THE DEVELOPMENT OF STRUCTURAL FABRICS & FOILS

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INTRODUCTION

Fabrics have been used as a means of weather protection since early civilisation. These fabrics were usually woven or spun from natural fibres, eg flax, cotton, wool or animal hides and skins. However these fabrics have short life spans and were subsceptible to creep and ultraviolet degradation.

From comments in Roman literature, the theatre vela were supposedly introduced in 69 BC and a fresco in Pompeii dating from 59 BC showing a Pompeii amphitheatre velum was discovered in a building near the amphitheater in 1869. Little is known of the actual working of these roofs. They consisted of cables attached to massive beams, and cloth was fastened to cables with eyelets. Linen was predominantly used, though as decadent as Rome was, various theatres were shaded by silk. Some vela were also beautifully decorated. The vela of ancient Rome covered areas that the existing structural technology was unable to duplicate with rigid materials.

This century has seen the development of synthetic fibres and polymer coatings. Thus materials with greater strength, durability and a longer life span are now readily available in the industry. These developments have led to the industry's term of permanent architectural fabric structures.

The fabric fraternity has over the years developed its own jargon and neology. This paper takes the opportunity to provide a very brief introduction and insight into the various materials that are currently available for the engineering of fabric structures.

FIBRES & WEAVES

The Oxford dictionary defines fabric as a woven, knitted or felted material. If the yarns are very close together with no holes, it is known as a cloth. If the yarns are apart it is called a net.

The most commonly used synthetic fibres for architectural fabrics are polyester and glass. Aramid high performance fibres can also be used. This is not very common and usually used when high strengths are required from the material.

For structural fabrics, these fibres consists of bundles of continuous filaments. Twist in the yarns give them coherence. In order to hold the filaments together, a low twist would suffice. High twist in the yarns are usually applied to increase the elongation of the yarns and reduce its breaking stress.

The basic plain weave consists of yarns being laid alternately under and over each other in both directions. This process causes the yarns to be crimped. During the weaving and coating process, yarns in the warp are generally tensioned straight and weft yarns shuttled up and down. Thus if the fabric is pulled uniaxially in the weft direction, these yarns will straighten out and the warp yarns become crimped. This phenomenon is called crimp interchange. The result of crimp interchange causes the extension in the weft and contraction in the warp direction with very little increase in strain energy. The crimp interchange has both its advantages and disadvantages but mostly the latter. It is particularly important with respect to low elongation glass fibre weaves.

Heavier fabrics are usually woven with a basket or panama weave in which two or three yarns are woven together. This reduces the effects of crimp interchange.

Another weaving technique developed to avoid the crimp interchange problem is a *weft inserted warp knit weave.* This process involves the laying of weft yarns on top of the warp yarns. The warp and weft yarns are loosely held together by stitching or a tie yarn. Neither the warp yarns or weft yarns are locked tight.

Research and experimentation into triaxial weave material has resulted in its development. In brief, the material is formed by weaving three yarn systems at 60° to one another. The fabric can achieve high burst, tear and shear resistance with nearly uniform strength in all directions. This material has not been popularly utilised in fabric structures because of the difficulty in measuring the load extension properties. Furthermore with uneven stresses, the strain in two yarn directions will produce strain in the third.

