AN INTRODUCTION TO ETFE ARCHITECTURE

LEARNING OBJECTIVES

By the end of this educational unit you will be able to:

1. Compare and contrast the benefits of ETFE architecture and structures over traditional building techniques.
2. Identify the complete process—from design through construction—for creating an ETFE structure.
3. Learn how to select the right ETFE and describe key properties and performance attributes of each.
4. Explore the new innovations and see how these allow you to design according to the new building requirements and codes while still keeping your freedom of design.

CONTINUING EDUCATION

CREDIT: 1 LU

COURSE NUMBER: ARoct2014.1

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INTRODUCTION

Tensile structures have been used for thousands of years. Their simplicity and efficiency have brought about a recent increased awareness of, and demand for, tensile architecture. Ethylene tetrafluoroethylene, or ETFE, is a relatively new product within the tensile membrane industry in the United States, and it is growing in popularity. It is a fluorine based plastic that was developed to be strong across a wide range of temperatures and be highly resistive to corrosion. This course provides a brief background on the following: ETFE architecture; the benefits of ETFE structures over traditional building techniques; identifying the complete design through construction process for creating an ETFE structure; as well as learning how to select the correct ETFE system and the key properties and performance measures of each.

HISTORY OF TENSILE STRUCTURES

Before looking specifically at ETFE, it is important to understand how tensile structures have developed over time. Tensile structures date back to early nomadic people, such as indigenous North Americans, North Africans and East Asians. These groups required shelter that was lightweight and portable, yet structurally sound enough to withstand harsh winds, driving snow, sandstorms, and torrential rains. Combining lightweight fabric, animal hides and small, easily transportable structural elements was the most viable solution. Over time, these structures became symbols of the cultures that used them and other cultures have adopted fabric architecture throughout history. Tensile solutions have appeared in structures like the retractable Roman Velarium that provided sun shading for a more comfortable spectator experience at the Coliseum.

Many credit the rise of modern tensile architecture to 20th century American engineer Walter Bird. As an engineer at Cornell Aeronautical Laboratories during World War II, Bird worked on the design and development of late generation fighter aircraft. After the war, Bird's work shifted to the development of air-supported tensile cladding structures to be used as radomes—the protective weatherproof enclosures for radar antennae. This air-supported concept permitted minimal material thickness and avoided structural frame members that would interfere with RF signals.

In Europe, the German architect Frei Otto started to look a tensile and lightweight constructions right after WWII with the first PVC structure constructed in 1955, but most notably the German Pavilion at the 1967 Expo in Montreal.

At his home in Amherst, New York, Bird installed a similar air-supported structure over his swimming pool to extend the swimming season for his family. The revolutionary pool enclosure was depicted on the cover of Life Magazine in November of 1957, highlighting how the air-supported dome allowed for year round swimming. Seeing the tremendous potential for these new air-supported structures in real world applications, Bird left Cornell Aeronautical Laboratories and launched a new company focused on tensile structures.

In the mid-1960s, Bird learned of new advancements being made in tensile membrane materials that were triggered by the U.S. space program. NASA and DuPont were developing a strong, lightweight, fire-retardant fabric membrane for space exploration apparel. The result was the introduction of a fabric, woven with glass fibers and coated with polytetrafluoroethylene, or PTFE, also known as Teflon. This lightweight membrane per mass proved to be stronger than steel and non-combustible. Bird recognized that these characteristics could make this new material also viable for a variety of architectural applications. He noted the material's self-cleaning attributes could offer significant maintenance benefits in roofing and exterior applications.

Bird's new company partnered with a supplier of the new membrane material and became the first to design and build a permanent inflated roofing structure with the material.

Bird's successful introduction of tensioned PTFE fiberglass membrane led to its extensive use in the architectural community. A 1972 commercial installation at the University of LaVerne in California is still in use to this day. The structure requires little maintenance and continues to perform to its specified structural capacity. Today, after more than 40 years, it shows no sign of needing to be replaced.

