A HISTORICAL REVIEW

OF

MEMBRANE STRUCTURES

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INTRODUCTION;

No specialist sector of the building industry exists or develops in a vacuum. Searching for the creation myths of Membrane Structures involves not just the period post Otto but a significant dig into history for a proper look at the forces which developed the progenitors.

History is more an art than a science. Examining the short term gives the limited perspective often developed from being too close to the event. When we declare Membrane Structures to be novel, they are. Simultaneously they are the product of a long trend in building design and technology evolution.

The subject of this paper is tendency, in the annals of structure, towards lightness of construction , progressively with the passage of time.Specifically it looks at the source in design methodology and materials technology of Membrane Structures.

The thesis can be amply demonstrated by a comparison between the Pantheon in Rome (AD130) and Fullers Montreal Expo Dome (AD1967). Perhaps of better comparative relevance to this topic is the Denver Airport building, now nearing completion.

DEVELOPMENTS WITH IRON & STEEL;

The development in the UK of successful mass casting techniques using iron, fulfilled a long term desire by building practitioners to repeat structural elements in a design within acceptable tolerances. This could be seen as the birth of modular construction. The first (still extant) such structure was the Iron Bridge at Coalbrookdale in the UK, commencing the modern age of new materials.

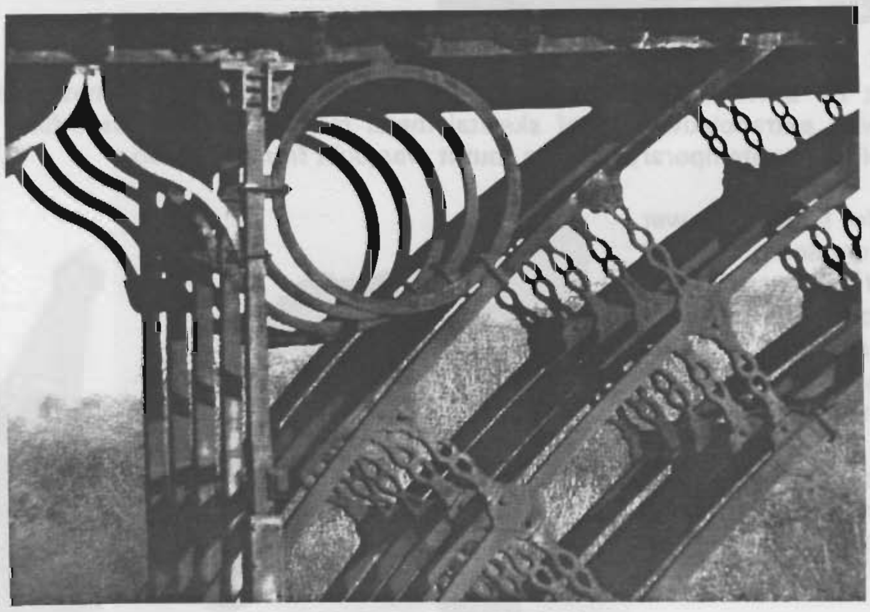


Fig 1 - Detail Coalbrookdale Bridge

Development in the theory and practice of structures accelerated following the development of mass produced iron castings and wrought works. An extremely creative period followed typified by experimentation with materials and forms. This was the beginning of contemporary science.

Initially Great Britain's economic and military dominance prevailed assisted by many brilliant and innovative designers like **Telford, Brunel** and **Stevenson** etc. who commenced the golden age of engineers where building as a science separated from building as an art or craft.

Isambard Kingdom Brunel ,a monument of the time carried out an impressive range of works including the Thames tunnel construction, railway and locomotive design, including their stations, metal ships, their propulsion systems and of course, bridges.

His *`hanging chain'* Clifton Bridge design at Bristol illustrates progress in his era when contrasted with his much heavier Saltash Bridge [1859]. The Clifton Bridge was completed following his death as a tribute to him by his peers.

He died before Bessemer developed the *blast furnace* in 1856 which made steel available to speed the development of lighter and longer span structures by improved material properties of metals.

Fig. 2 - Isambard Kingdom Brunel

The Crystal Palace, an early example of fast-tracked projects, also missed this milestone development by a whisker. Built by **Paxton** in 1851 it was a dramatic demonstration of modernity with extrapolative use of skeletal metal members and glass infill. It's very close philosophically to contemporary finishes, but it was built from cast iron.

Gustave Eiffel built his tower in 1889, containing 10,000 tons of steel and cast iron. It was then considered to be a temporary structure. One could observe that this is not a lightweight structure but by comparison, with the Tower of Pisa, the conclusions are obvious, masonry versus spatial construction.

Fig 3 - Tour Eiffel

The factors which drove this movement from massive to lightweight were various, important among them being building cost and scientific knowhow.

