International Conference on Textile Composites and Inflatable Structures
STRUCTURAL MEMBRANES 2011
E. Oñate, B. Kröplin and K.-U.Bletzinger (Eds)

LIGHTWEIGHT AND TRANSPARENT COVERS

IZIS SALVADOR PINTO*, BEN MORRIS†

* School of Architecture
University of Westminster
35 Marylebone Road, NW1 5LS London, UK
e-mail: i.salvador_pinto@my.westminster.ac.uk

† Managing Director of Vector Foiltec
1-5Vyner Street
London E2 9DG, UK
Email: ben.morris@vector-foiltec.com - Web page: www.vector-foiltec.com

Key words: ETFE cushions, transparent covers, lightweight structures, climatic envelops.

Summary. There has been a gradual shift in construction of long-span covers, from the use of opaque and heavy materials, to the use of transparent and lightweight ETFE (ethylene tetrafluoroethylene) cushions. This paper presents an overview on contemporary covers constructed with lightweight materials, from the research of Frei Otto and Buckminster Fuller, to the possibility of achieving a large city-scale dome enclosure.

1 INTRODUCTION

An enormous variety of efficient structural forms have developed in nature, over many millennia. As human beings, our future will depend upon the prosperity of nature, and our ability to make construction as adaptable and efficient as structures in nature. Human influences have dominated modern climate change, which is now beyond the bounds of natural variability[1].The primary causes of global warming are carbon dioxide emissions from the burning of fossil fuels. The emissions of carbon dioxide are directly proportional to energy consumption. For that reason, in our choice of building materials we must consider the natural resource base and the effects on the environment of the extraction, manufacture and processing of construction materials[2].That means that if we are unwilling to change the way we build, rapid climate change and harmful damaging effects will continue. However, the resources of the planet could be optimized by creating lightweight and adaptive structures.

“A Lightweight structure is defined by the optimal use of material to carry external loads or pre-stresses. Material is used optimally within a structural member if the member is subjected to membrane forces rather than bending”[3].The more a structure can carry with least weight the better. Furthermore, lightweight materials make construction easier and cheaper than standard designs, especially when vast open spaces have to be covered. Adaptive structures have the ability to evolve or change their properties or behavior in response to the environment around them and use knowledge of past events to improve future performance just as nature does.

In recent times, the development of lightweight materials has led to revolutionary changes in different fields of science. In architecture, the new material technology has allowed construction of previously utopian ideas. Frei Otto and Buckminster Fuller´s utopian idea of large city-scale enclosures has been only possible with ethylene tetrafluoroethylene (ETFE) cushions. The properties of ETFE which have allowed these improvements in construction are shown when compared to glass; ETFE is 1% its weight, transmits more light and costs 24% to 70% less to install. ETFE is an appropriate technology for building where the volume of space to cover is large and high light levels are needed because it allows reduction of the weight of the structure whilst providing the same level of stability[4].

2 EVOLUTION OF COVERS SINCE THE LAST 50 YEARS

Throughout history, there has been a gradual shift in the construction methods of long-span structures, from the creation of opaque and heavy constructions, to the creation of more transparent and lightweight structures. This evolution is related to the advance in material technology and the possibility of doing more with less weight, energy and time.

Roofs usually consist of two elements; the roof structure and the roof covering. The first is the structural elements which support the roof and the second is the material which is supported by the structure, and which provides shelter.

Since the 1960s, tensile structures have been built by engineers and architects such as Walter Bird, Eero Saarinen, Frei Otto, Ove Arup and Buro Happold. Tensile structures can achieve a very high level of efficiency because the elements of these constructions carry only tension. Most tensile structures are supported by some form of compression or bending elements, such as masts, compression rings or beams, for example the Millennium Dome and the Olympic Stadium Munich. Tensile structures have historically been used in tents. “The tent is man’s oldest dwelling except for the cave. Evidence of mammoth bones and tusks used as supports for animal hides has been found at sites verified to be more than 40,000 years old in the Ukraine region... The tent has been the dwelling in one form or another for most nomadic peoples from the Ice Age to the present”[5].