First ETFE Structure, Arnheim Burgers' Zoo, 1982

As a further development of the PTFE, Dupont created ETFE film as a protective coating used in the aircraft industry. Later in the 1980s it was discovered as a building material to create transparent envelopes.

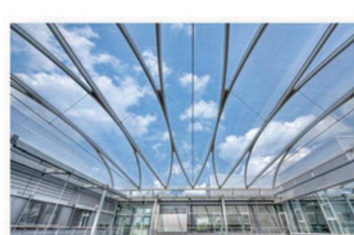
WHAT IS ETFE?

ETFE, or Ethylene Tetrafluoroethylene, film is durable, highly transparent and very lightweight in comparison to glass structures. ETFE film, conventionally used in agricultural applications such as greenhouses or for the coating of solar cells, has demonstrated its worth in the architectural sectors, as well.

The raw granulate is extruded into sheets called foil or film with a density of 1.012 oz. per cubic inch. ETFE is one of the most lightweight and transparent cladding materials in the building products industry. Due to the low coefficient of friction on its surface, dust or dirt does not stick on the film. As the film is UV transparent, it will not discolor or structurally weaken over time. ETFE can also be fully recycled.

The first ETFE application in the building industry took place in the early 1980s in Europe. Now, ETFE is considered the material of choice for a variety of projects, from traditional skylight applications to long span structures and building facades. Plus, when you want a structure that stands out from the crowd, few building materials can match ETFE for its impact or presence.

With the Eden Project in Cornwall, UK in 1988, the tremendous potential of ETFE was shown. With two major projects, the Allianz Arena for the 2006 Soccer World Cup and the "Water Cube" at the 2008 Beijing Olympics, ETFE film has gained recognition and is now considered the premium material for transparent cladding applications whether in roofing or facade construction.



ETFE structures offer flexibility with design (Project: DWI Aachen by Carpus+Partner)

CHARACTERISTICS OF ETFE

There are many benefits to using ETFE film for a building or structure. ETFE films can be highly transparent, from 90 percent to 95 percent, and allow for the passing of UVs which are responsible for the promotion of photosynthesis, thus facilitating plant growth.

ETFE film systems can incorporate a number of frit patterns on one or multiple layers to alter their solar performance. The foil is printed with various standard or custom patterns. During the extrusion process, color can also be applied, providing a consistent tint in various tones ranging from red to violet, contributing to ETFE's solar control and shading properties.

While ETFE films are very elastic, up to 600% at breaking point, they are still structurally resistant. The tensile strength at the limit of elasticity/plasticity is 21–23 N/mm², but tensile strength to breaking point is 52/Nmm². For the structural calculation, a limit of 15 N/mm² conservatively is usually taken.

ETFE does not degrade under exposure to environmental pollution, UV light, harsh chemicals or extreme temperature variations. This helps to make ETFE a long lasting material, especially in its outdoor applications.

ETFE film has approximately 70% acoustic transmission. Acoustically, the cushions are fairly transparent and dramatically reduce reverberations. This quality can be beneficial when used in a project that expects loud noises, since the sound will not be reflected back into the building.

From the extruding of the film to the transportation to the site, ETFE is sustainable and energy efficient. Compared to other similar cladding material, little energy is consumed in this process, thus reducing the overall carbon footprint. In addition to this, the nature of the product enhances the building physics through insulation and daylighting, therefore contributing to the global low-energy aspect of the building.

Due to the lightweight nature of ETFE, substructure support systems and concrete foundations can be designed more efficiently, making it a cost effective material.

ETFE is fully recyclable. The waste from the manufacturing process or even old ETFE elements can be remolded into new ETFE products such as tubing components, wires or castings, making it an easily recyclable material.