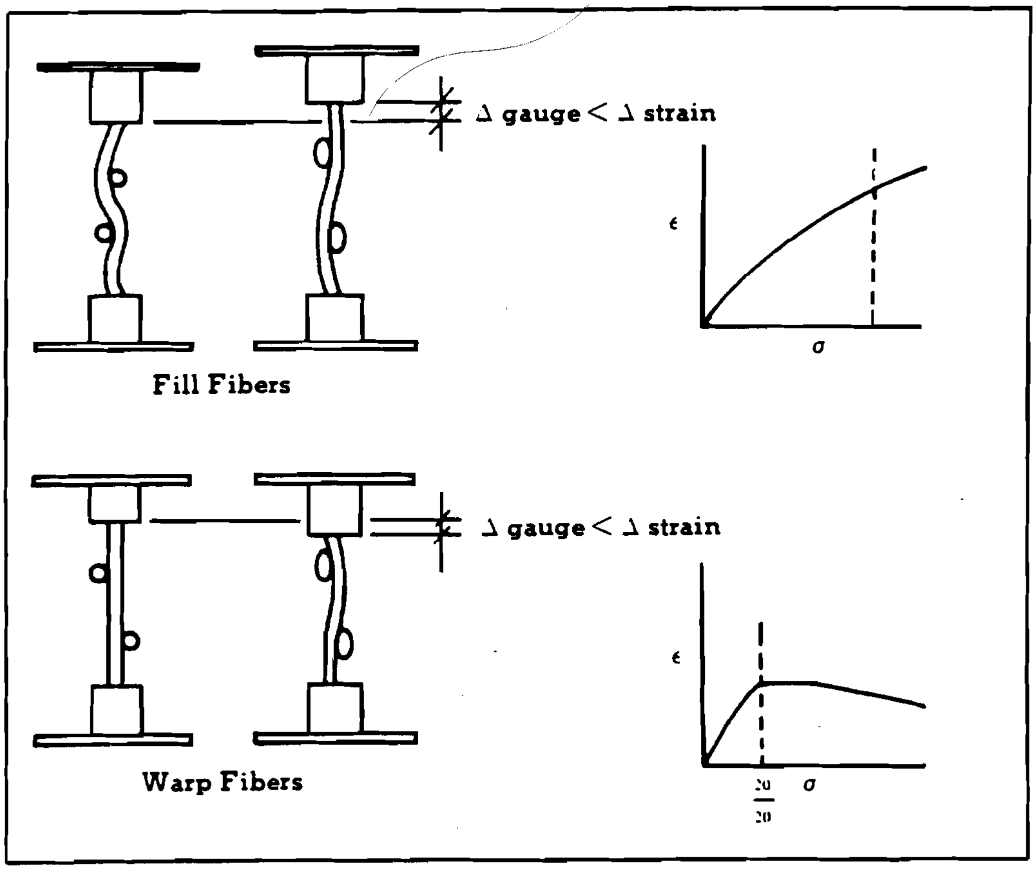


Fig 1 Apparent strain resulting form crimp interchange

COATINGS

There are various types of coating materials that can be applied to structural fabrics. As mentioned previously polyester and glass are the main weaves being used. An adopted industry practice is to distinguish the various types of material by naming them after their coating system.

(a) POLYVINYLCHLORIDE (PVC)

PVC is one of the successful coatings applied to polyester base cloths. Since the pioneering days of Frei Otto in the late 1950s and 1960s to today, this coated medium has been the most popular material in use for construction of fabric structures.

Special additives are added to the basic PVC formulation to produce an economical, flexible and fire resistant material.

Plasticisers are usually added to PVC to increase flexibility. However contact with oil, solvents or ultraviolet light can lead to migration of their plasticiser and breakdown of the plasticiser and the PVC leading to failure through embrittlement of the coating. Ultra violet absorbers and inhibitors can be added to reduce this problem.

Due to the high standard of requirements for use of material in the most Building Codes throughout the world , flame inhibitors are usually added.

The seaming of PVC coated fabrics can be achieved by high frequency radio waves welding or heat welding. Most fabricators adopt the high frequency technique as it is simple and quick, and also easier to monitor and control.

Most fabric manufacturers offer a range of colours in the various PVC fabrics. However in practice, it has been discovered that the pigments used for the colours degrade and become dull upon exposure to UV. This is a problem especially in Australia as she has high UV ratings. Hence most fabric structures are either made from white or light cream colours.

PVC fabrics are normally provided with an acrylic lacquer. However in recent years, development into various fluoropolymer lacquers have produced coatings such as PVF (TEDLAR) and PVDF (polyvinylidineflouride).

TEDLAR PVF film was first introduced by Du Pont in 1961 as the premium finish for house siding. Following twenty years of rugged outdoor exposure it has proven its durability and provides an outstanding protection against the ravages of weather, chemical corrosion and ultraviolet light. Its durability, inertness and non-stick properties have led fabric manufacturers world-wide to adopt the film as an additional coating on PVC fabrics to assist its cleanability and prolong the life of the PVC medium. The PVF coating is applied via a lamination technique.

PVDF is an inert fluoropolymer lacquer that has been used by fabric manufacturers both in its pure or modified form to replace the basic acrylic lacquer.