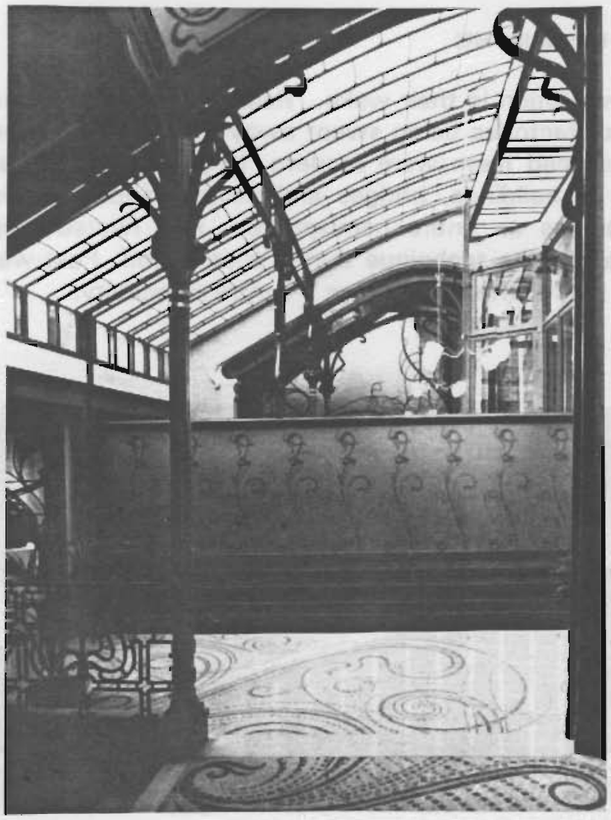
The really big breakthroughs in computer techniques were not to occur until late 20th century but from mid 1800's to 1900 was a fertile time in the western world with almost no comparison, where the forces of the industrial revolution reshaping the world.

Western economies boomed with expanding markets. New world colonies were being opened and exploited and new markets created. Transportation technology pushed contact across the world and products were interchanged massively with little opposition from trade barriers. Resistance was largely suppressed by colonial wars and Europe, with America emerging, dominated the world economically and politically.

THE TWENTIETH CENTURY;

With recently available high strength materials, an emerging engineer class rapidly developed innovative new ways to build longer and bigger. A high rise building construction boom began in the late 1800's with **Sullivan's** Wainwright Building in St. Louis using the first complete steel frame. Before 1920 in New York, the first 50 storey building had been constructed. By 1932 they were over 100.

Meanwhile metallurgy and chemistry developed side by side and developers as ever sought cost effective ways to turn buildings into profitable operations.



Architects at the turn of the century were fed and inspired by a new awareness of international destinations made possible by the increased speed of travel and its ready availability. The influences of Japan, China, Mesopotamia and Egypt was strong upon the designers' palette. *The Art Nouveau and Art Deco* period grew from these and we can see the legacy of this still today.

The streams of construction were extremely diverse as experimentation continued unbridled.

The beginning of the century saw air travel commencing, initially with massive air ships. Specially designed lightweight structural frames were required to reduce the mass and enable the lift equation to balance with their highly flammable hydrogen contents.

Fig. 4 - Art Nouveau Style

Pier Luigi Nervi moved in one direction with in situ and pre-cast concrete constructions of extraordinary, elaborate minimalism reducing the bulk of previously executed works by clever application of engineering design and materials..

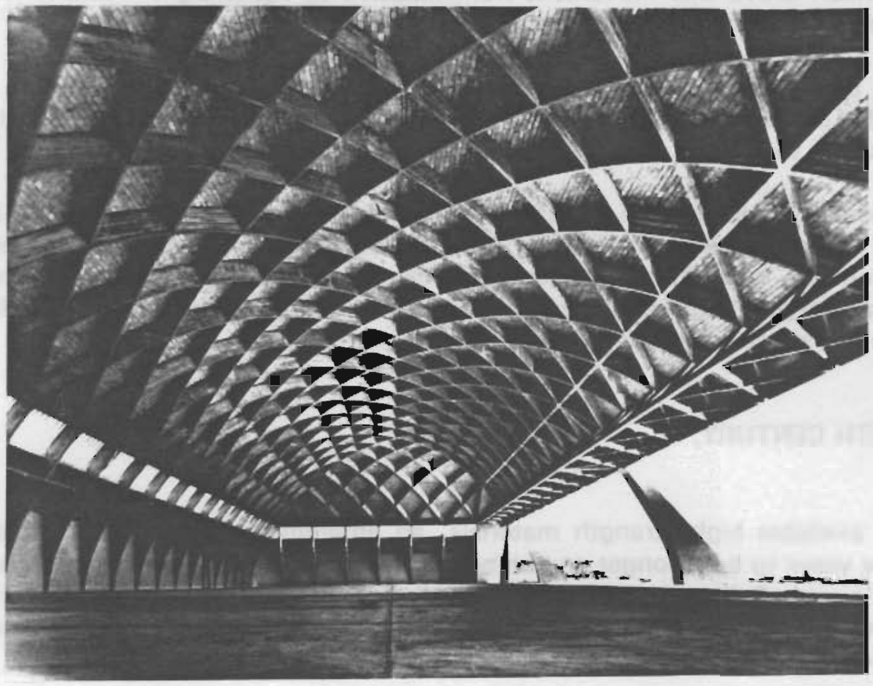


Fig. 5 - Nervi Hangar [ROME]

