2: SUBJECT BACKGROUND.

2:1. INTRODUCTION.

In the previous chapter the lack of existing information regarding the thermal behaviour of spaces enclosed by fabric membranes was highlighted and the emerging need for a greater depth of understanding in that area was identified. It was considered that addressing this need was a practical aim for the research presented in this thesis, and to that end a number of general objectives were stated.

Whilst the research presented in this thesis concentrates specifically on thermal issues, the historical review provided by this chapter recounts the general development of fabric structures, identifying some of characteristic features symptomatic of their evolution and locating this research within the wider picture. The environmental implications of some of these developments will be discussed as they arise, however it was only in fairly recent times that environmental performance became an important issue in its own right and the content of this chapter reflects that fact.

There are three major sections to this chapter. The first looks at the historical origins of fabric structures, the second concentrates on the more recent trend towards '*architectural*' fabric structures and the third focuses more specifically on the development of fabric membranes themselves.

2:2. THE ORIGINS OF FABRIC STRUCTURES.

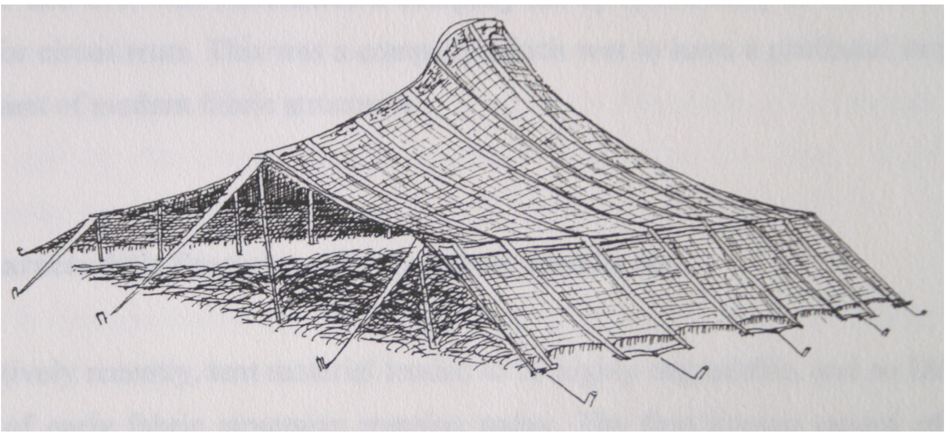
2:2.1 The Historical Development of Fabric Structures.

The word architect comes from the Greek words '*archi*' meaning *one who directs* and '*tectos*' which means *weaving*[1].

The origins of fabric structures can be traced back over 44000 years to the ice age and the Siberian Steppe, where remains have been found of simple shelters constructed from animal skins draped between sticks. It is likely that structures of this type were the first dwellings actually constructed by man, and it has even been suggested that simple textiles were used for spatial division and shelter before they were used as clothing[2].

Initially associated with nomadic peoples, one of the earliest and most successful types of fabric structure was the loosely woven black tent. The black tent spread throughout the civilised world during the Arab conquests of the eighth century, and its descendants are still in use today.

Figure 2:2.1 A Typical Black Tent.



From these nomadic origins, more permanent urban shading systems evolved. These were initially used to provide cover over streets and domestic courtyards, but later, larger '*velum*' or '*velarium*'[3] were developed, primarily in order to provide shelter at theatres. In more recent times, simple cable stayed, prestressed fabric structures have been used to provide decorative shelter for special events. These '*toldos*' or '*envelet*' were particularly popular at the end of the nineteenth century in the Cataluna region of Spain[4].

The lightweight portability of fabric structures inevitably brought about a long and close association with the military which began with the first major confrontations and has continued to the present day. By the first century BC the leather tents of the Roman Legions were commonplace, and the later Byzantine armies of the seventh century were recognised specifically by their simple tented shelters. More recently, Godfrey Rhodes, an English Army Captain designed the standard tented field hospital (1858), however both this, and the subsequent British War Office, '*Handbook of Tentage*', (1946)[5] only serve to illustrate the total lack of innovation in military tent design over the preceding thousand years.

During the twelfth century, elegant royal tents became fashionable in Western Europe. These '*novelty*' structures grew progressively larger and more ornate during the sixteenth century, becoming symbols of frivolity and wealth at special events and tournaments. Their appearance however was more architectural than '*tented*', with vertical walls and steeply pitched roofs. The famous '*Field of the Cloth of Gold*' meetings between Francis I and Henry VII in 1520 were gloriously symptomatic of this trend[6].