People need the shelter that roofs provide, but with the new technologies, more comfortable and adaptive spaces can be created. One of the first architects to introduce deployable structures into architecture was Emilio Perez Piñero. In 1961, Piñero won a prize in the VI International Congress of Architects held in London with the Travelling Theatre, a deployable structure based on the scissors system. In the same year, the roof of the Civic Arena in Pittsburgh became the first long-scale structure with a roof that could be opened and closed[6].Inspired by the studies of Emilio Perez Piñero, Mamoru Kawaguchi created the “Pantadome” erection system to minimize the construction costs and improve site safety in the construction of large space grids. The first building constructed using this system was the World Memorial Hall in Japan in 1984. Four years later, the Olympic Stadium in Montreal was completed. The cover of this Stadium has a system based on fabric that retracts in a roof created with rigid trusses and space frames. Escrig and Sánchez did the same in Jaen, but folding the parcel around the ring, and in Algeciras, sliding on a tensegrity structure[7]. The first dome with retractable roof was the Rogers Centre in Toronto, built in 1989. In 1991, the Ariake Colosseum Tennis Court was constructed by utilization of crane technology. In the same year, Chuck Hoberman created the sculpture of the expanding geodesic dome. Since then, Hoberman has created many deployable structures, some of which have been used in architecture, like the retractable spherical roof of the Iris Dome in the Expo 2000 in Hanover. In 2001, the Toyota Stadium was opened. The roof has an air-inflated dual membrane structure, and the roofs are opened and closed by controlling the inflow-outflow of air.

There are two types of pneumatic structures, which depend on the role of air pressure for their static principle. The air-supported structure is a dome shaped membrane with a fixed perimeter and an inner pressure higher than the atmospheric pressure, whilst an inflated structure is a closed inflated pneumatic beam with inner pressure lower than the atmospheric pressure. Using both systems, a variety of shapes can be achieved.

Engineers like Walter Bird and Peter Stromeyer were the pioneers on the acquisition of empirical knowledge and commercial applications of pneumatic structures. However, Frei Otto was the first to undertake academic research, especially about the process of form finding[8]. Many pioneering pneumatic buildings were built in the Osaka Expo in 1970 such as the U.S. Pavilion by David Geiger, one of the first air supported cable roofs.

The first movable ETFE cushion roof was the roof of the Meiderich Theater built in 2003 at the "Landschaftspark Duisburg-Nord" in Germany. The roof rides on wave shaped tracks but it does not utilise the whole potential of the pneumatic structure because the motion is not produced by the same mechanism without any extra motors or cable pullies.

Tensairity is a pneumatic lightweight structural concept that balances tension and compression. It has been patented by a Swiss company called Airlight. A tensairity beam consists of a membrane of cylindrical shape filled with low pressure air, a compression element connected to the airbeam and two cables running in helical form around the airbeam, connected at both ends to the compression element. The air is used to stabilize compression elements against buckling.

For the roof covering or cladding, several materials have been used throughout history, such as the skin of animals, metal sheeting, concrete, timber, fabrics, glass and plastics. There has been a progressive evolution from opaque to translucent and more recently to transparent coverings, and that has been related with material improvement. In history, there are some examples of mobile coverings such as Roman theatres and amphitheatres covered by velum to protect from rain and sun. However, the use of glass in architecture marked the beginning of an era described by Paul Scheerbart in 1914:

"We live for the most part in closed rooms. These form the environment from which our culture grows. Our culture is to a certain extent the product of our architecture. If we want our culture to rise to a higher level, we are obliged, for better or worse, to change our architecture. And this only becomes possible if we take away the closed character from the rooms in which we live. We can only do that by introducing glass in architecture"[9].

Transparent materials provide light and view without loss of warmth. Until the appearance of ETFE, glass was the most transparent medium but among the rigid plastics, polycarbonate and Glass Reinforced Plastic (GRP) both provide 85% light transmission.

3 ETFE TECHNOLOGY

ETFE, a modified co-polymer, was the result of a research programme to develop an insulating material for the space industry that was resistant to friction and abrasion, immune to radiation and extremely effective at both high and low temperatures. This material was patented by DuPont in 1940, but it started to be commercialized in the 1970s. In 1982, Vector Foiltec pioneered its architectural use. For almost thirty years, ETFE has been used in numerous buildings and public spaces all over the world.