Two wars came and went in Europe leaving devastation in their wake. Reconstruction followed with the first of the industrial revolution dirt floor factories being swept away by the bombs and artillery barrages. The new factories which replaced them were modern, long span buildings. These wars gave impetus to industrial design of buildings, bridges and military equipment in lighter and lighter materials to fight a war across an entire hemisphere. Hot riveted ship construction disappeared and welding developed as the technique during that period. Post-war reconstruction heralded a new boom which has now shifted to Asia as a centre of activity.

SADDLE SURFACES EMERGE;

US Engineer **Fred Severud's** firm was instrumental in inspiring works which were part of the genesis of membrane structures. **Mathew Nowicke** [architect] with **Severud**, built the saddle shaped Raleigh Arena in North Carolina in 1952, extensively using light weight, high strength cables.

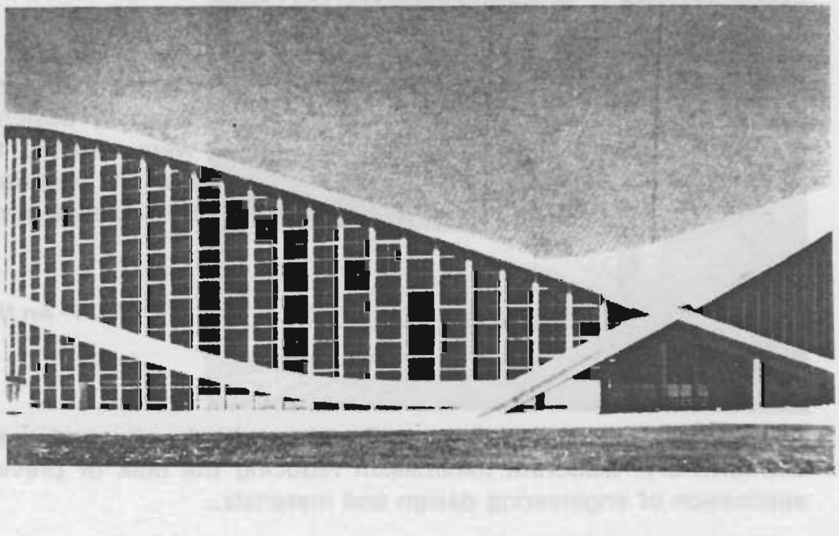


Fig 6. Raleigh Arena

In 1956, **Eero Saarinen** with **Severud**, built the TWA Terminal in New York, again a classical precursor to membrane forms as we know them.

Fig. 7 - TWA Terminal [NEW YORK]

Both **David Geiger** and **Horst Berger** worked in the firm and both became legends of design, the former in superdome pneumatics, the latter for long span tension structures. Sadly, **David Geiger** is now dead and recently **Horst Berger** rejoined the old firm of Severud.

In Australia in 1955, **Peter MacIntyre** with **Kevin Borland** (architects) designed the Olympic Swimming Centre, followed in 1958 by the more purist Myer Music Bowl by **Yencken and Freeman. Irwin Johnston** were engineers on both.

In 1961, **Kenzo Tangye** and **Koji Kameya** designed inspired stadia for the Tokyo Olympics. These were all major structures utilizing curved, sometimes anticlastic surfaces so familiar to tent structures of today.

They became a guiding light to the next generation. They had in common an extrapolative engineering approach to design and all were clad in somewhat traditional forms.

DEVELOPMENT OF TENT STYLE;

Meanwhile, quietly in Germany and in the U.S.A., **Frei Otto** and **Walter Bird** were separately working on developments using flexible fabrics. **Otto** developed through a productive long term working relationship with **Peter Stromeyer**, principal of an old firm of tent makers in Germany.

Wally Bird started in 1946 with his first air supported Radome. He and his group painstakingly developed the principles of flexible structures with the assistance of the U.S. mililtary and their developing needs for an extensive radar network covering the north west flank of the United States.

