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Applied Research of ETFE Membrane Gas Pillow Structure in Modern Stadiums

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Abstract: The ETFE membrane structure is a new type of building materials, compared to traditional wall material, which has a more significant advantages and modern forms of spatial structure and it will be trend to replace traditional materials. This study, using literature data, based on analysis of the ETFE cushions structure graphics and ETFE materials characteristics, taking the Beijing Water Cube Aquatics Centre as main case, focuses on the ETFE membrane structure of the basic information and this material in the field of sports building design principles and installation methods in order to promote the application of the ETFE membrane material in the field of sports building.

Keywords: ETFE membrane, gas pillow structure, stadiums

INTRODUCTION

Nearly 30 years, the various forms of large-span spatial structures have appeared all over the world, especially, in the developed countries such as Europe , the United States and Japan, With the rapid development of technology and new materials, the spatial structure has been greatly enriched and development (Sun *et al.*, 2008). Since many giant large-span building gradually completed, large-span space structure technology became an important symbol of measuring a country's development level of the construction techniques. Both the emergence of the membrane structure and its value has also attracted the attention of the people. We generally use the air pressure, or use a flexible cable or a rigid supporting structure to support membrane surface, so that the membrane surface to produce a certain pre-tension so as to form a certain stiffness and can cover a large space structural system. Compared with the traditional structure of the membrane structure, the membrane structure has the following advantages: Light weight, larger span, energy saving, sleek, security and so on Wu (2009). It contains architectural aesthetics, construction mechanics, materials science and computer technology as a whole and it has a high technical content. Membrane structure originated in Europe in the 1960s, with the development of materials science and raising the level of construction, the first generation of membrane structure is just a simple used in office, garden, medical facilities and the zoo. As roof and walls and other large-span, high strength construction requirements, it should be said that in that period, material of the membrane structure is also very difficult to accomplish. However, as technology continues to progress, when the emergence of ETFT membrane material, it means that the traditional plastic will be replaced by this new material and completely. Especially, completed in 2000, "Eden Project, Cornwall, UK (Eden Project), is considered to be an engineering myth, which fully demonstrated the unique charm of the ETFE material. In 2008, ETFE membrane material successful used again in the National Aquatics Center-the Water Cube confirmed that this new has the ability of making the building vision into reality. Although the study of membrane structure is late, but in recent years the development of this material is very rapid and China has a large number of membrane structure (Wang, 2009a, b). The awareness of ETFE membrane materials is rising, but a study of the new membrane is really few. So this study, taking Water Cube Aquatics Center of 2008 Beijing Olympics as a case, analyze the characteristics of ETFE material, as well as the problems that need attention.

REVIEW OF THE APPLICATION OF MEMBRANE STRUCTURE IN SPORTS ARCHITECTURE

American red bird arena: As shown in Fig. 1, the Nuo Moer City University of Illinois, United States Red Bird Arena is the first suspended membrane roof structure in the United States and is also the first non-circular top cable and membrane construction in the world. Apart from notochord using ordinary rope, the remaining components of the roof structure are used in 7 a bundle of prestressing cables. The connection

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Fig. 1: American red bird arena

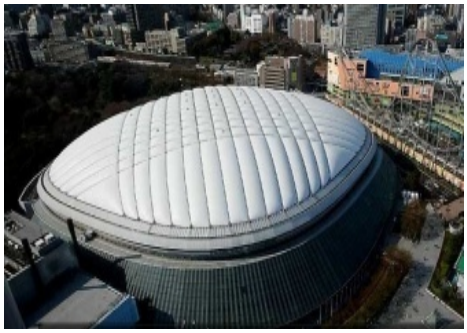

Fig. 2: Japan Tokyo indoor baseball stadium

Fig. 3: White color of Allianz Arena

Fig. 4: Red color of Allianz Arena

between the external oblique cable with the main ring cable and fly rod pieces are bronze pieces. The outside cable of the main tension ring-cable undertakes the changes in tension of the ova top (Robinson-Gayle *et al*., 2001).