Comparable to a glass system, the increased thermal performance of ETFE is possible for a multi-layered system. For a double or triple layer pneumatic system, multiple layers of film are welded into panels that are inflated with low pressurized air to stabilize the film and providing the thermal property of the system. In a single layered application, an R-Value of approximately 1 can be achieved. In a two-layer system, approximately an R-Value of 1.6 can be reached. Whereas, a three- layer ETFE system has an R-Value around 2.9 degrees F h / Btu or a U-Value around.35 BTU/ (h degrees F ft 2). In addition, integrating internal blankets of aerogel into the system will substantially increase the system's thermal properties.

Another key characteristic of ETFE is the Air Inflation System and Energy Consumption. A pneumatic ETFE cushion system is generally fed by one or more inflation units. Each unit consists of two redundant blowers forming a backup system for guaranteed structural stability. When entering the machine, the air will be pre-dried to avoid any condensation forming within the cushions. A series of pressure sensors will continuously monitor the internal pressure of the ETFE cushions maintaining them between 5 PSF and 6 PSF. In case of high wind or snow loads, if necessary, sensors can automatically and continuously adapt the pressure to compensate external loading up to 30 PSF.

Depending on air temperature and humidity, one unit can feed a roof of 15,000 square feet up to 25,000 square feet. They are UL certified and run on an 110V power, and the power consumption is minimal with less than 1kW.

Due to the non-adhesive surface properties of the ETFE, deposits of dirt, dust, and debris do not stick and are washed away by the rain resulting in a "self-cleaning" effect. ETFE requires minimal cleaning and the structure is easily maintained. However, as in all mechanical equipment, it is necessary to perform a yearly inspection. The inspection includes all necessary checks on the air blower system and filter replacements. The ETFE film and its attachments will also be inspected for possible damages to prevent any further deterioration.

When looking at fire resistance properties, ETFE films have been rated under various national and international standards as self-extinguishing with no burning drops. The film melts away at around 500 degrees Fahrenheit. ETFE is classified under several different standards, including ASTM E84 class A, UL 94VTM class 0, EN 13501-1 class B-s1-d0 and NFPA 701.

Safety is another important characteristic of ETFE film installations. Due to the high resistance and elasticity of the ETFE, it is an ideal building component where sudden extreme loads, such as earthquakes or blasts, may occur. Unlike glass, that will shatter and cause major concerns under similar shock load situations, ETFE will either deflect under the heavy load or, even in the case of any breakage, is unlikely to cause any major damage. ETFE is, however, not suitable as vertical railing and cannot prevent an intrusion.

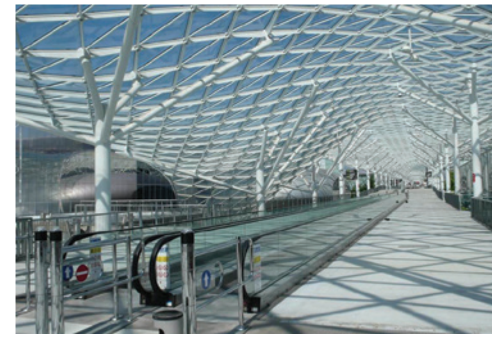
CONVENTIONAL VERSUS ETFE

With a greater understanding of the history of tensile structures, it is important to explore some basic differences between conventional construction and ETFE construction. With conventional construction, heavy weight and rigidity are the standard requirements, as these materials are placed in compression to create structural integrity. In order to support conventional construction, the design must follow limited geometry and often leads to high construction and development costs.

However, with ETFE construction, lightweight, flexible and elastic materials are preferred and structural form and integrity is achieved by placing these materials in tension. Using ETFE allows architects to break away from traditional geometric shapes and create free form designs while using these cost effective materials.

In conventional post-and-beam construction, structure is created through compression. Vertically aligned posts work in compression with horizontally aligned beams to create structure.

With ETFE, structural loads are carried by internal air pressure compensating the external wind and snow pressures. This creates a very light weight structural element.



The above glass canopy at the exhibition fair in Milan, Italy, (by Architect Massimiliano Fukas) is a masterpiece of engineering construction. However, due to the limited span capacity and the rigidity of glass, a very heavy steel structure with a triangulated configuration was required to achieve the organic shape.