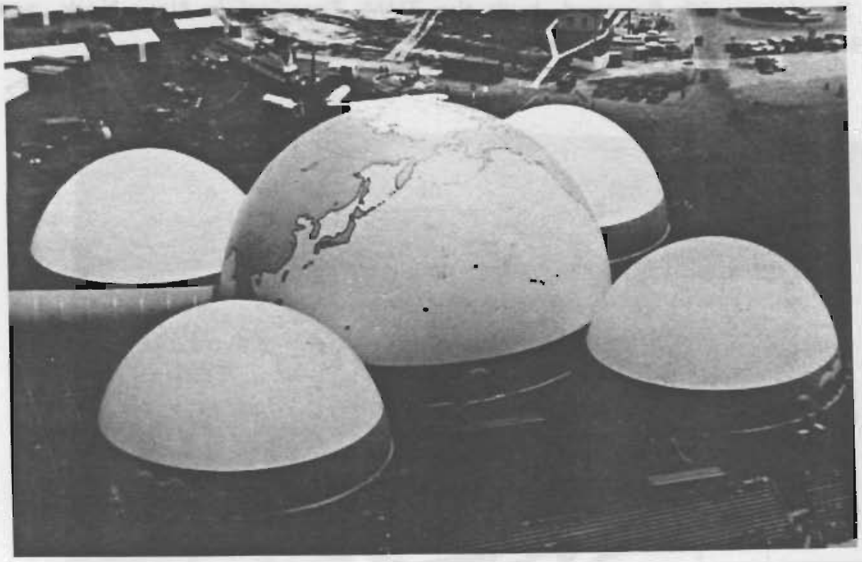


Fig 8.- Atoms for Peace-Birdair

While pure sources in architectural history are often blurred, one could draw clear lines between **Wally Bird's** early work and the resulting field of pneumatic structures while similarly recognising **Frei Otto** as the precursor of the tensile tent structure.

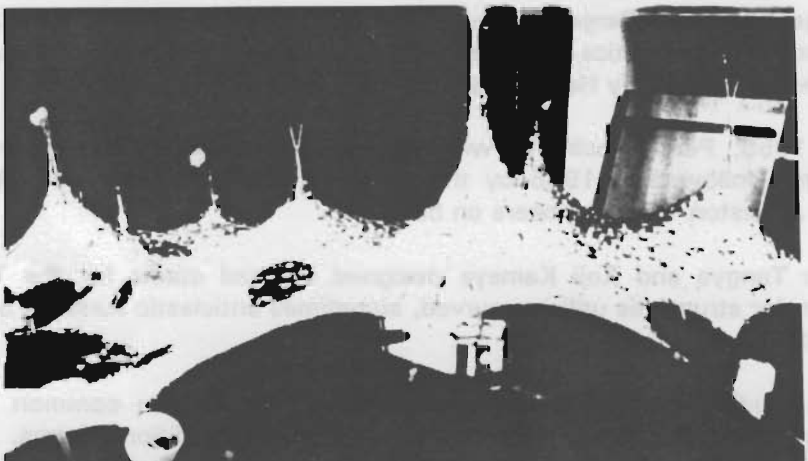


Fig 9 - German Pavilion [MONTREAL]

Otto teamed up with **Rolf Gutbrod** to win major competitions. A milestone in the development of membrane structures was the cable net supported German Federal Pavilion for Expo '67 in Montreal, an event which also featured **Buckminster Fuller's** equally brilliant geodesic dome. At about the same time, the **I.L. [Institute for Lightweight Structures]** in Germany began its life as a technology centre working in a full scale model of part of Otto's Expo structure.

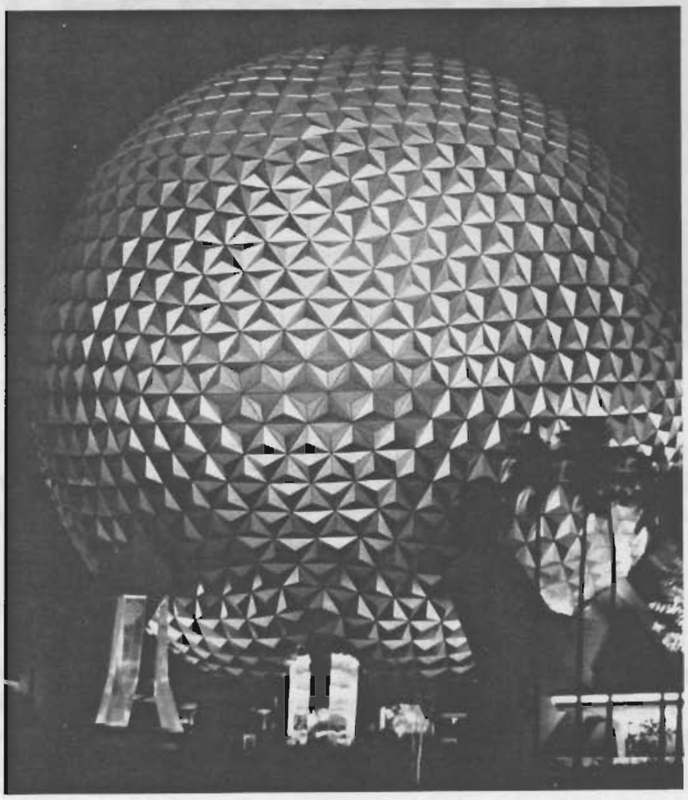


Fig 10 - Fuller's Geodesic Dome Form- Epcot Centre, Florida

Computational techniques for analysis or surface generation were very primitive with many of these early structures being generated and formfound by a laborious model making measurement supplemented by an ingenious but complex method of photogrammetry. Despite this arduous process, the work produced created sensations and is still without comparison in many instances..

