Lightweight Structures Past Present and Future

Professor Ian Liddell

Structure within the design process

Criteria for selection

Functional requirements

Sustainability

Cost v **Budget**

Buildability

Time

Quality

Styling

Lightweight Structures Past Present and Future

With added Sustainability

Professor Ian Liddell

It's what other people have to do to save the planet

Lightweight Structures Past Present and Future

With added Sustainability

80% off all CO_2

Professor Ian Liddell

About 25% CO_2 comes from housing

25% from other buildings

Sustainability

Buckminster Fuller

1960

"The way the consumption curves are going in many of our big cities it is clear that we are running out of energy. Therefor it is important for our government to know if there are better ways of enclosing space in terms of material, time, and energy. If there are better ways society needs to know them."

Lightweight Philosophy

Efficiency of materials - Minimum weight for the spans - Minimum energy

Minimum embodied Carbon - **Doing more for less** - Operational efficiency

R Buckminster Fuller - Frei Otto - Rocky Mountain Institute

Lightweight Structural Systems

Space-frames	AG Bell, Mero
Concrete shells	F Dischinger, F Candela, Ove Arup
Surface stressed structures	Frei Otto
Tensioned Cables	Fred Severud, Lev Zetlin, Schlaich Bergerman
Air-supported structures	FD Lanchester, Walter Bird Dave Geiger

Doing more with less

Where have we got so far?

Renault R4
1960s 600 KG

“To save resources Cars should be lighter”

Over the past 50 years cars have got heavier and sleeker.

but who can resist the comfort, safety, speed and technology,

Renault Twingo
1990s 790 kg

Renault Twingo -2
2007 1000 + kg

The car of the future

VW concept car. Aluminium + carbon fibre composite

Weight 380 kg

Fuel 189 mpg,

CO_2 39 g/km

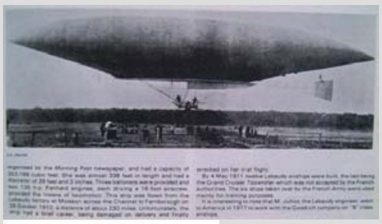
Early Lightweight structures

Space-frame Kites by Alexander Graham Bell 1898

AEA Silver Dart 1909

Early flying machines
1903-5 and 1915

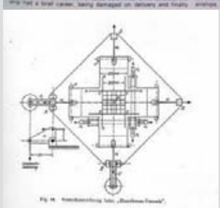
Less available power – lower weight



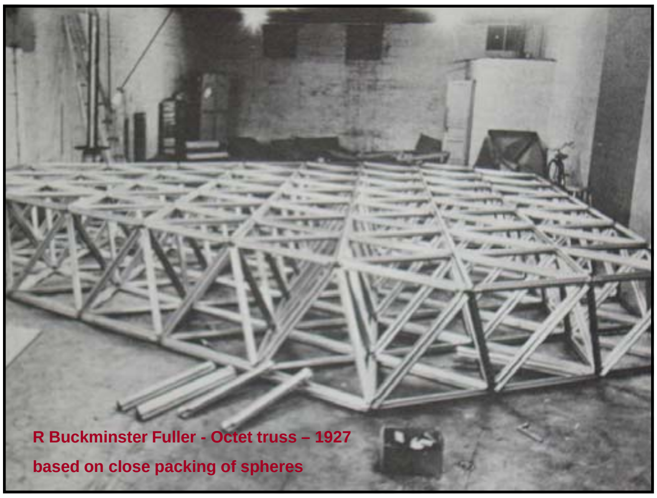
Airships

Lebaudy *La Jaune* 1903

Lebaudy *Patrie* 1906



Fabric bi-ax testing 1913



R Buckminster Fuller - Octet truss – 1927
based on close packing of spheres

R Buckminster Fuller

Space frame domes

Ford Motor Co Dome, 1953

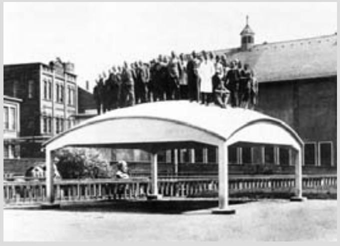
Union Tank Car dome, 384 ft dia – 1958

Expo 67 Montreal

“An environmental valve”

