Coated Membrane Materials for use in Construction of Stressed Membrane Structures

Peter Lim & David Mccready
SPACETECH PTY LTD.
2 Simpson St. Moorabbin Victoria Australia 3189

1. INTRODUCTION

Fabrics have been used as weather protection since the dawn of civilisation. These fabrics were usually woven or spun from natural fibres, e.g. flax, cotton, wool or animal hides and skins.

From references in Roman literature, the theatre vela were introduced at about 69 BC and a fresco in Pompeii dating from 59 BC showing a Pompeii amphitheatre velum was discovered in a building near the amphitheatre in 1869. Little is known of the actual working of these roofs. They consisted of cables (ropes) attached to massive beams, and cloth was fastened with eyelets. Linen was predominantly used, though as opulent as Rome was, some theatres were shaded by silk. Some vela were also beautifully decorated. The vela of ancient Rome covered areas that then existing structural technology was unable to achieve with rigid materials. This century has seen the development of synthetic fibres and polymer coatings. Thus materials with greater strength, durability and a long life span are now readily available to the industry. These developments have culminated in the industry using the term permanent architectural fabric structures.

The fabric fraternity has over the years developed its own jargon and neology. This paper takes the opportunity of providing a brief introduction into the range of materials currently available for the engineering of stressed membrane structures.

2. 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 (Kevlar) high performance fibres can also be used but are not very common and used only when very high strengths are required from a material.

In structural fabrics, fibres consists of bundles of continuous filaments, twisted to give coherence. In order to hold the filaments together, a low twist is sufficient. High twist in the yarns is 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 (Warp & Weft). This process causes the yarns to be crimped, not straight. During the weaving and coating process, yarns in the warp(length direction) are generally tensioned straight and weft yarns(cross direction) shuttled up and down.

If the fabric is pulled uniaxially in the weft direction, these yarns can straighten while the warp yarns become crimped. This phenomenon is called crimp interchange. The result of crimp interchange is extension in the weft and contraction in the warp direction with very little increase in strain energy. The crimp interchange has both advantages and disadvantages but mostly the latter. It is a particularly important characteristic to consider in design with respect to low elongation glass fibre weaves.

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

A 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 so that they are uniformly straight. 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. In this case the weaving tension is still non uniform as the length (warp) tension from roller to roller is always greater than the shuttle born weft tension.

Another style, triaxial weave, is formed by weaving three yarn systems at 60o 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 and the relative stiffness of the material. Extension is a desirable quantity.

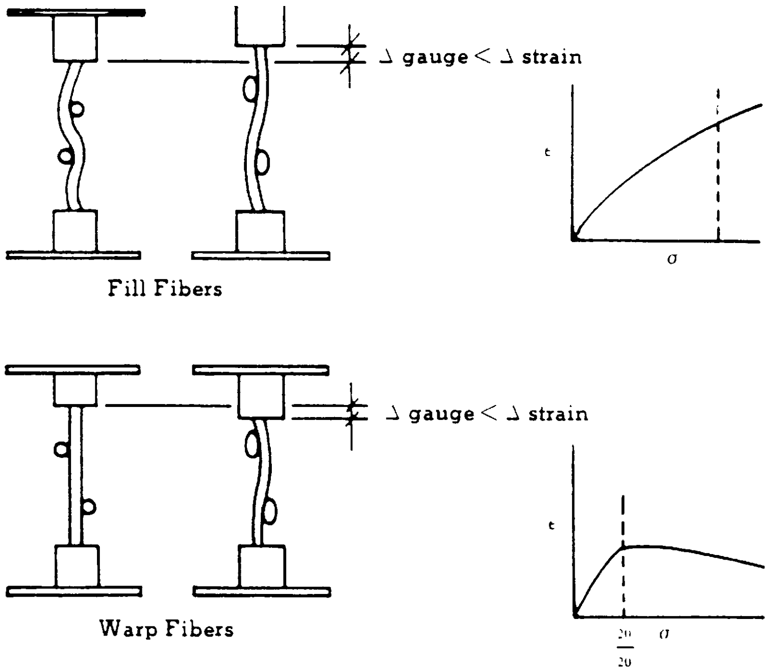

Fig 1 Apparent strain resulting from crimp interchange

3. COATINGS

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

3.1. 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 until today, this coating 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. It can be coated onto polyester or glass but is common mainly with the former.