These new lacquers and laminations reduces the plasticiser migration and reduce dirt retention and extends the fabric life. Manufacturers are estimating that these coatings will provide materials with a life-span of 15-20 years compared to the plain acrylic lacquer which would achieve a useful life of 10-12 years. This is also dependent on location and environment.

(b) POLYURETHANE

Polyurethane coatings on polyester weaves produce a material that has high flexibility and high resistance to abrasion and cracking at low temperatures. The disadvantage of these materials are its hydrolysis problems during long term weathering, and its to low flame resistance. This material are mainly used in balloons and airships. It's application for fabric structures are quite sparse and not common.

(c) HYPALON

Hypalon (chlorosulfonated polyethylene) is a form of rubber coating applied onto either polyester or nylon base fabrics.

It was initially developed by Du Pont to be a synthetic rubber and used as a raw polymer in the rubber industry. Rubber manufacturers compound, process and vulcanize it to produce a variety of end products.

The application of the coating onto polyester weaves involves a simple painting procedure. There is a wide range of colours available. Furthermore unlike the colour pigmentation used in PVC fabrics, the material has proven to have very good colour adherence with no change under 100 hours of accelerated UV testing. However one of the main disadvantage of this range of coatings is the non-HF weldability of the material. Glueing or sewing techniques need to be adopted to produce the necessary seams. These coatings are usually much heavier in comparison to PVC. The final product is opaque.

The cost of the coatings are much more expensive. These disadvantages contributes to its low usage in construction of air supported or tensile structures.

(d) POLYTETRAFLUORETHYLENE (PTFE & FEP)

In the late 1960s, the National Aeronautics and Space Administration (NASA), in its quest for a new fabric to be used in Apollo astronauts' space suits, commissioned Owens-Corning Fiberglas Corporation to come up with a durable and non-combustible, yet thin and flexible fabric.

Owens-Corning had been experimenting with an ultrafine glass yarn called Beta yarn. Under contract to NASA, they wove the yarn into fabric, had it coated with PTFE fluorocarbon resin manufactured by Du Pont Company, and the astronauts were set for takeoff.

In the early 1970s, David Geiger, one of the American pioneers in fabric architecture, in search of a suitable membrane to cover his newly developed air support structure system worked in conjunction with the Owens Corning Corporation and Du Pont to adapt this fabric for construction use. It was thickened, woven into stronger and more porous fabric and coated with more PTFE.

Due to the high temperatures involved in the coating process, this can only be applied to glass base weaves. In brief, the PTFE is applied as a dispersion to the pretreated basecloth and is then sintered. FEP, a PTFE thermoplastic coploymer is used as a surface sealing layer.

Welding of PTFE is achieved via direct heat platens which fuses the FEP surface coating. Panels and seams can be easily removed using the same process. This has the added advantage when conducting on-site repairs.

PTFE/glass fabrics exhibit high durability and is inherently flameproof. This together with it's chemical inertness and non-dirt adherence properties and easy welding techniques make it a successful material for use in fabric architecture. The first PTFE/glass structure constructed at La Verne College, Los Angeles in 1974 is still in good condition and is proof of the permanency of PTFE/Glass.

In comparison to PVC fabrics, the PTFE/glass fabric exhibits higher in-plane stiffness. The cost of the raw material and resins are also higher in comparison. This two reasons are primary in structures fabricated from this medium to have a low curvature shape.

The PTFE/glass is supplied in a beige colour. Upon exposure to sunlight, it bleaches out to white. This process takes a period of 3 to 6 months depending on its locality and environment. However recent developments in coating processes have made it possible to have a pre-bleached material available in the marketplace.

(e) SILICON COATINGS

Silicon resins are also used as a coating material. The silicon resins produce a highly transparent material. Glass base cloths are usually used for this coating as the use of other base cloths would breakdown upon exposure to ultraviolet light.

The seaming process is carried out by glueing with another silicon resin. The seams are pasted up, pressed together and allowed to set with weights to maintain the glue-line pressure.

It is not a common medium in fabric structures, but in recent years has been adopted for use as internal acoustic liners. A fine example of this can be found in the Alexandra Palace just outside of London.

STRUCTURAL FOILS

Polythene foils are normally used for horticultural greenhouses and also domestic swimming pool enclosures. The foils are treated with ultraviolet inhibitors and provide a life-span of approximately 5 years. Seaming is achieved via direct heat or hot air techniques.

