"Lightweight structures past, present and future".

Professor W.I. Liddell CBE FREng.
Visiting professor of engineering design at the University of Cambridge

PHILOSOPHY

Structures are always designed for a function and are often an integral part of the object be it a building, a ship or an aeroplane. For a ship the hull is designed to keep the water out and have a hydrodynamic shape and is also the structure resisting wave forces. For buildings structural designers have a vocabulary of structural systems that can be used and the selection is made against a range of criteria e.g. function, cost, appearance buildability, ongoing use, sustainability etc.

"Lightweight structure" implies efficiency of materials, minimum weight for the spans, Minimum stored energy, doing more for less. It is basically a philosophy that all engineers would agree with and should be good for sustainability. The past decade has been a time of plenty with an explosion of construction and competitively extravagant designs but also one when economics has been the prime driver in the selection of structural solutions and the key feature of the economics has been high labour costs with low material costs. The doing more with less aim was lost. The lightweight concept flourished in times of shortage and social struggle when materials were in short supply, the job market was difficult and labour rates low especially the 1950s and 60s. At this time the designers were prepared to put in the effort to carry out the more complex design work necessary to realise the lightweight aims and the owners would accept the risks. If the financial crisis and the expanding urbanisation of developing countries has an impact these aims may return but probably in different forms. In parallel with this we also have the drive for sustainability and the reduction of the carbon footprint within building.

The lightweight philosophy came into the engineering world along with improved methods of transportation especially the search for flying machines we saw balloons, triangulated space-frame kites from AG Bell and then airships and airplanes. Airships were pressurised balloons with a controlled shape and much of the fabric testing that we now rely on for our modern structures had been done by 1913 on the rubber coated silk or cotton fibres of that time. Controlled flight started with the Wright brothers who were carrying out wind tunnel tests and devising light space frames with wing warping to control roll. There were many others experimenting in the field and the Wrights new that their concept was out of date by the time they flew round the Statue of Liberty.

The lightweight philosophy was quite slow to move into building although you could say that the US system of "Balloon Frame" housing in the mid 19th C was just that. Steel space frames came into use in the 1930s at around the same time as geodesic domes. The great proponent of "Lightweight" was Buckminster Fuller whose aim was "doing more for less" and the use of industrialisation to improve the lot of the masses. Bucky thought that Thomas Malthus was wrong and that there was virtually no limit to the population of the world if these principles were followed. Bucky proposed the Octet Truss for structural floors and his vision for his expo 67 sphere was a "prototype environmental valve, enclosing sufficient space for whole communities to live in a benign physical microcosm". He was well ahead of us on the need to conserve our oil resources for special purposes and use renewable energy for everyday uses such as domestic heating.

CONCRETE SHELLS

Thin concrete shells, tried out by Franz Dischinger in 1924, became popular in the 1950s as a way of creating large spans with a minimum of steel and concrete. In the UK Ove Arup and his partner Ronald Jenkins engineered the shells for Brynmawr rubber factory in 1952. The firm also did several other shell structures up to 1964 when Paul Ahm was responsible for the record breaking span of Smithfield Market. Arup's shells were based on regular geometries the enabled his partner

Ronald Jenkins to solve the equations. The Swiss engineer Heinz Isler in the mid 1950s devised modelling methods using bubble forms and hanging nets to generate doubly curved forms for shells which had adequate buckling capacity. He built many shells with this method and there are two examples of his work in the UK built in 1988. There were many other engineers working with shells most notably Felix Candela, Edwardo Dieste, PL Nervi.

SURFACE STRESSED STRUCTURES

Recently, lightweight structures has come to refer to tensioned cable and fabric although it is a lot more that just that. The two people most associated with the development of fabric are Frei Otto and Walter Bird. Frei tells us that he started his researches while he was in prisoner of war camp in 1945/46 and Walter Bird was developing the air-supported radar domes in 1946 at Cornell and started Birdair Structures inc. in the same year. Both had an enormous impact on the development of tensile forms and fabrication. At this time, post the second world war, there were major developments in coated fabrics which also enabled the fabric structure industry to progress.

Otto's form studies used soap films to get minimal surfaces and stretch fabric that was easier to measure. Patterning and load calculations were also model based. His structures were built by the Stromeyer company lead by Peter Stromeyer. For the structures for Expo 67 in Montreal Otto used a cable net in the same way as he used fabric. The net was based on a 50cm grid that was safe to walk on and had considerably greater strength and stiffness than fabric.