The Munich Olympics Stadium in 1972 designed by **Otto and Gutbrod** and built by **Behnisch and Partners**, using **Leonhardt and Andra** as engineers, created an international yardstick for excellence in curved surface structures which is still sustained.

One could be forgiven for considering the post-war period as the *tensile era* if only in exposition and Olympic structures. Surely they have dominated in these fields.

German designers and practitioners received financial support for their research and development of innovative curved membrane forms from Federally funded *Garden Exhibitions*, held across Germany regularly. These featured emerging German technology, in particular tent structures.

Meanwhile Japanese fabricators who had visited Germany to look at developments , launched onto the international stage with gusto in 1970.

Expo 70 marked the emergence of a dynamic industry which has since become almost pre-emminent in the world.

Fig. 11 - Fuji Pavilion EXPO 70 [OSAKA]

Locally held Expos in Japan which regularly expect attendance in millions of persons, are the equivalent of the German Garden Shows. These Expos display an array of spectacular light weight structures including some of the more inventive membrane forms yet built, practice makes perfect.

At the 1970 Expo , the *US Pavilion* (Geiger engineer) unveiled a new form of long span air structure utilising a low profile cable net restrained membrane fixed to a perimeter berm. This structure opened the door for many super dome stadia built until the middle of the 80's mostly in the United States. These spectacular and monumental structures provided a ow cost, light weight solution to roofing football and sporting facilities in climates where snow and rain limit activity

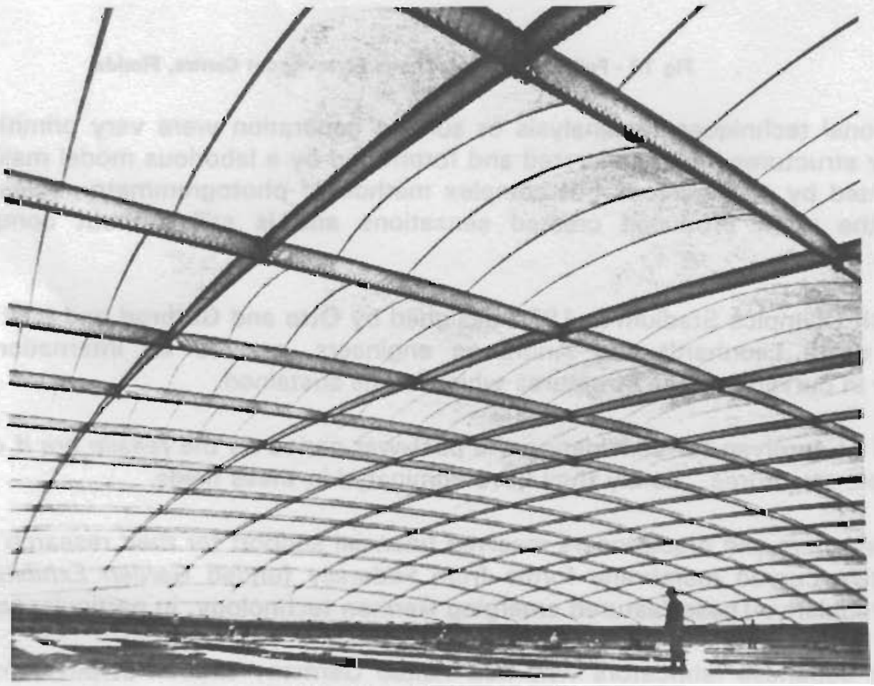


Fig 12 - US Pavilion EXPO 70 [OSAKA]

The use of large pneumatics is mainly in the USA and now Japan, although the *Burswood Resort* in WA is a small version. Perhaps when rules stipulating grass playing fields in Europe alter, we can expect to see stadia roofed there in a similar manner.

MEMBRANE MATERIAL PROPERTIES;

The technology of designing and building membrane structures has been directly influenced by the materials available for use at any time. During the short history designers have constantly sought a greater range in more durable and improved materials for use in structures. One of the intrinsic problems is the relatively minor share of the total market for composite fabrics, held by architectural fabrics.

Until the industry developed sufficiently, there were few manufacturers who would invest necessary funds in R&D to produce materials which the industry needed. A classic chicken and egg problem.

Being the traditional material used on tents and awnings, *canvas* was used on early projects. Membrane structures now owe much to the craft of tent making, the history of which stretches back into the obscurity of pre-history. This industry produced Circus tents of gigantic proportions up to the present day .It has traditionally supplied the military with temporary accommodation on a large scale.

Fabrication and construction methodology of the new prestressed tents, which were made by the existing industry, carried the signature of previous construction techniques. As the industry moved more into the mainstream of the building industry and distanced from temporary event structures, it required a new set of techniques, specifications and skills to accommodate the new demands of highly engineered structures.