Using conventional construction, it is difficult to span great distances without providing support columns to accommodate the suspended loads.

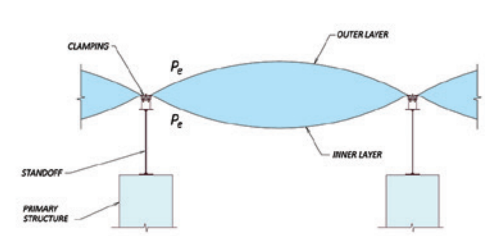
However, with tensile construction, spanning great horizontal distances is easy because weight is almost negligible, especially compared to conventional construction materials and methods. Standards spans are between eight to sixteen feet.

But with ETFE construction, free forms and larger spans can be readily achieved because of the great flexibility of the material.

The numerous and unique benefits of tensile architecture are well summarized here by British Architect, Sir Michael Hopkins. He wrote, "Increasingly we are exploring highly-efficient multi-functional elements, where structural performance, enclosure, light and thermal transmittance are combined in a single element. These are the reasons we use membrane."

THE DESIGN PROCESS

Again, a key benefit of tensile architecture is the ability to achieve dynamic forms. There are two basic forms of ETFE construction: single layer, where the tension in the ETFE is achieved through mechanically tensioning the ETFE, and double or triple layer cushion constructions,



where the tension in the ETFE is achieved through pressurization or inflation.

A variety of standard connection details are used in ETFE structures. Design-build contractors who specialize in tensile structures work with architects to provide details best suited for project conditions. These details are then often included in the construction documents, or, more frequently, in the design-build specifications included for the specialty contractor.

PROCESS STEPS

More often than not, ETFE architecture requires a design strategy involving the interaction of a wide variety of geometric forms, materials and tensioning options. Design involves sophisticated engineering programs to help architects and engineers create nearly any imaginable design. However, it's likely difficult to source the information you'll need from your firm's resource library. Consultation with a design-build contractor who specializes in ETFE architecture is an important and extremely valuable step, as successful ETFE structures are designed, engineered and constructed in close cooperation with such companies. Architects who work extensively with ETFE structures recognize this cooperative effort as a standard of best practices. Cooperation with an ETFE architecture specialty contracting firm, with in-house design and fabrication resources, minimizes undue risk for the client, designers, architects and engineers. Using third-party brokerage firms is not recommended and can lead to problems in the construction and performance of the structure.

ETFE Cushion System being installed at Empire City's Casino, Yonkers, NY

QUIZ

1. True or False: Bird's successful introduction of tensioned PTFE fiberglass membrane led to its extensive use in the architectural community.

2. In comparison to glass structures, ETFE film is:
   a. durable.
   b. highly transparent.
   c. lightweight.
   d. All of the above

3. True or False: ETFE films are not very elastic, up to 60% at their breaking point, meaning they are not structurally resistant.

4. ETFE is considered the material of choice for a variety of projects, such as:
   a. traditional skylight applications.
   b. long span structures.
   c. building facades.
   d. all of the above.

5. True or False: Due to the non-adhesive surface properties of the ETFE, deposits of dirt, dust, and debris do not stick and are washed away by the rain resulting in a "self-cleaning" effect.

6. What are inflated ETFE structures usually called due to their form? (Select all that apply)
   a. Blanket
   b. Cushion
   c. Pillow
   d. Sheet

7. Which of the following refers to the increase in temperature in a space, object or structure that results from solar radiation?
   a. Solar Heat Gain
   b. Global Warming
   c. HVAC Installation
   d. None of the above

8. True or False: The first ETFE application in the building industry took place in the early 1980s in Europe.

9. Which of the following is a test performed on ETFE?
   a. Crease fold tensile test
   b. Flame resistance
   c. Uniaxal test
   d. All of the above

10. ETFE film has approximately what percentage of acoustic transmission?
   a. 20%
   b. 45%
   c. 70%
   d. 90%

ETFE structures are generally specified as design-build projects. When designing an ETFE structure, the desired geometry and form need to be addressed first. Then, an analysis of how the membrane will interact with the support structure will help determine which type and details may be used to meet the load requirements.