In 1770 the first known circus tent, a large linen structure, was erected at Westminster Bridge[7]. Travelling circuses began performing in '*nomadic*' big tops around Europe around 1830, and by 1867 the first American railway circus had begun touring.

These early travelling circuses occupied roughly conical shaped '*big tops*' which could be up to 50m in diameter. Such large enclosures required careful design and regular replacement because of the highly degradable nature of available materials. In 1872 Stromeyer and C.o. was established a company set up specifically in order to satisfy the demand for circus tents. This was a company which was to have a profound impact on the development of modern fabric structures.

2:2.2 Some Characteristic Features of Early Fabric Structures.

Until relatively recently, tent material tended to be highly degradable, and so little physical evidence of early fabric structures remains today. The first known record of the actual appearance of primitive tents dates from the first century AD when early Persian Kibitkas were depicted in a wall painting at a grave in Kerch[8].

It is known however that fabric structures developed and thrived predominately in regions where materials were scarce, or where survival required mobility; both conditions which tend to be brought about by low rainfall[9]. Changing climates brought about slow transition from tents to huts and vice versa, and it was from the resultant process of intermediate modification that an enormous range of composite dwellings evolved. Many of these basic generic forms of structure are still used in remarkably unevolved forms throughout the world today. In Mongolia for example three quarters of a million people still live in yurts[10].

The evolution of tents themselves can be categorised into urban and nomadic forms[11], however the essential characteristics of both types were similar. Their purpose was very similar to that of clothing; that is to provide privacy, environmental modification and protection, intended as a means of generating shelter when necessary rather than as enclosures of permanent space.

Form these purely functional origins however, the tent evolved over a period of many centuries to become a symbol of frivolity. Their temporary and degradable nature led to the inevitable emergence of style, as re-erection necessitated maintenance which required creation and so allowed personalisation[12]. In architectural terms, their application eventually became monumental, providing a resource for which there was no fundamental need, and indeed historically many permanent monuments were preceded by temporary fabric structures. More recently, particularly in the West, fabric structures became almost entirely recreational, and other than for military purposes were used in ways which ran entirely contrary to their functional origins.

2:3. THE HISTORY OF ARCHITECTURAL FABRIC STRUCTURES.

2:3.1 The Development of Modern Fabric Structures.

The simple dwellings described in the previous section tended to be fabricated in traditional ways by the intended occupants. As they degraded, their components were replaced, and so the overall design evolved. More complex fabric structures were predominately the craftsman's trade and not the domain of the architect[13].

This was to change during the nineteenth and twentieth centuries as architects became inspired by technological breakthroughs in structural engineering, made more appealing by architectural theorising on the emerging functional aesthetic[14].

In 1823 at around the same time that strong ropes first became commercially available, Claude Navier published a seminal study on suspension structures[15]. The teething problems of the resulting generation of long span structures were substantially laid to rest in 1838 when J.M. Rendel identified torsional stability as the major cause of bridge collapse. Large suspension structures rapidly became a common feature of engineering design, and it was not long before their spanning potential was used for large buildings.

At the 1896 Nizny Novgorod exhibition in Russia, the Structural Engineering Pavilion designed by V.G. Shookhov consisted of a large radial steel cable net pretensioned in both directions and clad with steel panels. It was believed that a similar structure composed of thicker 3mm steel sheets could span over 300m[16]. This provoked an interest in the spanning potential of tension stabilised surfaces which has continued to the present day.

A parallel development to these pretensioned structures began in 1918 when F.W. Lanchester patented a design for an '*air tent*' in which it was proposed that a patterned balloon fabric could be inflated at a low pressure to form a habitable enclosure[17]. In 1938 Lanchester developed the concept further with a design for an air supported dome spanning over 650m. Such air supported and air inflated structures had many potential applications but in 1946 a mass market was identified, creating '*radomes*', minimal structure shelters which provided climatic protection for radar dishes.

Following successful trials between 1946 and 1950, the radome concept was applied to the DEW line early warning system, and in 1953 Walter Bird established the company Birdair primarily for the manufacture of radomes. Since 1946 over 40,000 radomes have been manufactured, some of the largest being more than 60m in diameter[18]. This generated a great deal of interest in the whole subject of tensile surface structures and stimulated intensive research into fabric composition. Fabric structures had become big business.

