crown joint is 124.3mm, which satisfies the limitation. And the maximum horizontal displacement of the sliding bearings is 47.8mm, which is less than the limitation of 70mm.

As a new hybrid tension structure, profound analysis to the load-bearing performance should be carried out, so that the integral structural security can be evaluated exactly. It reveals that there are two main reasons causing material yield. Firstly, integrality of the roof structure and cooperative performance between radial trusses are both weakened, when the compression ring truss and bracing members are yield. Secondly, restraint condition is weakened, when the members near bearings are yield. Because of the causations above, the roof structure reaches the ultimate bearing capacity with the maximum deflection of 497mm , when the load factor is 4.

5.3 Structural Optimization

The shell structure will bring large horizontal thrust force to its supporting frame structure, especially in the roof of Beijing University Gym, because of its small curvature. So, the roof structure should be optimized to reduce the horizontal thrust force. First, it is skillful to set up sliding bearings to reduce the horizontal thrust force through releasing deformation. Second, the cable tension should be accommodated to ensure the outward and inward deformation of the sliding bearings within limitation of 70mm. Meanwhile, the cable tension could bring advantaged upward deformation to improve the vertical stiffness which is weakened by the sliding bearings. These measures reveal the excellent performance of hybrid tension structure and its efficiency in controlling internal force and deformation.

6. CONCLUSION

（1） The main virtues of hybrid string structure include the initiative stress control and deformation control as well as self-balance characteristic. It not only reasonably changes internal force distribution of traditional rigid elements like truss and shell, but also enormously improves the structural overall stiffness and reduces structural deformation.

（2） Cable pretension force is one of the most important factors of structural optimization of HSS. Apropriate cable pretension force should be integrated with strcutural internal force, deformation, cable slack and constrcution scheme. In addition, together with siliding bearings, horizontal thrust force at the support could be reduced greatly, which lighten the burden of the supporting structures.

（3） The analysis methods of roof steel structure generally include linear analysis and nonlinear analysis. Regarding the traditional rigid structure, the linear method has enough precision and has accumulated many experiences about research and practice in terms of stability and destruction mechanism. However, as for hybrid string structure, using of pretension cables brings obvious nonlinear characteristic to the structure. Therefore, in order to comprehensively understand the changing rule of its strength and stiffness when load-bearing, as well as the overall stability and destruction mechanism, it is proposed to use nonlinear method, which includes nonlinearity of geometry and materials as well as nonlinearity of supporting condition caused by sliding bearings, to truly reflect the structural plastic development order and provide reliable basis for the structural system.

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