Japan Tokyo indoor baseball stadium: Since the Tokyo indoor baseball stadium opening in 1988 and is Japan's first indoor baseball stadium. Positioning "BIG Entertainment and Gold Game!" abbreviated as "the BIG EGG (large eggs), English intent should be" DOME (dome), therefore, the English name is the Tokyo Dome (Robinson-Gayle *et al*., 2001). The Tokyo Dome Is also the home of the Yomiuri Giants Team of Nippon Professional Baseball. People often organize basketball, football games, professional wrestling, mixed martial arts, K-1 events and music performances. The egg-shaped roof is a flexible membrane, in general, pressure inside the Dome be controlled more 0.3% MPA than outside. Using of such methods, the roof can maintain the appearance of eggs top as shown in Fig. 2.

Germany munich allianz arena: Allianz Arena, the Bundesliga, Bayern Munich home stadium, completed and put into use on May 31, 2005. The opening ceremony of the 2006 World Cup in Germany was held here. Allianz Arena stadium is the most modern in Europe. When Bayern Munich is the home game, it can become a red luminous body in the mapping of the lighting system. The stadium can accommodate 66,000 spectators and can be seen in several miles away. Its unusual surface is constituted by the 2874 rhombic membrane structure. Membrane structure has the following features: self-cleaning, fireproof and waterproof and heat insulation performance and it always maintain the atmospheric pressure of 350 Pascal in it. At night, each membrane structure can be illuminated into the red, blue and white. The three colors represent the colors of Bayern Munich, 1860 and the German national team as shown in Fig. 3, 4 and 5. The Allianz Arena should be regarded as the manifestation of the great progress of the ETFE membrane material technology in 2005 (Han *et al*., 2008).

Appearance of ETFE gas pillow structure in water cube: The Water Cube was completed on January 26, 2008 as shown in Fig. 6 and the construction unit is the first branch of the China State Construction. The visual effect of water is realized by the ETFE membrane structure and it is completely consistent with the interior surface effect. A large number of Gas Pillow structure is used in Water Cube. Expand the area of the

Fig. 5: Blue color of Allianz Arena

Fig. 6: Water cube

membrane structure is about 300,000 m2 and it is the world's largest membrane structure building. It is used only by the membrane structure of fully enclosed large buildings. Not only design but also construction is a great challenge. The use of ETFE membrane material is a very difficult and technical subject because of the ventilation and air conditioning fire protection, sound, light, electricity control and so on.

ETFE MEMBRANE INTRODUCTION

The ETFE is an ethylene, tetra fluoro ethylene copolymer, which is a transparent and colorless granular crystal.

ETFE membrane is extruded by raw material. It is a typical non-fabric membrane and is currently the most advanced membrane materials in the world. The ETFE Initially was developed for the space program by NASA. In1982, Germany Foil Tec Company first used ETFE membrane in the construction. The oldest ETFE buildings located is in a Dutch zoo. Thereafter, in Europe the new technology is widely used in the building's roof and facade. A large number of engineering examples and test data are proved that ETFE compared with traditional building envelope has a lot of advantages, small weight, long life, high tensile strength, ductility. Its architectural appearance is crystal clear and beautiful. The exterior facade is light and low cost.

Table 1: Comparison of different materials

	ETFE	PC	PVC	Ordinary glass
Transmittance %	95	89	95	80
Tensile strength /MPa	40-60	56-70	45-63	30-90
Elongationat break %	400	105	200	
Density/g/cm^2	1.75	1.2	1.4	2.5
Thickness/mm	0.05-0.30	2-15	0.05-0.20	3-19
Melting point/°C				

Basic characteristics of ETFE membrane material: As the technology continues to progress, the ETFE membrane material has been used for nearly 30 years in other countries. Its architectural features and advantages have been apparent from the traditional materials. From Table 1, we can get the following main characteristics (Li, 2009).

ETFE membrane material useful life: In Table 1, the durability is a major disadvantage of the membrane material, but the durability of the ETFE membrane material has been improved significantly. Which currently used in Burger's Zoo of the Netherlands Arnhem mangrove Office, the ETFE membrane materials has been used for 25 years. Its various characteristics did not show obvious signs of decay. In National Aquatics Center, the design life of ETFE peripheral structure is 30 years. Compared with traditional materials, it is not only inexpensive, but also long-term durability.

The mechanical properties of ETFE membrane material is very prominent: First, light-quality: (1.75 ± 0.05) g/cm3. Second, good-ductility: When the material is stretched by 15% to 20%, first yield point appears and continues to be stretched to 25%, the second yield point appears. When the material is stretched to 300% to 400%, the brittle failure occurred (Huang, 2006). Third, high-strength: tensile strength 45~50 MPa, tear strength 40~50 MPa, it can effectively withstand wind load and snow load.