In the same year that Birdair began trading, the L.S. Dorton Arena in Raleigh was completed. Designed by Matthew Norwicki and Fred Severud, it was the first modern, doubly curved, prestressed saddle structure. Whilst itself not actually made of fabric, its completion is popularly believed to signify the birth of the modern '*tent*'. The Raleigh Arena influenced many architects, and directly inspired both Saarinen's Yale Hockey Rink (1956) and Tange's two stadia for the Tokyo Olympics (1961)[19].

A young German architect with a personal interest in lightweight and tension structures visited America during this period, where he met both Saarinen and Severud. The architect, Frei Otto, began exhaustive investigations into the structural principles behind this new generation of buildings. Even before the publication of his thesis '*Das Hangende Dach*' in 1954, the practical implications of his work were brought to the attention of the tent manufacturer Stromeyer and Co. Peter Stromeyer made both his experience and resources available to Otto, and between them over the next twenty years, they were to undertake much intensive research and experimental construction which served to bring prestressed fabric structures into the vocabulary of the contemporary architect.

In 1957 Frei Otto established the Development Centre for Lightweight Construction using money he had received for commissions, and in 1964 re-named the Institute for Lightweight Structures it became affiliated to the University of Stuttgart. The Institute was primarily concerned with developing methods for deriving the ideal forms for tensile surfaces. Initially these investigations were based on detailed studies of soap films and wire mesh models, however later Otto was to meet the mathematician Fritz Leonhardt, who set about making this form finding process more mathematically explicit.

The variety of Otto's designs was wide. The first fabric structures he had built were a series of small music pavilions at the Federal Garden Exhibition at Kassel (1955)[20], which were followed in 1957 by the similar twin saddle structures at the entrance to the Cologne Federal Garden Exhibition. He also designed convertible structures in the tradition of the Roman velarium, his first being the Theatre Terrace at Casino (1965)[21].

Much of Otto's early research was embodied in the Montreal German Pavilion (1967), and a new permanence was heralded by the plexi glass clad cable net of the Berlin Olympic Stadium (1969/70)[22].

At a more theoretical level, he investigated the potential of giant envelopes, ranging from his project for a roof over a dock at Bremen which was intended to span 390m, to plans for a 2 km diameter air supported dome over '*the City in the Arctic*' (1970/71), and the contrasting '*Shadow in the Desert*' (1972). These structures inevitably raised a number of environmental issues, and in particular there was much physiological theorising about concepts such as the '*meso climate*'. Such debates however did nothing to provide the practical tools which were needed in order to tackle actual design problems and partly as a consequence of this, none of these projects were actually built.

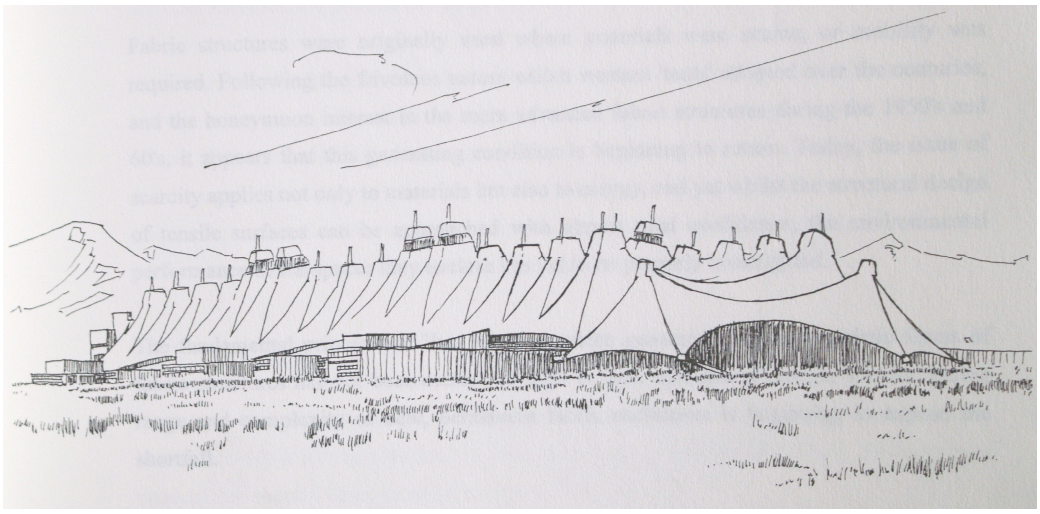
In the late 70's the world recession depressed the market for air houses, and this was compounded by a series of severe storms which resulted in a number of highly publicised deflations. Fabric structures in general, and airhouses in particular, were considered contrary to the new '*long life / low energy*' construction ethic increasingly advocated by architectural organisations such as the RIBA. This hindered the development of fabric structures, especially in Europe, and in 1974 Stromeyer's company went into receivership.