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

Due to the high standard required for use of material in the most Building Codes throughout the world, flame inhibitors are added to reduce smoke, heat evolved and potential to burn generally.

The seaming of PVC coated fabrics can be achieved by high frequency welding, heat welding or sewing. Most fabricators adopt the high frequency technique as it is simple, quick and easy to monitor and control. Welds can develop 100 – 90% of the full strength of the material.

Most fabric manufacturers offer a range of colours and engineered grades in increasing strengths.. In practice it has been found that pigments used for the colours can degrade and become dull after differing exposure to UV. This is a problem especially in Australia due to high UV levels, hence most fabric structures are either made from white or light cream colours. These have the added advantage of reflecting off more ambient heat so that passage of infra–red heat is less than for a dense colour which absorbs more.

PVC fabrics are usually finished with an acrylic lacquer which seals the otherwise sticky coat.. However in recent years, development of a range of fluoropolymer lacquers has produced coatings such as PVF, known as Tedlar (Poly–vinyl–flouride) and PVDF (poly–vinylidine–flouride).

TEDLAR PVF film was introduced by Du Pont in 1961 as the premium finish for metal house siding. Following twenty years of rigorous outdoor exposure it has a proven durability affording 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.

PVF is made in clear and opaque, the former being used for architectural grades. UV resistance is of reducing effectiveness over time with the clear material. Use in Australia is limited to 8 years and failure has been noted on one project at about Tropic of Capricorn latitude where UV and insolation is quite extreme.

Performance generally cannot be assessed until a broader sample has been tested, however life could be assumed to be minimum 7–8 years in higher UV zones while around 15 in lesser UV climates.

The advantage of the coating is the preservation of the top surface and resistance to atmospheric soiling which otherwise typifies PVC coatings. The ultra slick PVF allows for virtual self washing in a zone where rainfall is regular.

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 reduce plasticiser migration and dirt retention, extending fabric life. Manufacturers predict that these coatings will allow materials with a life–span of 15–20 years compared to the plain acrylic lacquer which now achieves a life of 10–15 years. Surface condition and effective life is quite dependent on location and environment. Pollution acts as a corrosive agent on PVC surface causing erosion. Vehicle emissions are among the worst agents of this action.

3.2. 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 or in food applications. Generally this coating is not used for structures.

3.3. 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 as a synthetic rubber and used as a raw polymer in the rubber industry. Rubber manufacturers compound, process and vulcanise 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 retention. One of the main disadvantages of this coating is the non–HF weldability of the material. Gluing or sewing techniques are adopted to produce strong seams. These coatings are usually much heavier than PVC and the final product is opaque.

The cost is much more than PVC, these disadvantages contributing to its low usage in construction of air supported or tensile structures.

3.4. Polytetrafluoroethylene (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 ultra fine glass yarn called Beta yarn. Under contract to NASA, they wove the yarn into fabric, had it dispersion coated with PTFE fluorocarbon resin manufactured by Du Pont Company, and the astronauts had a new suit of clothes.

In the early 1970s, David Geiger, one of the American pioneer membrane engineers sought an improved material to cover his newly developed, long span air support structure system. Working in conjunction with Owens Corning Corporation and Du Pont they adapted this space suit fabric for construction use using heavier bundles of glass yarn and more PTFE dispersions.

Due to high temperatures involved in the coating process, PTFE cannot be applied to polyester. PTFE is applied as a powder dispersion to pretreated basecloth and then sintered. FEP, a PTFE thermoplastic copolymer–polymer is used as a surface sealing layer.