Good Transmittance of ETFE Membrane Material: ETFE membrane is very transparent in the visible region (380~780 nm) and its transmittance is 94% to 97% or even higher. The transmittance of the UV (320~380 nm) is also very high (83%~88%) (Ding and Zhang, 2000). So we can give ETFE membrane various patterns by printing to control light and heat radiation and we can also use the ETFE good dye ability to

reduce direct sunlight. So we can make the building look with special visual effects without undermining its transparency. In addition, we can also get translucent building effects by using the multi-layer membrane

ETFE membrane material fire performance: The melting point of ETFE is about 275°C. Because the ETFE contains element fluorine, which means that ETFE can be self-extinguishing. The ETFE start burning melting, non-liquid trickle, no harmful gases.

The self-cleaning properties: ETFE is new membrane material, because of the smooth surface and water resistance; therefore, it is bright as new after the rain.

THE APPLICATIONS OF ETFE MEMBRANE GAS PILLOW STRUCTURE IN WATER CUBE"

Engineering overview: The National Aquatics Center is one of three landmark buildings in the 2008 Beijing Olympic Games, so it is also the only one building designated by the Beijing Municipal Government which is donated by the patriotic personages of Hong Kong, Macao and Taiwan. During the Olympic Games, swimming, diving, synchronized swimming and other games was hold in this venue. After the Olympics game, here will become a multifunctional water sports center where will be holding international events, but also can provide water recreation, sports, leisure and fitness services to public. The National Aquatics Center is located in the Olympic Park Area B, the southwest corner of the Olympic central area. The project covers an area of 62828m2 and construction area is 79532m2 (excluding underground garage) (Sun *et al*., 2008). The building eaves are height of 31 m and the basement area is 177 m×177 m and has standard seats 17,000 and 11,000 temporary seats (will be removed after the game). This project is a premium sports building and the design life of the main structure is 100 years.

The preparation before construction:

- **Water cube peripheral structure system:** "Water Cube" is jointly designed by a team, including China State Construction Engineering Corporation, Australia PTW and Australia ARUP. The project is constructed by Yuanda Group and other units. The Water Cube building model as shown in Fig. 7, is produced in accordance with the 1:3000 ratio and length, width and height is 60cm; 60cm; 10cm. The model is standard ETFE membranes, which can effectively simulate the construction process of the Water Cube.
- **Water cube data:** The ETFE membrane structure of the National Aquatics Center is produced by German FOILTEC and Shenyang Yuanda Aluminum Industry Engineering Co., Ltd. co-production. Winding and bottom chords of the roof are covered by ETFE membrane gas pillow structure including the same four walls (inside and outside) and two interior partition walls (inside and outside). Among them, the roof covering area (gas pillow area) is 58757.48m^2 and the exterior cladding area is 34687.81 m^2 and the interior wall coverage area is 9382.80m^2. Total is 102828.09 m^2. The quantity of the roof gas pillow is 803, 734 of the ceiling, 1436 of wall and 126 of bubbles. Total is 3099 as shown in Table 2.

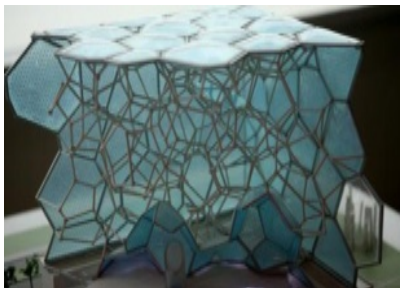

Fig. 7: Construction model

Table 2: Basic data of ETFE in Water Cube

Coverage area of ETFE (/m^2)	100,000
The total number of ETFE (num)	3099
The type of shape ETFE (num)	24
The single largest area of ETFE (/m^2)	90
The layers of ETFE (num)	3 (wall side), 4 (roof, ceiling)
The color of ETFE	Blue(wall side); transparent(others)
The working pressure of ETFE (/pa)	500
The number of air pump (num,/m)	18, 12000 m