However in the last decade, a number of more sophisticated and long life span fluoropolymer foils have been developed.

(a) ET FOIL (ETFE)

ETFE is a modified ethylene tetrafluoroethylene copolymer. Unlike polytetrafluoroethylene which can be processed by compression moulding and sintering techniques, this modified copolymer can be processed like a thermoplastic to produce among other things, films which are highly transparent and weather resistant.

The wide spectral range transmitted by the film corresponds well with naturally occurring radiant energy and so permits optimum plant growth in greenhouses.

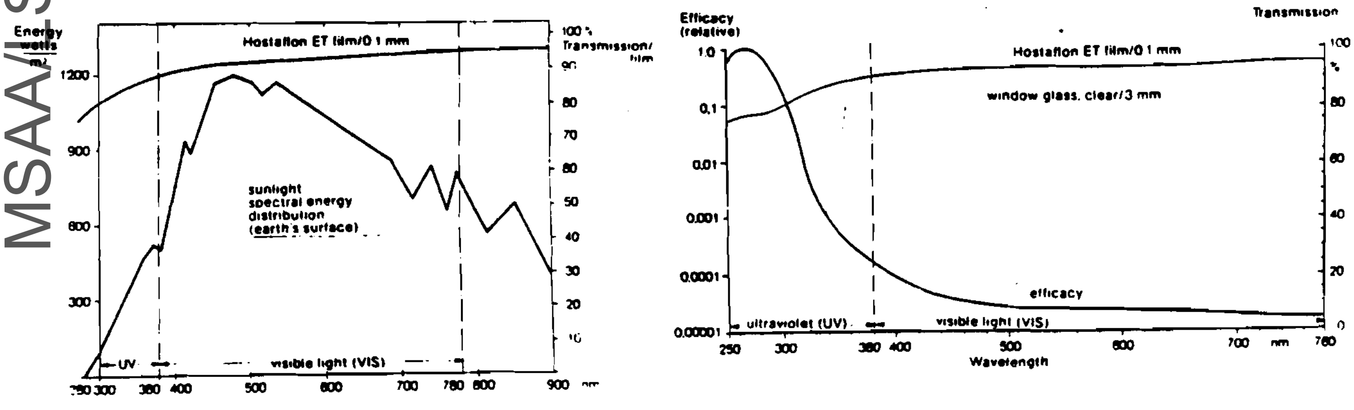


Fig 2 Light transmission of ET film as a function of wavelength in the ultraviolet and visible light region

In line with other fluoropolymers, it exhibits high resistance to weathering, has good durability and excellent non-dirt adherence properties. Outdoor exposure tests conducted in Germany after 11 years have shown no visual change in the material. The mechanical properties of the membrane remains the same.

ETFE has been used as a building cladding in the form of inflated cushions. This pneumatic film system is similar in principle to a sealed glazing unit. The air cushions are formed between the two or three film layers. With an additional internal layer, this gives the equivalent insulation of triple glazing at greatly reduced costs compared with glazing and lower maintenance. For these reasons, it is ideally suited for leisure pool and other large transparent roofs.

The medium can be either be welded using electrically heated bars or using conventional sewing techniques. The latter being less popular .

Its usage is gaining popularity in the European countries as a system for cladding over leisure centres and greenhouses. It also offers an alternative to most conventional glazing systems using acrylics or polycarbonates.

(b) GORE TENARA

Tenara is based on expanded PTFE and has a woven structure. This material was originally used for the radome covers in the manufacture of wavelength radio telescopes. Following years of research and development, the end result is a material that has a silky translucent look to it but possessing excellent durability, inertness and ability to withstand cyclic loadings.

The material has only been recently released in the market place and is being tested in the design of special purpose umbrella type structures in Saudi Arabia. Following a successful year with tests into the cyclic opening and closing of these structures on a daily basis, there is a high expectation of the manufacturer in the usefulness of this product.

The high expense and low strength of the material is presently limiting its adoption in the industry. Research is underway in Germany and USA, it will only be a matter of time before further breakthroughs occur in making this material more economical.

