Study on Prestressed Steel Dome Structure

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Abstract. With the rapid development of new materials, new processes, and new structures in recent years, the application of prestressed steel structures has been increasingly used, especially for long-span spatial structures. Among the commonly used prestressed steel structural systems, the suspend-dome structures and cable-dome structures can effectively resist loads through prestress distribution. This article explains and demonstrates the features and development of the suspend-dome structure and the cable-dome structure based on the background and characteristics of the prestressed steel structure. Some engineering projects based on these two systems are introduced. Due to their great properties and stress distributions, suspend-dome structures and cable-dome structures can adjust their shapes to meet different architectural requirements, especially shown in many public venues like sports centers. It is expected that prestressed steel structure has bright prospects in the future and the development of prestressing disciplines can be increasingly more significant. This article may offer a reference for the development of prestressed steel structures.

Keywords: Prestressed steel structure; suspend-dome structure; cable dome.

1. Introduction

The prestressed steel structure has been widely used in engineering projects for decades. A specific method to pre-stress the steel structure or components is adopted before applying a load on the structure. When a load is applied, this method can ensure the safety and proper use of the whole structure.

The idea of prestressed structures emerged as early as ancient times, such as the strings of bows and arrows. During the post-World War II reconstruction period, the discipline and practice of introducing prestressing into traditional steel structures began to emerge due to scarcity of materials, funding shortages, and the need to reduce costs [1]. After the 1960s, large-scale spatial structure systems emerged in traditional steel structures, such as grid frames, lattice shells, folded plates, suspension cables, and cable-membrane structures [1]. Large-span prestressed steel structures that apply modern prestressed technology to grid structures have also become an important symbol of a country's construction technology level.

The prestressed structure has completed the process of theoretical analysis, basic performance research, solution exploration, structural design, production technology, and other stages, proving its reliability and economy. Many great civil projects have shown the strong vitality of prestressed structures around the world, like the five-span continuous highway steel bridge in Novokuznesk (1959), the sports building complex of the Moscow Olympics (1980), and the long-span coal transportation trestle of Dawukou Power Station (1986).

The prestressed structure technology can be divided into two categories according to its mechanical properties and layouts: semi-rigid and semi-flexible structural systems composed of rigid components and flexible cables, as well as cable dome structures and suspension structures based on flexible cables. The prestressed structure has the following characteristics. First, it meets the requirements of various architectural functions and expression forms freely, adapting to a variety of layouts and outlines, which makes it convenient for architectural modeling. Secondly, the use of high-strength cables can reduce the weight, and materials effectively. The material strength can also be fully exerted by resisting the external load through the axial stretching of the cable. Additionally, the prestress can adjust the stiffness and deformation of the whole structure, as well as eliminate pre-deformation during the manufacturing process. If the prestress can be adjusted properly, the mechanical performance will be improved, and the bending moment effect will also be minimized.

Finally, the design and construction of prestressed steel structures are closely related, thus the seamless connection between constructions process simulation analysis and structural design should be considered [2].

Commonly used prestressed steel structural systems include beam string structures, suspend-dome structures, cable-dome structures, cable-stayed structures, suspension structures, and prestressed truss structure systems. Among them, the suspend-dome structures and cable-dome structures can effectively resist loads through prestress distribution, making them frequently employed in current dome projects, especially for public venues [3].

2. Classification of Dome Structures

The dome structure based on prestressed steel structure has popped up across the world nowadays, which commonly consists of a suspend-dome structure and a cable-dome structure. The suspend-dome, as a self-balancing system, can reduce the lateral force of the lower supporting structure, which is suitable for square, circular, and rectangular planes. The cable-dome structure can make full use of the tensile strength of steel and improve structural efficiency with few compression components.

2.1. Suspend-Dome Structure

The suspend-dome structure is a new type of composite space structure that has become rapidly popular in the past two decades. It was first proposed in 1993 by Professor Kawaguchi of Hosei University in Japan.