It wasn't until the 1980s that computational methods for form-finding, load analysis and the preparation of cutting patterns enabled the industrialisation of the design and manufacturing process with freedom in the choice of shape. At first the new technologies were used by specialist engineers working with fabricators who had a background in traditional tent or other fabric production. The engineers would provide the patterns with compensation for stretch included to the fabricators who would be required to add in the adjustments for the edge and corner details. Now suitable software can be acquired from several suppliers but as with all such the users have to know what they are doing. The current software cab be linked to 3D CAD packages that enable the details to be modelled to the exact geometry and the allowances bolt holes etc included in the patterns.

AIR-SUPPORTED STRUCTURES

The development of air-supported structures was started by Walter Bird who was working on a project at Cornell University to build radomes for the US air force. The first of these was built in 1948. The company Birdair Inc. was formed in 1946 to build air shelters for the US army. The company moved into commercial applications with tennis court covers and the like. Bird was also promoting the concept of low-profile wide span air structures. The big breakthrough came when such a structure was adopted for the US pavilion at Expo 70 in Osaka. Shortly after this the concept was taken up for covering football stadia. At this time Dave Geiger, Owens Corning Fiberglass, Chemical Fabrics Corp. and others got together to develop Teflon coated Fibreglass fabric. The first structure using this material was the LaVerne College Centre built in 1971. It still stands with the original fabric.

The first air-supported roof on a stadium is at Pontiac, built in 1975. A number of such stadia roofs were built including that for the Minnesota Metrodome in 1981. This roof suffered 3 deflations in its first year of operation under heavy snow loads. The structures were designed for this eventuality but the collateral costs of repair and re-inflation were high. Improvements were made to certain components of the inflation system and the facilities crew became adept at dealing with the snow, however it was clear that the design provisions for snow loads were inadequate. The last such roof was the Osaka Dome in 1988 which had closer spacing if the cables and much higher internal pressures for handling typhoons and snow. The problems with air structures have lead to their decline in favour of cable supported tension structures such as that at Seoul designed by David Geiger

Covered cities were dream structures around 1960. These were going to allow people to live in comfort in the cold parts of the globe. In 1980 Buro Happold were part of a study group lead by Arne Fullerton to research the possibility of a covered town in Northern Alberta, 58^{o}NT. BH proposed an air-supported roof as a cable net clad with ETFE foil cushions. At that time this material was very untried so it was quite a brave proposal. It is now being used for similar purposes but not on an air-supported structure.

GRID SHELLS

Grid shells are a specific form of construction of doubly curved surfaces using a square or rectangular net of rigid members. The system devised by Frei Otto used timber laths on a 50cm grid. He used this on some small rooms within the Montreal pavilion and another trial structure at Essen. He then proposed to use it for a multi purpose hall for the Bundesgartenschau at Mannheim. Thus structure was a huge jump in scale, the largest dome having a span of 100 x 60m. It was constructed from two layers of 50 x 50mm timber, in scale thinner and lighter than an eggshell. The form was developed from a hanging chain model so it was basically bending free. The laths were laid out flat and lifted up into position on scaffold towers. The challenge for the engineers was to add sufficient stiffness to enable it to stay in place.

A few other structures have been built on a similar principle but new technology has enabled grid shell to be built in steel.

USE OF FABRIC MATERIALS

For architectural purposes the main fabrics are PVC coated polyester cloth and PTFE coated glass fibre. The grade of cloth is defined by the total weight/m^2 and the amount of fibre normally in decitex. The strength is measured as the breaking load of a narrow strip. The peculiarities are the biaxial behaviour and the tear strength. For PTFE/glass the fibres themselves are very stiff and most of the extension comes from construction stretch, tightening of the yarns under first loading, and crimp interchange of the weave. This last is helpful in smoothing out the distribution of stresses under load but very difficult to model in analysis as the stiffnesses vary with stress ratio. For polyester based fabrics it is not so important.

Fabrics fail by tearing generally at a stress level much less that the strip tensile. Tears are initiated by local stress concentrations caused by fabrication details and damage such as small cuts. The result is that fabric engineers use relatively high safety factors of 6 or more for PTFE. One feature especially with PTFE fabric is that the material has a very long life of 30 years or more but does not give warning of deterioration. Owners are reluctant to change the fabric while it continues to look OK, so it is likely that the end point will happen when the fabric is severely damaged in a major wind storm. Because of this it is best to treat the material as cladding with provision for easy replacement.