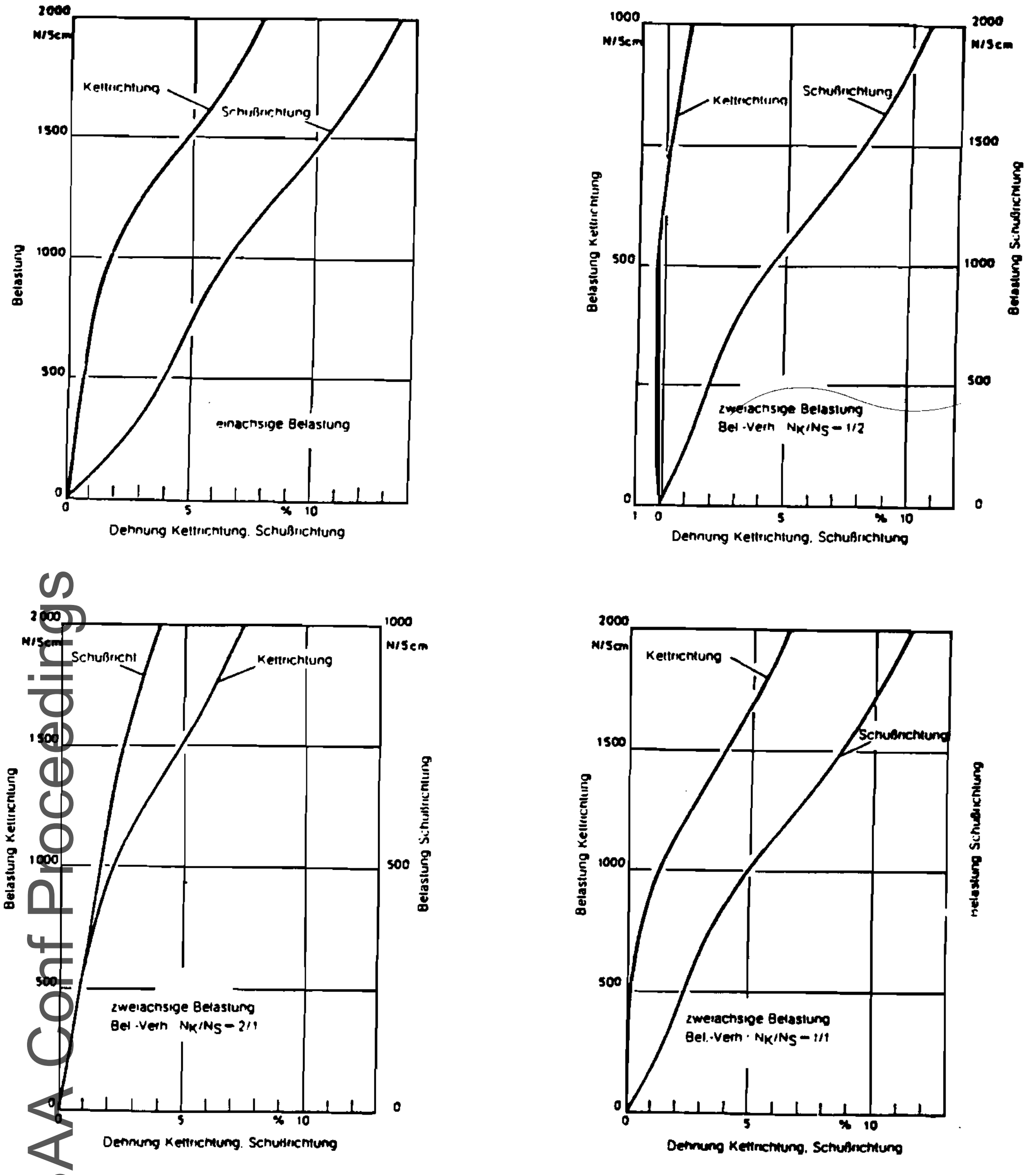
STRUCTURAL PROPERTIES

As documented in the previous sections, there is a wide range of fabrics available to engineers and designers for use in the design of a fabric structure. The following are some basic properties that designers and engineers take into consideration when evaluating a fabric.

(a) Strip tensile strength
(b) Biaxial elongation and constructional stretch
(c) Tear strength
(d) Fire resistance
(e) Welding technique, strength and adhesion
(f) Life span
(g) Insulation properties

The strip tensile strength is an ultimate uniaxial test on a 50 mm material sample and in accordance to AS2001.2.3. This test provides the ultimate tensile strength of the fabric.