A typical suspend-dome structure generally consists of an upper rigid dome, a lower suspension system, and vertical braces. The structural layout of a general suspend-dome structure is shown in Figure 1. The upper dome structure is generally a single-layer welded spherical shell, which can adopt various layout forms such as ribbed, sunflower, Kewitt layout form, and so on. The lower suspension cable system consists of ring cables and radial cables. Due to the short length of the radial cables, high-strength tie rods are generally used in actual projects.

The upper chord steel structure can also be a single-layer shell composed of radially arranged steel beams and ring beams. Moreover, the suspend-dome structure has a relatively strong outer ring beam, which can be made of thick steel tubes or steel trusses. The vertical struts have a certain supporting effect on the upper dome and improve the stress performance of the dome [4]. The suspend-dome structure mainly solves two major problems of traditional space structures: firstly, it increases the overall stiffness of the structure and ensures the overall stability of the structure; secondly, it has construction capabilities because of the certain initial stiffness of the upper lattice shell. In addition, it can reduce the horizontal thrust of the support and reduce the burden on the substructure.

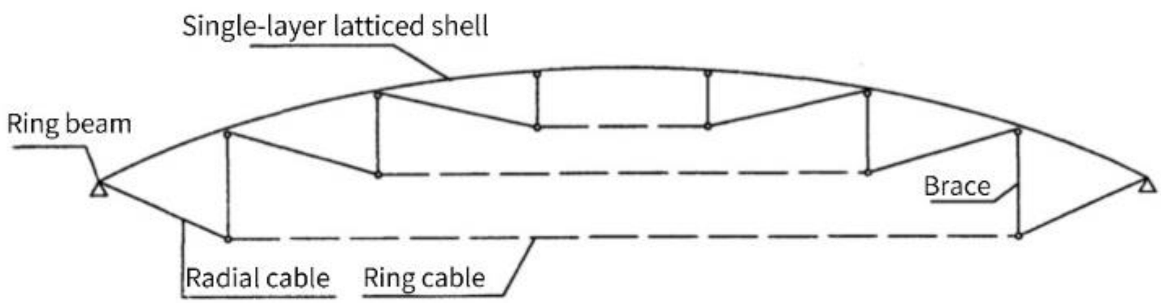

Fig 1. Structural layout of general suspend-dome structure.

The upper lattice shell of the suspend-dome structure is mostly a single-layer lattice shell. According to the different grid forms of the upper single-layer lattice shell, the suspend dome can be divided into rib ring suspend dome, Schwedler suspend dome, and Kewitt suspend dome. According to the material of the lower cable, the suspend-dome structure can be divided into three types: flexible cable suspend-dome structure, rigid rod suspend-dome structure, and partial rigid suspend-dome structure [5].

Loads of the string-supported dome structure mainly include permanent loads, variable loads, and accidental loads. The effect combination should be carried out according to the most unfavorable load during use and construction. Among them, the permanent loads acting on the string-supported dome structure include the self-weight of rods, nodes, the roof, the suspended ceiling, and the equipment. Variable loads include roof live loads, snow loads, and wind loads. For long-span suspend-dome structures, the wind vibration coefficient should be considered. For roofs with complex shapes, the shape coefficient should be determined through wind tunnel tests or numerical simulation analysis. Accidental loads include temperature effects and earthquake effects.

When designing a suspend-dome structure, its structural layout and supporting structure should meet the following requirements [3]:

It should be able to effectively transmit the earthquake effect of the roof to the lower supporting structure. It should have reasonable stiffness and bearing capacity distribution. The layout of the roof and its supports should be even and symmetrical.

The use of two spatial force transmission systems with balanced stiffness should be prioritized in the horizontal direction. The lower supporting structure should be arranged reasonably to avoid excessive earthquake torsion effect on the roof.

The structural layout should avoid weak spots formed due to local weakening or sudden changes, resulting in excessive internal forces and concentrated deformation. For possible weak parts, measures should be taken to improve earthquake resistance.