The new-ish material is ETFE foil which now has a track record of 20 years. This has a low yield point and an amazing amount of ductility of up to 300%. This makes it very tough so tearing is not a problem. Because of this it is normally used as inflated cushions which can have 3 or 4 layers providing some useful insulation. The material is also highly translucent which can be modified by tinting the foil or printing on the surface to provide shading. The acoustic effects are also interesting as it is nearly transparent to internal noise but heavy rain causes loud drumming. In spite of this the material has been used for several high profile structures like the Eden domes and the Beijing aquatics centre.

ETFE foil can be pigmented or printed with reflecting areas to reduce solar gain into the enclosure. The printed areas can also be arranged in a complimentary pattern on the outer and middle foils so when the middle foil is raised up to the outer layer most of the sunlight is blocked out. These techniques allow for a variety of translucencies to be used thus controlling the thermal and visual environment.

ENVIRONMENTAL LOADING

Lightweight structures are by definition going to be susceptible to imposed loads. There's no point in being able to carry out the most accurate calculation of load effects if the loads are basically guessed. The engineers need to have an understanding of the effects of wind and snow so they can design the structure to resist them. Snow loading is particularly problematic as it moves around on the fabric roof and will cause large deflections. If the slope of the roof surface is too shallow the deflection may cause the drainage to be reversed and a pond will form. The Millennium Dome was specifically designed to avoid this effect.

TRENDS IN TECHNOLOGY

I have presented above the development of formfinding and load analysis software that enabled tensioned fabric structures to be built in a totally prefabricated way. This software which used to be the preserve of consultants who wrote it can now be readily acquired. Further advances have come from integration with 3D-CAD software so the shop drawings of all the components can be prepared automatically.

This last is now developing into parametric modelling of geometry and Building Information Management (BIM) software. Some examples are given below.

Software source	**Capabilities**	Interface with analysis
Digital Projects (formerly Catia)	Very powerful software for specialist users	yes
Autodesk Revit	Autocad + parametric + BIM The industry standard	yes
Bentley BIM and	Microstation + parametric + BIM + analysis	yes
Tecla BIM (formerly XSteel)	Production orientated but moving towards design integration	yes
Rhino	NURBS based 3D surface modelling. Can be exported to Autocad	manual

The developments in 3D modelling software have enabled architects to develop designs shaped to their liking and engineers import them into analysis software thus developing designs for complex shapes quickly and economically. Unfortunately this process does not include structural efficiency or the lightweight philosophy. Doing more for less takes more design time and will probably cost more.

Other drivers against the use lightweight structures are performance, in terms of deflection and vibration, safety, maintenance, availability of suitable engineers and contractors. The design effort required seems to discourage engineers from becoming involved and also increases costs giving fees that are above the normal scales

TRENDS IN PROCUREMENT

The way that work and responsibilities have been distributed between the various parties involved in the delivery of projects has changed as the knowledge and skills have been distributed. This is summarised below:

1980 Specialist engineer prepares design with full load analysis and cutting patterns of fabric.
Fabricator makes up membrane with allowances for edge details.
Fabricator installs

1990 Architect and Engineer prepare schematic design and specifications
Fabric contractor completes design, fabricates and installs
Sometime contractor will prepare design directly for the architect or client

2000 Contractor becomes a project manager and provides bid-bond and warranties
He employs engineers and fabricators as necessary on low cost bids
New technology in CAD etc allows fabrication to move to low cost sources

In the early days the knowledge was in the hands of very specialist engineers who were developing and understanding how these structures worked. As the knowledge trickles down the initiators move on and others acquire the software and provide the service. The contractor becomes a project manager who believes he can buy in the skills he needs and goes for the lowest price. This trend has resulted in a lot of churn in companies and individuals working in the field and has not always produced satisfactory results.

The current situation seems to be that there are two major world-wide fabric contractors Taiyo-Birdair and Seele-cover and about 5 or 6 medium sized contractors capable of all aspects of design, engineering and fabrication who also work in countries around the world. There are probably quite a number of smaller players that I do not know about.

TRENDS IN APPLICATIONS

Structures for buildings are always designed for a specific function and for a business plan. The appropriate applications for single skin fabric structures have not changed much over the years and are basically restricted to situations when low insulation is not required. A criterion that has strengthened with the current requirements for energy saving.

Canopies for stadia providing rain protection and shade
Climate moderating – shading in high sun areas and solar capture in cold climates.
Covered atria, Railway stations, Walkways, Arrival canopies.
Thermoflex insulation for fabric structures may extend range of applications in cold regions.

ETFE foil cushions with 3 transparent layers can provide some insulation and also allows capture of the sun’s energy which makes in suitable for very large area climate moderating enclosures. They can be used for walls as well as roofs and there is also a system in which the middle layer can be moved up to the upper surface and if printed with a complimentary pattern will reduce the amount of solar energy entering.