- **Gas pillow production process:** ETFE membrane generally has a thickness of 20 mm and 25 mm, tensile strength of 40 of 60 MPa, elongation at break of up to 400%, more than 90% of the light transmittance. Compared with other transparent building materials, it has a good anti-aging properties, self-cleaning properties and elongation. Compared to glass, it has advantages of chipping resistance and deformation follow-up property, light weight and so on. Therefore, ETFE membrane is a very favorable transparent building material. The most troublesome problem is the control of the stress level and the level of the internal pressure during the designing of ETFE gas pillow structure. Controlling stress levels can ensure the tensile strength and anti-creep strain properties. Controlling the pressure changes can ensure requirements of carrying capacity. According to

Fig. 8: ETFE gas pillow model

Table 3: Thickness of ETFE membrane material

		Thickness /μm			
Wall parts	Layers	Outside	Inside1	Inside2	Cavity layer
Outside	3	250	80	-	150;200;250
Inside	3	200	80	-	200
Roof	4	250	80	80	200 or 250
Ceiling	4	100 or 150	80	80	100 or 150
Within the partition	3	100	80	-	100

regulation between the internal pressure and the external pressure, the internal pressure is mainly determined by the external pressure. Three factors: the membrane thickness, the span ratio and pressure related to the stress level. Generally, the pressure has been set, so the span ratio and thickness selection becomes a important questions. The design process is shown in Fig. 8. Pressure within the normal gas pillow is determined by 250Pa. According to architectural renderings, the span ratio is set from 12% to 15%.By calculating the thermal, the facade gas pillow is a 3-layer membrane and roof and ceiling gas pillow is 4-layer membrane structure. Loading conditions, according to the National Aquatics Center, we can be calculated membrane thickness from the various parts of the layers as shown in Table 3.

The following aspects are usually the technical requirements of ETFE gas pillow. Structural properties, first calculated by the computer, gas pillow structure is designed and then analyzes the wind load, snow load, internal pressure, water and other issues in the different parts of gas pillow. Optical characteristics, controlling the reflection and transmission of visible light to control the room light and heat transfer. Thermal characteristics, heat cold outside can cause condensation, so take the U-value as the evaluation of the thermal. The acoustic characteristics, because of the raindrops noise and echoes of the membrane itself, it must rely on sound-absorbing and soundproofing materials to ensure the closure of the building mute. Life and durability, it is more than 25 years of life, low maintenance, anti-UV and special climate and self-cleaning. Sound, light and mechanical effects can guarantee in a long period of use. Using the 3D software, engineers make structural design. Through computer control, using a special welding machine take the membrane weld so that the membrane with the frame are assembly into separate gas pillow unit. The facades and roof overall area of The 2008 Beijing Olympic Natatorium is about 100,000 square meters, which is over 3000 gas pillow and the largest gas pillow area is about 9 square meters and the smallest one less than 1m^2. According to the load requirements, five is the maximum number of layers. All ETFE membrane is close to 300,000 square meters. The engineers use specially crafted welding equipment work, which can weld length up to 10 m.

- **Analog installation:** In order to learn the pillow installation characteristics of the ETFE membrane structure gas better. The Yuanda Company (ETFE project team members) make fifteen steel structure gas pillow in accordance with the ratio of 1:1 in Shenyang, through which workers can experience the real installation process. These gas pillows can be installed in the position of the steel facade, roofing and ceiling and this installation program can be effective technical training for construction workers such as: transport of materials, sub-structure installation and other aspects. During the process of 500 m^2 template construction, the FOILTEC technicians train the construction workers hand by hand. The Model is shown as Fig. 8.

The major technical difficulties about "water cube" project:

- **The facades gas pillow construction technology:** Abroad, the installation of the facade gas pillow is generally the completion of the high-altitude operation truck, so the construction worker is in the basket, but the operation is inconvenient and inefficient. In order to further improve the speed of the facade gas pillow installation, in accordance with the actual situation and construction conditions identified, in east and south facades, we use the cantilever type hydraulic lifting platform and in west and north facade we use telescopic scaffolding to complete the facade gas pillow construction.
- **Construction technology of the roof gas pillow:** The traditional construction facilities of roofing ETFE in foreign is construction network. The disadvantage of this construction process is that: a long Installation time, which was very convenient, low efficiency of construction. When the construction workers stand on a soft, flexible

online, they stand instability and cannot walk easily. So using this construction process, the project cannot guarantee the requirements of the construction schedule. Since this construction method is never used in the country and there is certain insecurity. Therefore, it is difficult to get the recognition of the safety supervision department. In order to further improve the speed and security of the installation of roof gas pillow. Using installed gutter cover all the roof with the safety net, so that everywhere is the size of the enclosed cavity. We erected three platforms in the roof and set the channel between the platform and gas pillow parts, therefore the channel was set on both sides of each 2.4 m by 1.5 m high railing, last we pull two wire ropes as a fence between the rails for safe. As installing the roof gas pillow, worker standing 400 mm wide and 240 mm high gutter expand their air pillow and placed it on the safe network. Before installing, workers untied the connecting ropes between the nets and the gutters, until removed the safety net for all.