2.2. Cable-dome structure

The cable dome has been gradually formed and developed since the 1850s according to Fuller's idea of tensegrity structure and has become a structural system suitable for long-span roofs. Cable-dome structures can be divided into two systems: Geiger system and Levy system.

American engineer Geiger constructed the Geiger system cable dome based on Fuller's ideas [6]. The load is transferred from the central tension ring to the peripheral pressure ring through a series of radiating notochords, hoop cables, and intermediate diagonal cables. Only the struts and outer pressure rings are subjected to compression, and other components are subject to tension, which means the stiffness of the roof comes entirely from prestressing. By controlling the height of the struts, the undulating architectural shape of the roof is achieved, and the compression ring is used to provide support for the cables to form a tension field. The structural layout of a Geiger system is shown in Figure 2.

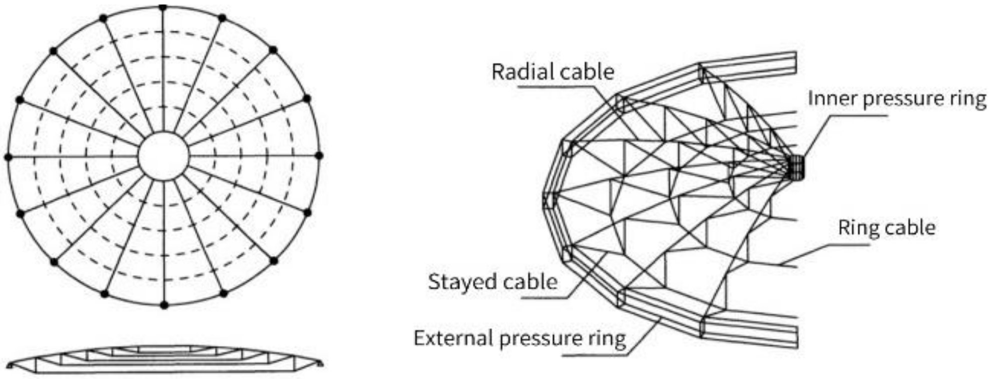

Fig 2. Structural layout of Geiger system.

After that, Levy of Weidlinger Associates believed that the in-plane stiffness of the cable network in the Geiger cable dome was insufficient and prone to partial instability, so he changed the radial notochord in the Geiger cable dome structure into a square shape, which is referred to as a Levy system cable dome [7]. This change eliminates the mechanical risks of the structure, improves the geometric stability and spatial collaboration capabilities of the structure, and makes the cable dome structure suitable for more planar shapes. In addition, the shape of the structure can be a large opening in the middle [8]. The structural layout of a Levy system is shown in Figure 3.

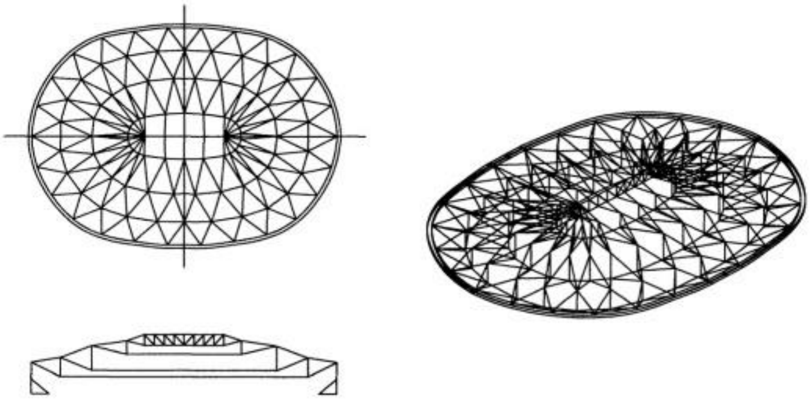

Fig 3. Structural layout of Levy system.

Based on the characteristics of the cable-dome structure, the main attention needs to be paid to its design analysis. The external pressure ring, as the most critical stress-bearing component, bears pressure and a certain bending moment, and may also suffer from instability problems, so it is required that sections of the external pressure ring with large stiffness have a larger bending moment of inertia. The tensile force of all cables will eventually be transmitted to the external pressure ring, so using a circular plane can avoid relatively large bending moments in the external pressure ring [8]. In addition, the cable dome structure can span a large span from 20m to more than 200m, according to current engineering application examples [1].