Would the idea of a covered city or town work in the arctic of the desert? We have plenty of examples of huge covered areas to judge it by. For example the Hadj terminal, The millennium Dome and large city centre developments such as that at Astana in Kazakstan.

In other forms of structures where the lightweight philosophy might apply the components have become heavier. This is to meet the requirements of deflection, vibration, sound isolation robustness, safety etc. In the recent period of low material cost and high labour cost this was often done by just increasing the amount of steel or concrete used and saving weight but having an efficient structural form was ignored. Generally lightweight means high tech with more components and more industrialisation.

MEETING FUTURE NEEDS

There are changes going on. Populations are increasing especially in less developed areas and much of this will migrate to cities hopefully to live in civilised areas where lives can be fulfilled. We have heard about eco housing, eco-towns and eco-cities but do yet know what they really are. The current level of population is very dependent on oil just for food production and distribution.

To accommodate the future urbanisation within the capacity of the available resources there will have to be lightweight thinking. There will also have to be increases in the output of habitable shelter by the indigenous people who need to have creative employment related to their lives. Sustainable thinking has generated renewed interest in such low-tech solutions as mud and straw bale walling which could be an answer to housing if the techniques are understood by many. Young people form the highly developed countries are already aware of these needs and have formed organisations such as Engineers Without Borders to help with these issues.

The alternative is high-tech industrialised systems that use a minimum of material. To be efficient these require precise geometry and careful assembly. Developing these will require committed designers and companies and also education of the people who will build and live in them. At all levels there will be opportunities for engineers and designers who can work with these old and new technologies.

REFERENCES

1. Buckminster Fuller, R.: *Utopia or Oblivion, The Prospects for Humanity.* Pelican Books, 1969.

2. Buckminster Fuller, R. and Marks, R.: *The Dymaxion World of Buckminster Fuller*. Doubleday Anchor 1973.

3. Chilton, J.: *Heinz Isler*, *The Engineer's Contribution to Contemporary Architecture.* Thomas Telford. 2000

4. Esquillan, N.: "The Design and Construction of the Shell Roof of the Exhibition Palace of the National Centre of Industries and Technology, Paris" Societe des Ingenieurs de France (British Section) and The Cement and concrete Association. 4th December 1958.

5. Arup, O. N. & Jenkins, R. S.: "The Design of a Reinforced Concrete Factory At Brynmawr, South Wales." *Proceedings of the Institution of Civil Engineers,* Dec. 1953

6. Ahm, P. & Perry, E. : Design of the dome shell roof of Smithfield Poultry Market, *Proceedings of the Institution of Civil Engineers,* Jan 1965, pp 79 – 109

7. Remo Pedreschi.: *Eladio Dieste, The Engineer's Contribution to Contemporary Architecture*, Thomas Telford Publishing, 2000

8. Borrego, J.: *Space grid Structures*. MIT press 1968.

9. Buckminster Fuller, R.: *Utopia or Oblivion, The Prospects for Humanity.* Pelican Books, 1969.

10. Buckminster Fuller, R. and Marks, R.: *The Dymaxion World of Buckminster Fuller*. Doubleday Anchor 1973.

11. Roland, C.: *Frei Otto: Structures.* Longman 1970

12. IL8. *Nets in Nature and technics.* Institute for Lightweight Structures, University of Stuttgart. 1975

13. Bird, W.: "The History of Air Structures in the USA" *IL16 Tents*, Institute fur Leichte Flachentragwerke, 1976

14. Geiger, D.: "US Pavilion at EXPO 70, Osaka". *Civil Engineering,* ASCE, March 1970

15. I Liddell.: *Minnesota Metrodome* Structural Engineering Review, Vol 6 No 3-4,1994

16. Happold, E. & Liddell, W. I.: " Timber Lattice Roof for the Mannheim Bundesgartenschau". *The Structural Engineer 53/3",* IStructE March 1975

17. *IL 13 Multihalle Mannheim*. Institute fur Leichte Flachentragwerke, 1978

18. Liddell, W.I.: "Large Environmental Enclosures , The roof of the Millennium Dome". *Widespan Roof Structures, Barnes, M. and Dickson, M eds.* Thomas Telford 2000.

19. Hawken, P. Lovins, A. Lovins, H.: *Natural Capitalism*. Earthscan Publications Ltd. 1999

20. Forster,B. Mollaert, M.: *European Design Guide for Tensile Surface Structures.* Tensinet 2004