During the nineteen eighties and nineties, the fabric structures industry became more tentative. Recent developments seem to have been concerned with a confidence building process involving the consolidation of structural design techniques and the development of more reliable fabrics. This has however provided a sound base from which the size and complexity of new structures is again beginning to increase.

The fabric roof of the Hajj Terminal at Jeddah Airport (1981) covers nearly half a million square meters, and more recently, *cable domes* have begun satisfy the demand for large span roofs left following the decline in interest in air supported structures.

The test case twin skin Denver Airport (1994) is the perhaps first important fabric enclosure to be located in a predominately cold climate. It is thought by many that if Denver Airport is a success, it may inspire many similar developments.

Figure 2:3.1 Denver International Airport.



2:3.2 Some Characteristic Features of Modern Fabric Structures.

The characteristic doubly curved shape of prestressed tensile surfaces had been known since the time of the black tent, however prior to the detailed analysis facilitated by Otto large span structures were predominately built based on past experience by craftsmen. As the degradable fabrics used for such structures had to be replaced every few years so patterns could be periodically adjusted and improved with little or no understanding of the structural principles involved[23].

During this century, Frei Otto bridged the gap between design and manufacture, developing a method by which the ideal shapes of individual tensile surfaces could be derived from first principles. Initially however, these structures were restricted by the short life of the fabrics used, and so they were generally only considered appropriate for temporary applications.

These temporary uses were subject to relaxed design codes, and so were particularly suitable testing grounds for a newly developing fabric structures industry. The World Expositions of 1964 in New York and 1970 in Osaka provided great publicity for fabric structures. Applications such as radomes were also ideal as military clients were not concerned with standards, so long as the job was done.

The success of these applications stimulated a new demand for permanent fabric structures, for which no such performance allowances could be made. In the competitive and regulated '*architectural*' market, durability must be proven and performance assured. Whilst problems of durability were substantially laid to rest by the development of modern composite membranes however, performance issues have yet to be properly studied.

Fabric structures were originally used where materials were scarce, or mobility was required. Following the frivolous nature which western 'tents' adopted over the centuries, and the honeymoon interest in the more advanced fabric structures during the 1950's and 60's, it appears that this generating condition is beginning to return. Today, the issue of scarcity applies not only to materials but also to energy, and yet whilst the structural design of tensile surfaces can be approached with almost total confidence, the environmental performance of the spaces they enclose has yet to be properly investigated.

The fundamental principle of '*less is more*' which generated the characteristic forms of fabric structures has not been carried through to their operational design. The increasing range and complexity of new, permanent fabric enclosures is beginning to expose the shortfall.

2:4. THE MODERN TENSILE MEMBRANE FABRIC.

2:4.1 The Development of Structural Membranes.

The earliest fabrics used to provide shelter were formed by simple membranes extracted from animals or vegetables. Later these membranes were cut into strips and interlaced to form larger, more practical textiles, and eventually these strips were twisted into circular sections allowing the manufacture of flexible, continuos fibres with enhanced strength.

The black tent was most commonly made of loose woven, spun goats hair, but regional variations used yak hair, sheep wool, camel hair, and even reed mats twined with wool. Other early membranes were constructed from cured leather, deer skin, seal skin, and even tree bark[24]. Linen was used for the Roman velum and the first circus tents, however cotton was the first material to possess any significant structural strength.

Otto's first structures were fabricated from the traditional cotton canvas with which Stromeyer was accustomed. These early canvas fabrics however were relatively weak and ineffective. Performance improved with the introduction of heavy cotton canvas, but its limited strength and poor UV resistance, meant that canvas structures had a maximum span of just 25m and they were only expected to last for around three years.