Seaming of PTFE is achieved via welding with direct heat platens which fuse the FEP surface coating, this acting virtually as a hot–melt adhesive.. Panels and seams can be unwelded by application of heat of the same quanta. This has advantage when conducting on–site repairs or replacement.

PTFE/glass fabrics exhibit high durability, are practically inert to most agents and are inherently flameproof. This together with low–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 1973 is still in good condition and is proof of the permanency of PTFE/Glass.

In comparison to PVC fabrics, PTFE/glass fabric exhibits higher in–plane stiffness. The cost of the raw material and resins are substantially higher. Typical highly curved structures are more suited to PVC materials because panel cutting efficiencies are lower with high curvatures and waste on the cutting floor is greater. Thus the more costly PTFE has forced a change in shape toward lower curvature where the panel cutting efficiency is improved.

PTFE/glass is supplied, ex factory in a beige colour which bleaches out to white on exposure to sunlight. This process takes a period of 1 to 6 months depending on locality and environment. Recent developments in coating processes have made it possible to have a pre–bleached material available in the marketplace.

3.5. Silicon Coatings

Silicon resins are also used as a coating material for woven glass. The silicon resins produce the highest transparency material.

Seaming is carried out by gluing with a silicon resin. The seams are pasted up, pressed together and allowed to set with weights to maintain 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 is the Alexandra Palace just outside of London. ODC in Atlanta worked for several years to introduce the material and several exemplary structures were built. This group stopped operations several years hence but a new group is now following the same path in the USA.

4. STRUCTURAL FOILS

Polythene foils are normally used for horticultural greenhouses and 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.

4.1. ET Foil (ETFE Film)

ETFE is a modified ethylene tetra–fluoroethylene copolymer. Unlike poly–tetra–fluoro–ethylene 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 perhaps enabling grass to grow under a roof.

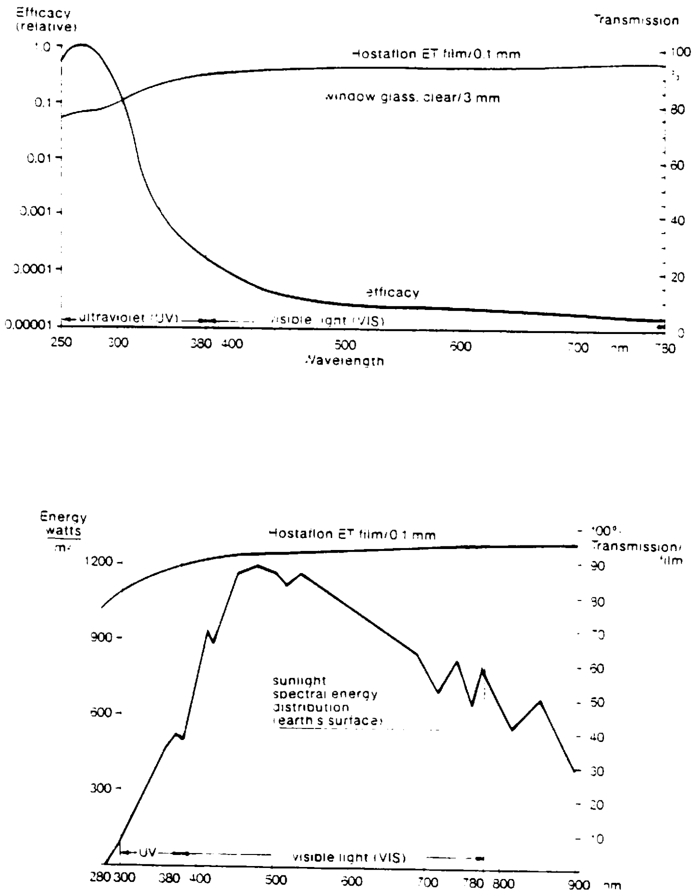

Fig 2 Light transmission of ET film as a function of wavelength in the ultraviolet and visible light region

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 remain the same.

ETFE has been used as a building cladding in the form of air 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, clamped at the edges and formed into a roof array. With an additional internal layer, this gives the equivalent insulation of triple glazing at greatly reduced costs compared with glazing.