Early work in air structures for radomes needed a gas tight membrane, immediately excluding canvas. **Ottos'** work in tension structure design called for membranes which could carry higher tensile loads than canvas and and posses better tear strength. Light weight synthetic fibres were successfully trialled with *Polyester* being the most applied for the ensuing three decades.

Physical properties of high strength, lightness and flexibility along with relative cheapness and ease of production turned the page of history forever away from organic fibres as the industry began the long and successful application of *PVC (Polyvinyl Chloride) coated woven Polyester cloth.*

1970 proved to be a milestone in development of materials as it pointed to a long span potential, previously not applied. The US pavilion at Expo 70 had been fabricated from PVC coated, woven glass fibre, a departure from polyester which heralded a new era of flourocarbon coatings. The potential and need for enduring membrane structures was recognised and within four years the first structure was built from *PTFE (Teflon) coated woven glass fibre.*

La Verne College sports facility (1974) became the first structure built using this new material. Thus the industry moved further from its craft base with two materials available. Each held intrinsic advantages for applications in structure but now the designers could more completely select the engineering properties wanted for the specific project parameters.

Each fabrics' particular properties brought about subtle and gradual changes in design methodology as the designers responded to fabrication limitations of new materials. The highly curved forms typical of the flexible, inexpensive PVC coated materials slowly gave way to lower curvature shapes which reflected the economies of panel cutting required by the much more costly PTFE/Glass fabric.

Fig 13 - La Verne College [LOS ANGELES]

New *flourocarbon coatings on PVC* arrived to improve finish , durability and appearance. In the US ODC experimented with Silicone coated glass for several years until closing in the late 80's. The material is re-emerging there again at present. *Woven PTFE fibres (TENARA)* and extruded clear *ETFE film* sheet have begun new application areas in unworked parts of the market. In this country the capacity for providing large areas of shade with porous material, has hardly been exercised.

WORLD MILESTONES IN MEMBRANES;