- **Gas pillow installation tools:** As the ETFE gas pillow being used an embedded self-locking structure, the gas pillow rope need to add some external force to pull it into the aluminum clamp inside. Tension is main tool for installation gas pillow, because it is small and easy to carry. Because of the principle of leverage, workers can pull the gas pillow into the internal of the mirror, thus it greatly improve the working efficiency.
- **Caution of special gas pillow installation:** The normal gas pillow installation is a process: first tension and second fixed. Here, the special shape of the gas pillow is generally triangular. There is a gas pillow, the acute angle of which is small (typically less than 55°). Comparing all gas pillow shape, the small triangles gas pillow is the most difficult to install. By trying, we summarize a well-established method of installation, the secondary (multiple) stretching method. First, install the Air Pillow short side and then tension and install two long sides. As installing the long side when rely on the direction of the small acute angle and then we take back to the opposite direction. Last again tension and take the long side right.
- **Inflation system design:** The inflation system of this project consists of eighteen permanent air pumps, eight on facade and roof and ceiling are five, weight of 540 kg. The facade air pumps are located in the basement. The roof and ceiling of the air pumps are placed in the upper surface of the core tube. There is no inflatable pillow on the top of core tube, so the position of the air pump has no relationship with premises roof lower chord. Air pump input some pressure air through the main pipeline into inflation system for all parts of inflatable gas pillow. Each inflatable pump is composed of two fans, a drying unit and four air regulators and each of inflatable pumps is to be controlled by their own control means as an independent working device.
- **Condensation and prevent:** Natatorium normal used in the winter, even if the air conditioning system is under normal operating conditions and the temperature and humidity of the museum respectively be controlled at 28 e, about 70%, then the dew point temperature correspond to 21.9 e. According to the original design, the heat transfer coefficient of the natatorium roof double-layer ETFE membrane is 0.8 W/ (m^2 # K) and then the temperature of the layer below is 23 e, so it should be able to avoid the occurrence of condensation. But when the museum air conditioning system does not work, one hand, due to the continuing wet bulk of the museum water, the air humidity is further increased and on the other hand because the air-conditioning stop running, the museum temperature drops, resulting in membrane surface temperature drop. So as below a museum air dew point temperature, the condensation will be inevitable. Especially in the cold winter night, the next morning, the museum air relative humidity is highest, however, the temperature is lowest and so the condensation is most likely to occur at this time.
- **Welding:** Width of the plastics membrane is to be restricted, such as the maximum width of the Nowofol production is 1.55 m. Therefore, in order to effectively use the width of the membrane material, some of the connection method of ETFE membrane is created. In Water Cube projects, the ETFE membrane connection is an adhesive connection. The adhesives connection required to do completely preparation in PTFE-based ETFE. For the adhesive connection, chemical etching, electrical processing or fire treatment is very important to prepare the surface of the ETFE membrane. The adhesive may be any suitable compound, but must be a react adhesive; otherwise it will not be a good connection. Comparatively speaking, because the adhesive has low UV endurance so that the construction period should be selected when the direct sunlight is weaker.

CONCLUSION

This study taking Water Cube project as a case study focuses on characteristics of ETFE membrane structure and describes the installation method and caution of ETEF membrane gas pillow. The following

major conclusions can be derived from the present study:

- The limitations of traditional technology in the renovation of existing buildings encourage people to invent new technology. Water Cube project proved that The ETFE gas pillow structure is a new structural system and it is a good carrier for the construction of new technology.
- ETFE compared with traditional building envelope has a lot of advantages, small weight, long life, high tensile strength, ductility and the others.
- Although it is difficult to install and it easily lead to condensation, or have welding and other technical problems, but for ETFE human technology is constantly advancing, so these problems can be solved perfectly.

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