Seaming is a heat welding technique.

Its usage is gaining popularity in European countries as a system for roofing over leisure centres and planthouses. It offers large promise as an alternative to conventional glazing systems.

4.2. Gore Tenara

Tenara is made from expanded PTFE and is a woven cloth, generally porous. 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, but possesses 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 mechanically opening umbrella structures for Saudi Arabia. Following a successful year of testing cyclic opening and closing of these structures, there is greater expectation of the application of this product.

The high cost 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 developments make this material more economical.

4.3. Shade Material

Shade materials are available in a number of composites or single material forms. All of this class are porous materials, lacking in rainwater protection. They are graded as products in accordance with the degree of shading provided by the mesh.

Generally these are simple warp/weft weaves of fibres coated with a material. Chief among these is polyester as the fibre and PVC as the coating. This type is similar to the coated material described above.

PVC coated materials are acrylic coated and life expectancy, flammability, tensile etc. values vary widely according to the size and density of the yarn and the style of weave. Shade materials are all typified by lower strengths than fully coated fabrics and often the weave is quite light.

Another style is knitted polyethylene which has gained wide use in the agricultural shade market covering hectare areas with simple undulating structures.

This material has substantial extension in warp and weft so that curved surfaces can be formed by distortion of the material without detailed patterning usual with fully coated materials.

Life expectancy is around 10 years depending on location.

5. STRUCTURAL PROPERTIES

As referenced in 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 performed on a 50 mm wide material sample and in accordance to AS2001.2.3. This test provides the ultimate tensile strength of the fabric by testing a sample to destruction between opposing jaws of a test machine.

Fabrics using either a high modulus glass fibre or polyester yarns and coated with a low modulus coating produce a composite that is anisotropic. Crimp interchange effects due to the weave causes differential biaxial load–extension results. Biaxial properties of the material has to be measured in a biaxial testing machine pulling a sample simultaneously in two directions This test is normally conducted for each production batch of fabric to accurately chart the behaviour of the batch.