The resulting fabrics using either a high modulus glass fibre or polyester yarns and coated with a low modulus coating produce a composite that is anisotropic. The crimp interchange effects due to weaves on the fabrics causes it to exhibit differential biaxial load-extension results. Biaxial properties of the material has to be measured in a biaxial testing machine This test is normally conducted for each batch of fabric as the crimp interchange effects can vary from one production run to another.



einachsige Belastung	–	force de traction unidirectionelle
	–	uniaxial stress
zweiachsige Belastung	–	force de traction bidirectionelle
	–	biaxial stress
Belastung	–	effort
	–	stress
Kettrichtung	–	direction de chaine
	–	warp direction
Schußrichtung	–	direction de trame
	–	weft direction
Belastungsverhältnis	–	proportion des charges
	–	loading-ratio
Dehnung	–	elongation
	–	elongation

Fig 3 Typical biaxial stress/strain curves provides varying results for differing warp/weft ratios (1:1, 1:2 and 2:1)

All fabrics exhibit irrecoverable constructional creep. This is caused by the material's pull of the crimp in the weft direction. Biaxial testing provides the results of constructional stretch in the material. Compensations for this are taken into consideration in the pattern design to ensure the structure fits correctly thus avoiding *soft* spots or wrinkle marks.

The standard tear strength are to be conducted in accordance to AS2111.16. This test provides results on the worst mode of failure, i.e. the propagation of tearing in the membrane. Most designers and engineers use this result as a gauge to determine the factor of safety required for the design of the membrane.

Fabric structures are usually built over shopping centres, building entrances, tourist and resort centres, in short over areas trafficked by high volume of people. Therefore the concern on its fire resistance is of prime importance. The Unified Australian Building Code has outlined that materials to be used for Class 2 to Class 9 buildings should exhibit the following indices in accordance to AS1530 Parts 2 and 3.

(a) Smoke developed Index not greater than 8
(b) Spread of flame Index not greater than 5
(c) Flammability Index not greater than 5

Fabric manufacturers world-wide have undertaken research into the behaviour of material under full scale fire tests. It is interesting to note that a report conducted by the National Building Technology Centre in Sydney on PVC/Polyester/Acrylic fabrics comments as follows:-

> *The fabric charred over the flame source. No ignition of the canopy material was observed. No portion of the canopy material detached. The canopy shrank and opened holes over the flame source. The fabric did not form droplets.*

The best results for the above three indices is obtained by the PTFE/glass material which gives a zero result. This result is achieved because the glass fibres are not thermoplastic and the PTFE resins are inert.

All joints and seams are usually specified by the designers to achieve at least 80 to 90% of the ultimate strength of the parent material. The ease of welding using either of the two developed welding techniques (HF welding and direct heat platen) plays a role in determining the choice of material as well.

As mentioned in previous sections, the life of the material varies from 10 years and more. PTFE/glass being more inert has a longer lifespan in comparison to the PVC fabrics. The new fluoropolymer films to date are showing no signs of deterioration after a period of 11 years under outdoor exposure tests and are therefore expected to have even longer life.

The table below provides a comparison of the heat conductivity and heat transmission values of fabrics in comparison with other roofing materials. It should be noted that these values are approximate and should be comparison purposes only.

	Fabrics	Glass	Corrugated Iron	Asbestos	Wood
Thickness (mm)	1.0	3.0	2.0	4.0	5.0
Heat Transmission (kcal/m^2h^oC)	5.0	5.1	10	4.8	4.3
Heat Conductivity (kcal/mh^oC)	0.15	0.70	50	0.30	0.12

Table 1 Comparison of heat transmission and conductivity of fabrics and other building materials

From the figures above, the heat transmission of fabrics are very similar to glass but its heat conductivity is much more similar to wood. In order to achieve better insulation of the enclosed space, the use of double or triple layer membranes is not uncommon.

CONCLUSION

Synthetic fabrics have come a long way in the last 50 years. From the early experimentation years with various yarns and material, we now presently have a range of materials that can meet the engineering and constructional requirements of both pneumatic air supported and tensile structures. However the search continues by all leading fabric manufacturers and designers for the ideal material being one that exhibits excellent durability, maintenance free, possess adequate strength and stiffness, easy to fabricate and handle, translucent , economical and last but not least permanent.

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