It is important to remember the interfacing details between steel and the ETFE system. Proper coordination is critical to the overall aesthetic and performance of a structure. Involvement with an ETFE specialty contractor early in the process can assist in this effort.

This article continues on http://go.hw.net/AR1014Course1. Go online to read the rest of the article and complete the corresponding quiz for credit.

TENSILE CONTRACTORS

The use of special software packages, incorporating finite element analysis, provides detailed output for proposed designs. These software packages are found in-house with the specialty contractor. A third party engineer can be engaged for analysis services, but first, be sure to check their qualifications and experience with tensile structures.

It should be noted that full design responsibility usually rests with the tensile contractor, and is inclusive of both the membrane and structure, which is usually composed of steel and/or cables.

Membrane products such as ETFE, PTFE, and PVC, are purchased in stock lengths and widths. The engineering and detailing required to pattern the material to the desired form should be included in the scope of the tensile contractor's work. During membrane fabrication, stock lengths of membrane are cut to the patterns as designed.

Then, the cut patterns are assembled to the desired panel sizes required for installation though heat/pressure welding, radio frequency welding and/or sewing.

Since most tensile contractors provide design-build services, they're also responsible for detailing all elements of the tensile structure. Detailed design drawings of each element of the structure are required to effectively produce fabricated elements for the tensile structure. It is important that the architect clearly understands the process by which the tensile contractor will be handling the design and engineering component of their project.

The construction phase of ETFE systems is also extremely important to the success of a project. Forces applied to the structure during installation need to be analyzed to prevent unbalanced loads and failures. Since the integrity of a structure relies upon elements erecte d and set in tension, the membrane, steel and cables, and the methods developed to install the system, all require detailed engineering and planning.

KEY CONSIDERATIONS

Once you have decided you want to use ETFE, the specific design criteria needs to be determined. For example:

- Do you need an insulated cladding for heated spaces?
- Do you want a certain degree of solar control using frit patterns?
- Do you want to add features such as colors or light?

As you can see, there are many different items to consider when selecting an ETFE system.

Testing of the Membrane

ETFE film is extruded in special machines with constant thickness measurement to keep the evenness of the film's quality.

Even if all ETFE suppliers have tested their films to different international standards as the German DIN, UK British Standard or US ASTM, some projects require specific custom tests to demonstrate the fire performances of ETFE systems.

Because membrane materials are essential to the performance and integrity of the finished structure, a material testing regimen is required for each project or design development process. Many of the tests outlined here are critical to the life span of the structure and the establishment of a quality assurance/quality control process. These tests should be provided by the specialty contractor through in-house testing resources or third-party facilities approved by internationally recognized tensile organizations:

- Tensiles—Breaking Strength and Elongation
- Crease Fold Tensile Tests
- Trapezoidal Tear Strength
- Tensile Test of an Overlapped Joint (Lap Shear) Biaxial Testing
- Uniaxial Test
- Static Load Tests
- Flame Resistance

Let's look briefly at the types of tests membrane materials must endure. Extensive testing determines the strength and flexibility of tensile membrane. Testing assures that the membrane and selected connections will manage calculated loads and stresses under harsh conditions found during seasonal weather extremes likely to be found on the site.

A weather machine that produces accelerated weathering effects is used to test the membrane's ability to withstand UV rays in wet and dry conditions. Light transmission and reflectance are also measured.

ETFE CONSTRUCTION TECHNOLOGY

The design criteria and testing processes of ETFE are important to understand when considering it for an upcoming project. Not only is it important to have a greater understanding of the system, but this knowledge will help when looking at the different types of ETFE and specifying one for an upcoming installation.

As noted earlier, ETFE construction can be used either as single layer pre-stressed structures or as several layer inflated structures. It is important to understand the differences between the types of ETFE structures and learn how to decide which type to implement for each project.