Due to the geometric nonlinearity of the cable dome structure, the analysis process of the cable dome structure includes two stages: the morphological analysis and the load analysis stage. The purpose of morphological analysis is to confirm a surface geometry with reasonable prestress distribution. The load analysis stage is to find out the response of the structure under the action of external static and dynamic loads and judge whether these reactions can meet the requirements of standards [9].

The morphological analysis includes shape finding and internal force finding, and the shape that satisfies the equilibrium conditions is found gradually. The theoretical methods commonly used in morphological analysis are the nonlinear stiffness method, dynamic relaxation method, and force density method. The load analysis stage [10], which focuses on static and dynamic analysis, studies the response of the structure under the action of external loads. The nonlinear finite element method is generally used in this process.

3. Engineering examples

3.1. Example of suspend-dome structure

The 2008 Beijing Olympic Games Badminton Hall is located at the Beijing University of Technology and is the venue for the badminton and rhythmic gymnastics competitions of the 29th Olympic Games [11]. The roof of the badminton hall is shaped like a flat badminton ball, which adopts a suspend-dome structure.

The plane projection of the building is elliptical, with the maximum dimension in the long axis direction of 141m and the maximum dimension in the short axis direction of 105m. The elevation is in the shape of a spherical crown, with the highest point height of 26.55m and the lowest point height of 5.020m. The upper single-layer shell is composed of 12 rings of rods and 56 groups of radial rods [1].

3.2. Example of cable-dome structure

The Ordos Yijinhuoluo Banner Gym is the first large-scale cable dome structure in China, which adopts the Geiger system The roof building plane is circular with a design diameter of 71.2m and a height of about 5.5m[12]. There are 20 notochords, 20 valley cords, and 2 ring cords in total [12].

The inner ring is rigid, and the connection between the external pressure ring and the valley cord is a low point, as well as the connection with the notochord is a high point.

The roof steel structure of the Desheng Sports Center Gymnasium located in Foshan adopts a cable dome structure with an elliptical plan projection, which is a combination of Geiger and Levy system [13]. The cable adopts the 16-equal system in the inner circle, and the 32-equal Levy system is used from the third circle to the outermost circle [13]. The shape of the inner pull ring is adjusted from the original circle to an elliptical shape which not only facilitates the adjustment of the cable force but also reduces the complexity of the outermost ring cable clamp structure.

4. Comparison

The suspend-dome structure and the cable-dome structure are two distinct architectural forms. The suspend dome emphasizes curved arch ribs, while the cable dome relies on tensioned cables to support the roof. The choice between these structures depends on specific architectural requirements and design considerations. The suspend-dome relies primarily on curved arch ribs to sustain the roof, forming a structure akin to arches. The curved shape of the arch ribs aids in transferring loads to support points while ensuring stability. On the other hand, the cable-dome structure depends predominantly on cables, often made of steel or other high-strength materials to uphold the roof. These cables under tension can efficiently distribute the load. Cable-dome structures are often lightweight and flexible, making them suitable for large-span constructions like sports arenas and exhibition halls.

5. Conclusion

With the rapid development of new materials, new processes, and new structures in recent years, the application of prestressed steel structures has been increasingly used, especially for long-span spatial structures. According to different architectural and structural requirements, the suspend-dome system and cable-dome system can be utilized to build the dome. The suspend dome has clear forces, and the joint structure is relatively complex, so it is often used in actual projects. By adjusting the prestress of the lower cable, the stress on the structure can be reasonable and the deformation of the structure can be adjusted. According to different geometric topological forms, cable-dome structures are divided into the Geiger system, the Levy system, the combination system, and other forms. The cable-dome system has very few compression components, can give full use to the tensile strength of steel, and has extremely high structural efficiency, especially suitable for long-span public buildings.

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