Exhaustive research into membrane combinations during the fifties and sixties resulted in experimentation with a wide range of high performance materials intended to replace cotton. Possible alternatives included coated glass fibre, steel meshes, aluminium meshes, acrylic sheets, coated synthetic fabrics, foam insulated fabrics, wire reinforced resins and so on. Otto also experimented with PVC coated polyester and nylon, although these early varieties had rather unpredictable properties[25].

Otto's Interbau Building at the City of Tomorrow exhibition in Berlin (1957) was his first attempt to use a non cotton based fabric in a real project. The building consisted of a highly elastic, flat, polyurethane membrane which was distorted into a doubly curved three dimensional form by an internal frame. Unfortunately this experimental form of polyurethane deteriorated very quickly, possibly due to an incorrect mix of the fibre additive titanium oxide, and had to be replaced by a heavy cotton fabric[26].

More complex membrane combinations were also tested. The Dortmund Ice rink (1963) for example was fabricated from a continuous filament polyester, coated with a rolled on aluminium foil to protect against UV degradation, which was in turn protected against

corrosion with a polyacrylonitrile topcoat. This had a predicted life of 20 years but was opaque and cost about 4 times as much as canvas[27].
Many membrane combinations were experimented with during this period, but research gradually converged on a small number of practicable alternatives. The German Pavilion at Expo '67 in Montreal was one of the first buildings to use a PVC coated polyester membrane[28]. It was dismantled after six years and showed little sign of degradation[29]. Within a relatively short period of time PVC coated polyester and its sister membrane PVC coated nylon (used for air houses due to its high elasticity) became the industry standards.

As a demand for more permanent fabric structures emerged, so better performing alternatives to PVC coated polyester and nylon were sought. In 1972 PTFE coated glass fabrics were introduced following their development by NASA for the manufacture of space suits. PTFE coated glass is relatively inelastic, and so requires more accurate patterning than the more accommodating polyester or nylon based fabrics. PTFE coated glass is also more expensive, but tends to be longer life. The first application of PTFE coated glass was in the La Verne College Student Centre, in California (1973). In 1993, twenty years later, the original membrane was still in place, and was still capable of withstanding around 75% of its original design load[30].

More recently, high performance materials such as silicone coated glass have been developed. Whereas Teflon is translucent, silicone is transparent[31], and silicone coated glass has an anticipated life of up to 50 years. A combination of high cost, industry scepticism and early performance problems however, have meant that silicone coated fabrics have only been used to a limited extent so far. Other developments have included woven PTFE fibre (hydrophobic, microporous, and extremely durable), laminated open weave grids, foils, multiple membranes and more theoretical active membranes such as those developed by Graham Stevens and Nickolaus Laing[32].

A comprehensive list of currently available membranes combinations is presented below. This was compiled from information provided by membrane manufacturers, and recent announcements of new products.

Figure 2:4.1a List of Uncoated Fabrics.

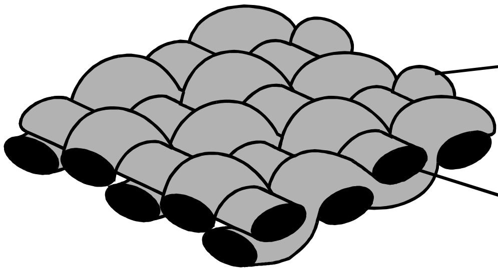
Examples	Common Configuration
Cotton. Woven PTFE fibre.	

Figure 2:4.1b List of Films.

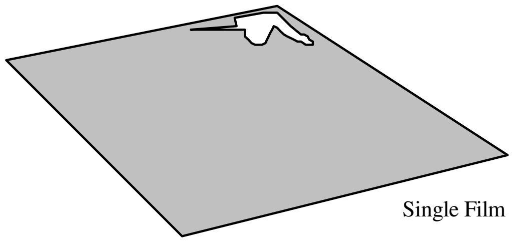
Examples	Common Configuration
Polyethylene. PVC. Polyester. FEP. ETFE. PTFE. Vinyl. PVF.	

Figure 2:4.1c List of Mesh Reinforced Films.