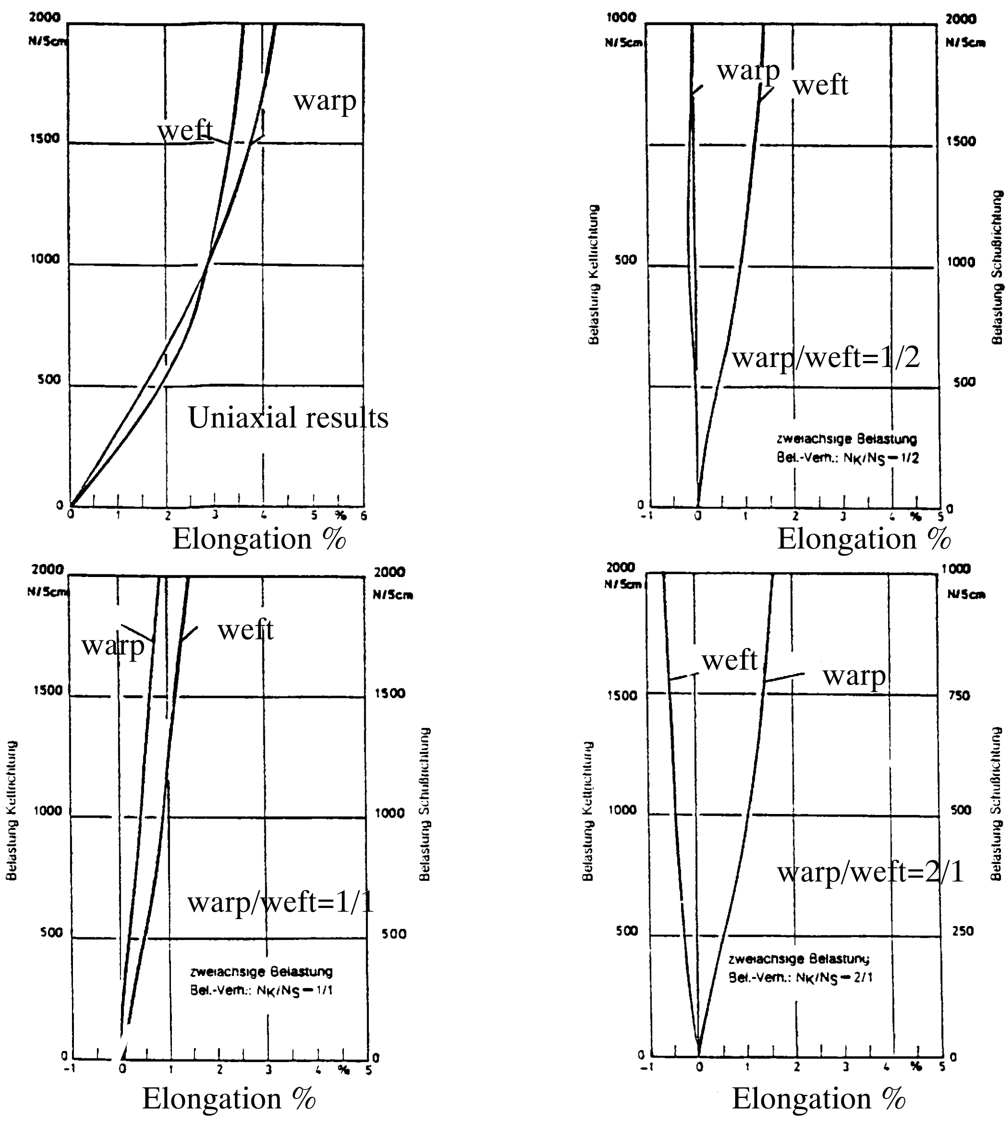

Fig 3 Typical biaxial stress/strain curves provides varying results for differing warp/weft ratios (1:1, 1:2 and 2:1)

All fabrics exhibit irrecoverable constructional creep from set of the fibres and strain. Biaxial testing provides the results of constructional stretch in the material. Compensations for this are taken into consideration in production of pattern data to ensure the structure fits correctly thus avoiding soft spots, wrinkles or uniaxial load transfer in the surface. Structures are designed smaller than the actual frame or perimeter, allowing the degree of fabric stretch which is known to occur under tensioning loads.

The standard tear strength tests are to be conducted in accordance with AS2111.16. This test provides results on the most critical mode of failure for fabric, i.e. 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.

It is most common for membrane structures to develop problems from a detailing issue where high point loads on the fabric cause a tear which can propagate.

Fabric structures are often built over public places, shopping centres, building entrances, tourist resorts, in short over areas trafficked by high volume of people. Therefore concern about fire resistance is of prime importance. The Building Code of Australia has outlined performance requirements for materials. It has set down test methods in accordance with AS1530 Parts 2 and 3 to determine the appropriateness of a material.

In some conditions material can only be used where a sprinkler system is installed. This is also common for glazing media, glass, plastic etc.

General indices required are:–

(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 PTFE/glass material which gives a zero result. This result is achieved because glass fibres are not thermoplastic and the PTFE resins are inert.

All joints and seams are usually specified by the designer 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 mentioned in previous sections, the life of the material varies from 10 years upward, PTFE/glass being more inert, it has a longer life span than PVC fabric.

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	Asbes-tos	Wood
Thickness (mm)	1.0	3.0	2.0	4.0	5.0
Heat Transmission ($kcal/m^2h^0C$)	5.0	5.1	10	4.8	4.3
Heat Conductivity ($kcal/mh^0C$)	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 in heat conductivity is similar to wood. In order to achieve better insulation of an enclosed space, the use of double or triple layer membranes is not uncommon, although more costly.

6. CONCLUSION

Synthetic fabrics have come a long way in the last 50 years. From the early experimentation years with various yarns and material, we currently have a range of materials that can meet the detailed engineering and constructional requirements of both pneumatic and tensile structures.

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 possessing a long life.

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