Inflated ETFE structures are usually called cushions or pillows due to their form. They were the original structure of the first ETFE projects. This is because ETFE itself is very thin and has little resistance. However, applied as a pneumatic system, ETFE has high load bearing capacities.

ETFE cushions make excellent insulating cladding. Thus, with several layers of ETFE, it is possible to achieve good U values. The U value measures the heat transfer from one side to the other side of an element.

The G-value (solar gain), also known as solar heat gain coefficient (SHGC) or passive solar gain, refers to the increase in temperature in a space, object or structure that results from solar radiation. The amount of solar gain increases with the strength of the sun, and with the ability of any intervening material to transmit

Here is an example of single layer pre-stressed structure and of an inflated structure.

Here it is easy to see what kind of shading can be provided when utilizing some sort of print pattern on the ETFE film.

or resist the radiation. To control the solar gain with ETFE, it is necessary to either add pigmentation to the ETFE or to print on the ETFE film.

The "Shading Coefficient" (SC) is a coefficient used mainly in the glass industry. The relationship between SHGC and SC is as follows: SHGC = SC × 0.87.

A middle layer can be added to improve the thermal insulation of the cushion as it prevents convection within the chamber.

Printed ETFE is usually achieved through a roll process, which means that it will be a repetitive pattern. However, some new technology is under development that allows the printing of nearly any color and/or design. There are also standard print examples available.

ETFE can be colored by adding pigmentation during the fabrication process, making it possible to have a variety of colored ETFE film choices. However, not all colors are available due to the potential for UV degradation.

LEDs can be added at the back of the ETFE giving tremendous results and much more freedom of design

ETFE cushions rely structurally on an air inflation system. The air inflation machines create the "heart" of the construction and must be high quality. Air machines are composed of two air blowers (one of them being a backup), one dehumidifier and control elements. The unit is within a weather tight stainless steel compartment that can be put nearly anywhere.

ETFE cushions under snow loads at the Allianz Arena, Munich, Germany

The control panels monitor wind and snow and command the machine to add more pressure by necessity. Also, the pressure control guarantees a constant inflation of the system to keep up with natural air pressure losses and possible losses through damages.

Another benefit is sunlight control through having the middle layer move through variation of pressure.

Pre-stressed ETFE structures are sometimes referred to as "single skin" as they only have one layer or "skin". These tensioned structures were developed in the early 2000s as some specialty membrane contractors started to examine this new product and adapted the knowledge of tensile fabric structures to ETFE. All other aspects such as color, print, and LEDs can be incorporated into a single layer system as well. As the ETFE film doesn't have enough internal strength to withstand loading, it is necessary to incorporate cables to the ETFE film. Those cables are usually set with a 2 to 3 feet spacing. The advantage to a single layer of ETFE is that no machine (and thus electric power) is necessary to warrant the structural integrity of the system.

LATEST INNOVATIONS

Fenestration has historically been the weak link in the building envelope, and it has created limitations in aesthetic design. Occasionally, it can conflict with code performance requirements for energy reduction goals. Fenestration products are typically the only building materials that can be seen from both the exterior and the interior of a building, and can be the largest contributor of heat loss as well as heat gain for the building.

Unlike transparent glazing systems, most membranes are translucent or transparent and therefore allow diffuse, glare-free and sufficient sunlight to be transmitted into an interior space.

TD-E-30

U-value of profile: 1,53 W/m²K

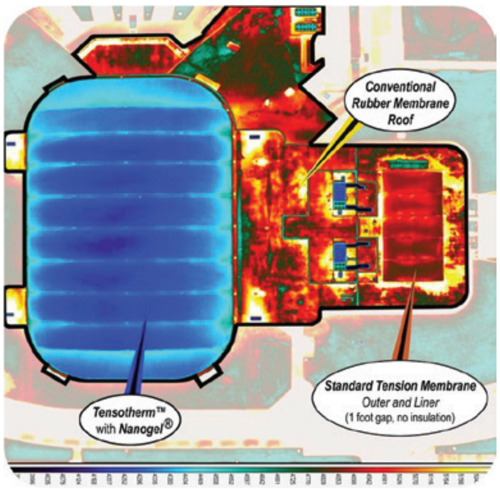
Example for roof structure		Unit	No. of layer	U-value	No. of layer	U-value
			pcs	W/m²K	pcs	W/m²K
Roof area	54,000	SF	3	1.799	4	1.306
Clamping profile	8.200	FT		1.53		1.53
			Total	1.74		1.35