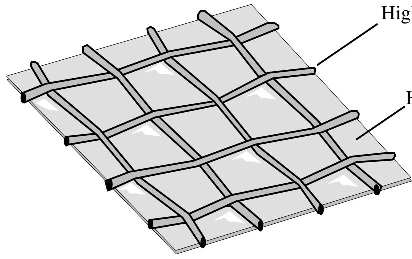
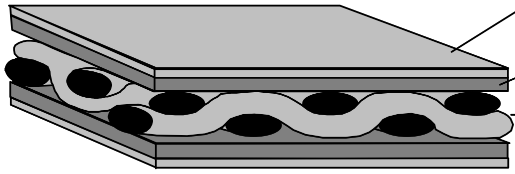
Examples	Common Configuration
Polyester reinforced PVC. Glass reinforced FEP. Aramid reinforced FEP. Steel reinforced FEP. Glass reinforced ETFE. Aramid reinforced ETFE. Steel reinforced ETFE Polyester reinforced ETFE. Glass reinforced PTFE.	

Figure 2:4.1d List of Coated Fabrics.

Examples	**Common Configuration**



Acrylic painted cotton.
Vinyl coated cotton.
Hypalon coated polyester.
Neoprene coated nylon.
Hypalon coated nylon.
Polyester coated cotton.
PVC coated nylon.
PVC coated polyester.
PTFE coated glass.
PTFE coated polypropylene.
PTFE coated polyester.
PTFE coated acrylic.
ETFE coated glass.
ETFE coated polyester.
PVF coated glass.
PTFE coated aramid.
PVC coated aramid.
PVDF coated polyester.
PVDF coated glass.
Silicon coated glass.
Vinyl coated nylon.
Vinyl coated polyester.
Vinyl laminated polyester.
Acrylic coated polyester.
Copolymer olefin coated polyester.
Polyurethane coated nylon.

2:4.2 Some Characteristics Features of Architectural Fabric Membranes.

Traditional membranes tended to be obtained simply from commonly available materials, whereas more modern membranes are composed artificially based on desired performance requirements. All structural membranes however have the common characteristics of high tenacity and great pliancy, but little mass or compressive strength.

Modern tensile membranes tend to consist of a woven fabric substrate protected from degradation by an inert plastic coating. A more recent development involves the application of a further topcoat to the outside surface of the membrane which mimics the performance of PTFE. It is generally claimed that this topcoat makes membranes entirely '*self cleaning*'.

A huge range of membrane types have been made available over the last twenty years as manufacturers have become increasingly able to vary the way in which they select and combine the constituents of their products. A variety of base fabrics, coatings, topcoats, and colours have emerged resulting in a wide range of membrane strengths and translucencies.
Because of this ever increasing variety, it has become necessary to establish industry standards by which designers can gauge the relative performance of different alternatives.

Eight standard types of PVC coated polyester have so far been designated; types zero to seven, and 5 standard types of PTFE coated glass. The fabric type number increases with strength, however type 0 tends to be used for tents only, and the kind of forces necessary to require use of the very strong membranes are uncommon. In practice therefore membranes other than types one to four are rare[33].

No reference is made to environmental properties in manufacturers specification of these standard types. Historically this was because the limited range of manufacturing techniques available offered little opportunity for tailoring environmental properties. The main aim was to achieve the desired tensile strength, and the result of this was that the higher the strength required, the thicker the membrane and so the lower its translucency.

With the recent development of high tenacity fibres and durable transparent films however, it is now possible to satisfy both environmental and structural requirements. High tenacity mesh reinforced foils can have virtually any combination of structural and optical properties, and the emerging ability of manufacturers to produce one off membrane combinations for individual customers is increasingly providing designers with almost limitless choice.

2:5 CONCLUSION.

In this chapter, the historical development of fabric structures was reviewed and some of their distinctive features were highlighted. With only a few exceptions, the fundamental characteristics of these structures were found to be related to strict functionality, involving the minimum use of materials and resulting in maximum resource efficiency.

The rigour with which their structural behaviour was researched however was not carried through to other aspects of their performance. Occasional studies of their environmental behaviour were made and a number of innovative environmental structures were designed, however little or none of this work filtered through to the market place in a practical form.

In recent years, there has been an increasing demand for permanent '*architectural*' fabric structures. These structures are being required to compete in the domain of more conventional building types which have well established standards of environmental performance and increasingly strict regulations on energy consumption. This demand has come at a time when the development of high strength fibres and high translucency films is freeing the environmental properties of fabric membranes from any structural constraints. As yet however, the designers of fabric structures seem unable to exploit this situation, and as a result the environmental inadequacies of the spaces they design continue to be cruelly exposed.

In the next chapter those parts of the existing body of knowledge which do relate to the environmental, and specifically the thermal behaviour of spaces enclosed by fabric membranes will be critically reviewed.

---

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