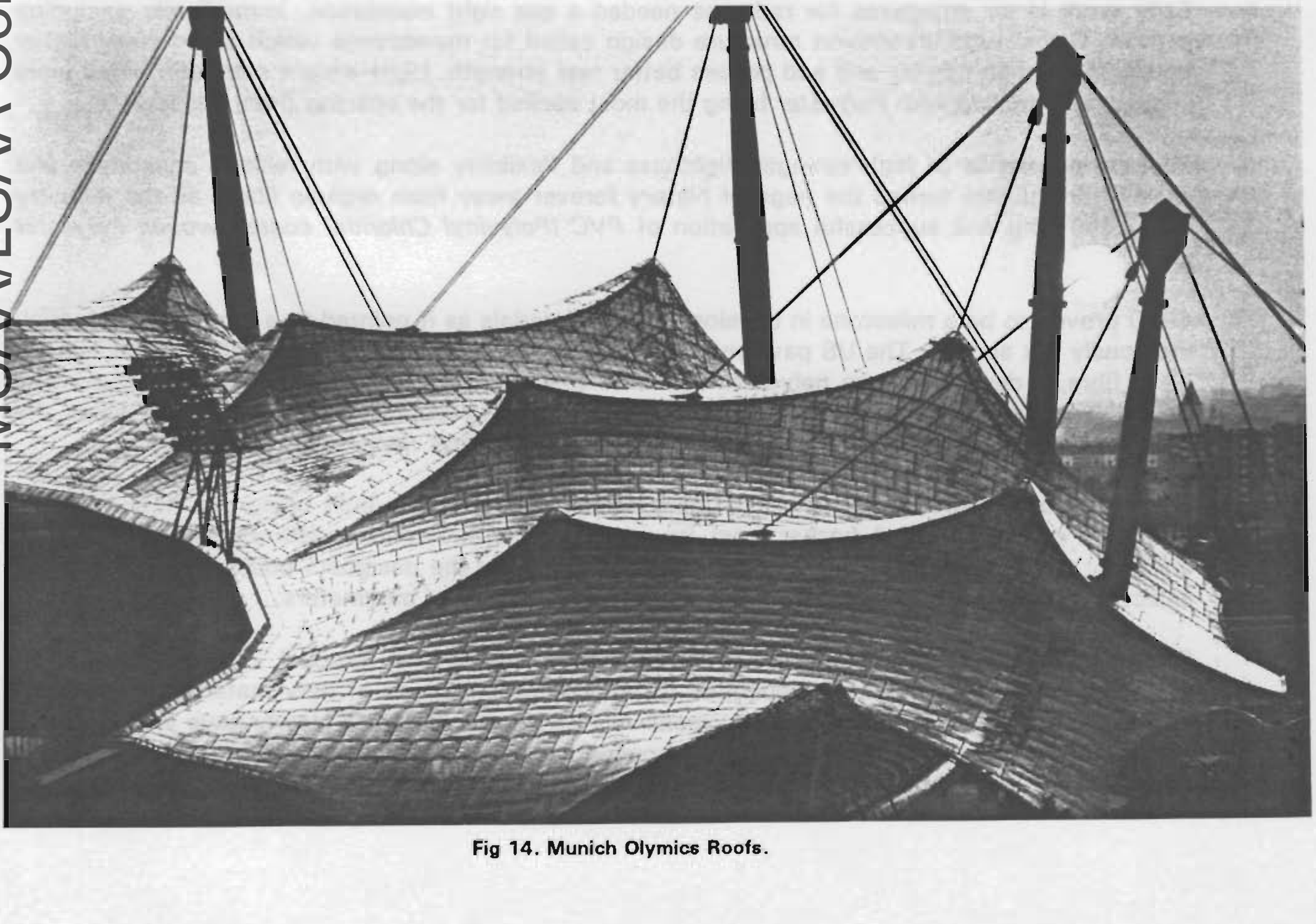


Fig 14. Munich Olymics Roofs.

As the *Munich Olympic Pavilions* were to Germany , *Expo 70* was to Japan and construction of the *Pontiac Silver Dome* was to USA , while *Yulara* was to Australia and the *Haj Terminal* was to the world. Each of these were significant structural events which transcended parochialism of genre or country. They symbolised the reality of this soft shell stuff to those who previously considered it whimsy.

Respectability flooded in and from that day to now Expos and Olympics , exhibition halls , swimming pools , shopping malls and atria are increasingly getting the quality which these indoor/outdoor forms lend to buildings.

By the early 80's sophisticated and dedicated computing techniques abounded so that not only analysis and shape finding but graphic imaging of these sculptural forms were possible and readily available. Specialist fabrication groups evolved usually from existing fabrication companies and designers emerged often from the influence of **Frei Otto and the IL team.**

Like any new field the apparent development is exponential in the earliest times and indeed spectacular works of stunning complexity and ambition were successfully undertaken with meagre facilities by todays standards. Pioneering stuff for sure.

Recent works have seen a maturation of application in structures such as **David Geigers** *cable dome system* which borrowed a form of Bucky Fullers *Tensegrity* idea in conjunction with fabrics to roof structures at the Seoul Olympics and St Petersburg. The same principle is dehind the recently completed Atlanta Dome by **Matthys Levy.**

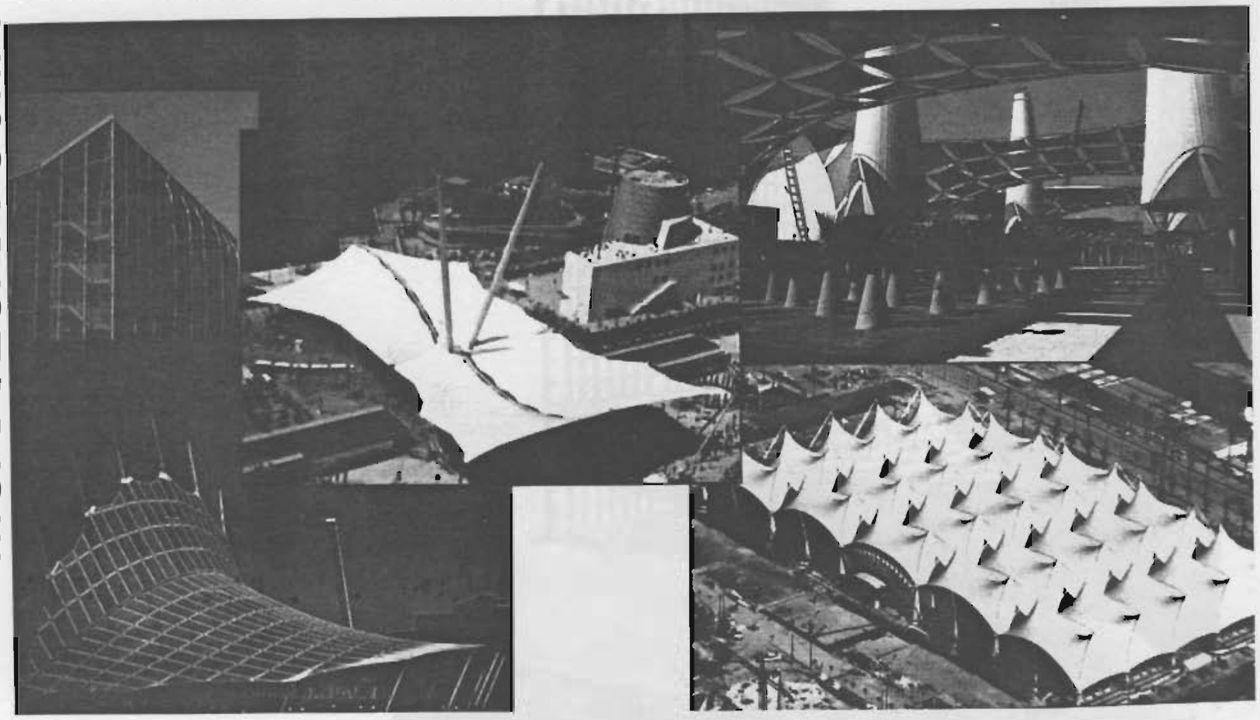


Fig 15 - Expo Seville]

Large areas of pneumatic pillow roofs have covered a tropical plant house at Arnhem in Holland using the revolutionary ET film and a forest of Tenara clad mechanised, auto opening umbrellas of 10 metres diameter have finished testing and are planned for use in Mecca. Seville was another glittering array featuring the extensive works of **Harald Muhlberger** and the new **Michael Barnes/David Wakefield** combination.