This chart is an example of the U value calculation for a typical ETFE roof.

With newly developed and better thermally broken aluminum extrusion, it is possible to get far greater U values of the entire component.

By adding a layer or more of aerogel blanket, the thermal performances of the cushion can be dramatically improved. The cushion is not transparent anymore but still allows enough light for a natural lighting of the covered area.

Munich's municipal waste management department features a roofing system where Photovoltaic (PV) cells have been integrated inside on the middle layer of the three layer ETFE cushion system. A specially developed system allows the top layer to be uncovered to maintain the PV elements. Approximately 35,000 square feet were covered with PV cells (for 80,000 square feet of ETFE) producing 140,000 KWh per year.



This is a thermograph of an aerogel insulated composite PTFE membrane installation on the left compared to a new conventional rubber membrane roof in the center, and a standard, uninsulated double layer, PTFE membrane roof on the right . The shades of blue dramatically indicate the superior insulation capability of an aerogel insulated composite fabric membrane roof versus the other systems. Not only is the insulation performance apparent, the consistency of the aerogel system is also evident.

The roof of Munich's Municipal Waste Management Department

CASE STUDIES

Case Study 1—Empire City Casino at Yonkers Raceway, Yonkers, NY

This picture shows the latest development in ETFE printing. With new digital technology, it is now possible to nearly print anything on the ETFE.

This 11,000 square foot porte-cochere was part of a $50 million expansion project for the Empire City Casino designed by STUDIO V Architecture. The canopy was designed and engineered by FTL Design Engineering Studio. This canopy utilizes a two-layer ETFE application to welcome the guests in an interesting and exciting way. ETFE was selected due to the aesthetics, performance benefits, and sustainable properties.

By using ETFE membrane, daylight is able to flow through to the space below, while also providing shade to visitors as they arrive. Since the casino also features night-time entertainment, this installation also incorporated the use of custom colored LED lighting to create a more exciting experience for the casino visitors who arrive in the evening.

The structure was inspired by the unique landscape at the hill-top track, and need to find a structure and material that was able to bring this idea to life. The materials used in this ETFE structure were also highly recyclable, making this project a sustainable one, as well. The lightweight nature of the ETFE film itself made it a very cost-effective option for the casino's expansion project.

Case Study 2—Ruhr Park Bochum, Germany

2015 will celebrate the 50th anniversary of the "Ruhr Park" shopping mall in Bochum, Germany. For this occasion a $190 million refurbishment started 2010 with a new arrangement at the so called South Mall.

Less surface but more diversity and quality was the motto. The idea was to change the flow of visitors. Instead of getting straight through the mall, they should be led to a smooth curved pathway, giving more time and relaxation to the shopping experience. The architects Mass & Partners therefore created the new square shaped area with shops arranged at its perimeter. Situated at the center of the shopping mall, it is now the meeting point where everything and everybody gathers.

This new building has been furthermore enhanced with a transparent single layer ETFE canopy giving protection from the rain and still letting enough light through. Through special lighting, the approximate 7,300 square feet pre-stressed ETFE canopy becomes a glowing ring at night, reinforcing even more of its central and unique signature design. ETFE was once more the material of choice for such an ambitious vision.

CONCLUSION

As you continue to explore the many benefits of tensile architecture, you begin to recognize its numerous inherent characteristics of sustainability. By its very nature, the efficiencies of tensile architecture and sustainable design are virtually inseparable concepts. ■