ETFE cushions are pneumatic structures inflated with low-pressure air, restrained in aluminium extrusions and supported by a lightweight structure. When ETFE is used for cladding, the sheets are usually assembled into cushions which are inflated by compressors. "ETFE cushions are a multi-layer system that consists of two or more layers of ETFE foil (100-200 μm thick) heat sealed and clamped in a frame. They are inflated using a small pump to a pressure of 250-400 Pa and topped up intermittently"[4]. ETFE cushion systems are inflatable structures because the inner pressure is lower than the atmospheric pressure.

This material does not degrade under ultraviolet light and is unaffected by atmospheric pollutants. Moreover, ETFE combines exceptional light transmission with high insulation which can reduce winter heating costs. Each layer of foil has a transparency of between 90-95%. The amount of solar shading and the transparency of the building envelope can be modified by changing the translucency, density and number of layers. If desired, photovoltaic cells can be integrated in the cushions to create pollution-free electrical energy.

ETFE can deal with large deflections in the support structure because of its toughness, high resistance to tearing and ability to work harder over a 300-400% elongation range. ETFE is acoustically transparent with a mass of less than 1 kg/m2. In the case of fire, ETFE has the property of self-venting the products of combustion to the atmosphere. Due to its synclastic shape, ETFE has the ability to self-cleanse under the action of rain. Furthermore, the raw material is not a petrochemical derivative and many components are fabricated from recycled material.

3 ETFE EXAMPLES

The Eden Project in Cornwall designed by Grimshaw Architects and constructed by Vector Foiltec is a lightweight structure made with ETFE cushions. The weight of the construction is less than that of the air enclosed. It has a series of intersecting geodesic domes with structural spans of up to 124 meters. The dome structure is divided into two layers, the outer skin formed by hexagons and the inner layer by a triangular and hexagonal grid.

The National Space Center also called the Rocket Tower is the first tower built with ETFE cushions. The building was designed by Nicholas Grimshaw in 2001 and is located in Leicester, England. In the Olympics of 2008, the ETFE was used to cover the Beijing National Aquatics Centre, the Water Cube and the Beijing National Stadium.

While early ETFE clad buildings were located in temperate regions, recent projects have been located in places with harsh climates. One example is the Khan Shatyry Entertainment Center in Astana from Foster and Partners that was finished in 2010. An ETFE cushion envelope encloses multiple buildings and an urban-scale tropical landscape. It encloses an area of 100,000 square meters. The asymmetrical anticlastic conical form of the biaxial cable net is supported at its apex by a 20 meter high inverted cone that is balanced on a 70 meter tripod mast. The circumferential steel cables resist suction and the radial cables resist positive wind pressure. The ETFE cushions change their form as the structure deflects. The net is anchored to a perimeter concrete ring beam.

The utopian ideas of a city scale dome enclosure proposed by Buckminster Fuller with the Midtown Manhatan Bubble in 1962 and Frei Otto with the City in the Artic, 58 Degrees North in 1971, can be nowadays constructed with the new lightweight materials. The Walker Lake Dome Project in Westwood, California is an oblate ellipsoidal and geodesic dome made of ETFE that encloses the town. It is 6.4 kilometers (4 miles) in diameter, 183 meters (600 feet) tall at the center with a surface area of 120,774 square meters (1.3 million square feet). This project can be used to provide a ground for technology to enclose and protect cities prone to weather related disasters.

Figure 1. Buckminster Fuller.
Midtown Manhattan bubble. NY, USA. 1962

Figure 2. ETFE Dome. Walker Lake Dome Project.
Westwood, California. 2010

3 CONCLUSIONS

There has been a big evolution during the last years in materials used for cladding such as ETFE. Since the structure of the building is as important as the covering both fields should be improved in the same extent. Innovative ideas in architecture have been related to situations with very high expectations, under pressure and in critical and competitive circumstances. The climate change provides a very good pretext for innovation. However, architecture continues to focus on immobile structures while scientific fields like aeronautics and the car industry invest more in new materials and started investigating flexible lightweight structures a long time ago.

The evolution of roofs has changed between compression, tension and the balance of both. Moreover, it has been accompanied by the development of covering materials. The dream of architects and engineers to build long-span constructions has become reality with the possibility of building large city-scale dome enclosures.

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