The Nuage Leger (light cloud) at the Grand Arch in Paris (Peter Rice,Henry Bardsley,Ove Arup) for the Bicentennial of the Republic presents membrane as major sculpture and in Japan , well that's where the next millenia begins.

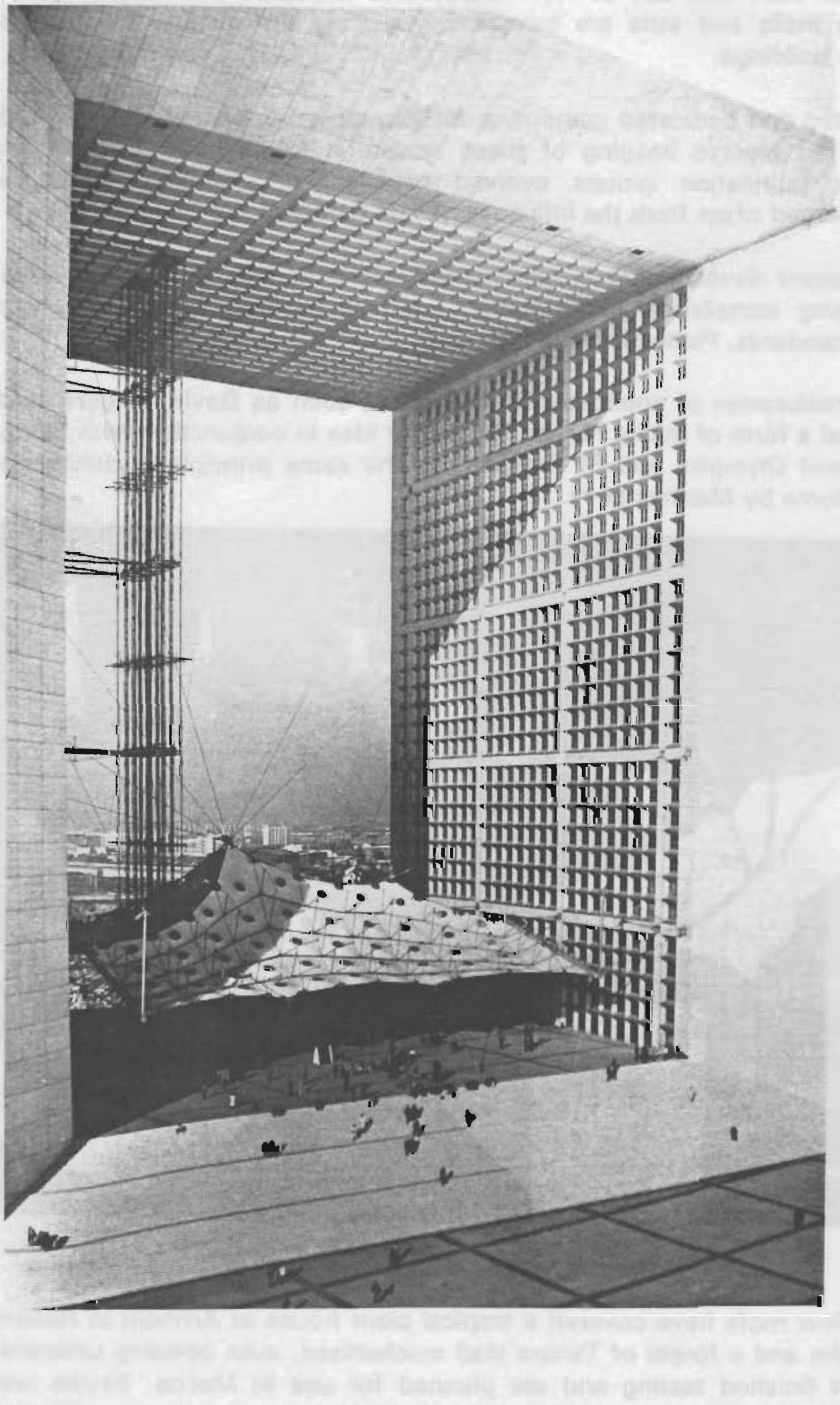


Fig 16. Nuage Leger [PARIS].

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Tents IL 16	Otto et al.
Patterns 5	Buro Happold
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Fig.17 Denver Airport.