Concrete Shell Structures

First developed by **Franz Dischinger** in 1924



test shell 1924

Jena planetarium 1925

A frame for a concrete shell

Marignane Hangars 1951

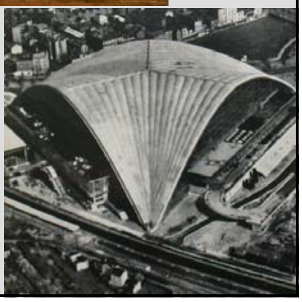
101m span

Nicholas Esquillan

60mm concrete shells

CNIT Paris 1958

208m span - double layer shells

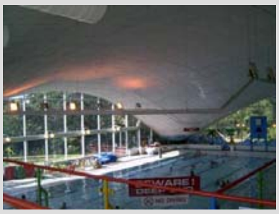


Concrete shell developments in the 1950s

Brynmawr – 1952 Ove Arup and Ronald Jenkins

Stockwell bus garage1952

Smithfield 1964 - 75mm shell



Heinz Isler standardised funicular shells – Norwich sports village - 1988

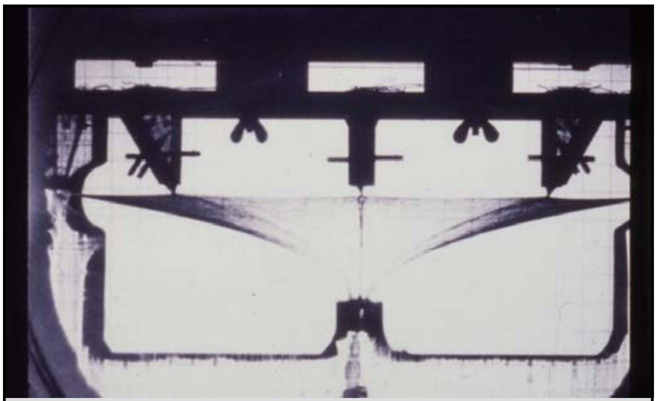
Surface Stressed Structures - Frei Otto

Frei Otto started into Lightweight structures in 1947.

1950 - doctorate thesis on tensioned cable roofs and this became his subject for his.

He later became interested in **equilibrium formfinding** and in ideas taken from nature and technic.

first structures were tents for the garden shows in 1955 and 1957



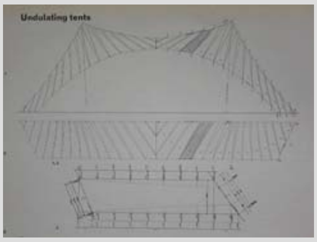
Soap-film model of an inverted umbrella

Otto's form-finding methods relied on analogous models using soap films or stretchy membranes

---

Otto's patterning was done using paper strips laid over the surface of the models.

The fabric was cotton canvas and the panels were often made up by "broad-seaming" to avoid cutting the selvedge.



Otto's method of patterning

Surface Stressed Structures

Load carried by deflection of the tensioned surface

OK for flexible fabric.

Non linear calculations required

Form models for direct measurement

The model defines the Structure geometry

Fabric carries load by deflection as well as stress

Tensions and stresses can be calculated by hand

1 :100 scale model of "Challenge" tent 1977

'Challenge' built structure

Transition to computerised form and pattern generation 1978 – 1990

Engineer led designs and patterns for fabricators to build

Stretch fabric models

More durable than soap films

Non-uniform stress fields, less accurate form.

Used to help with setting up a numerical model

Advantages of non-uniform stress fields:-

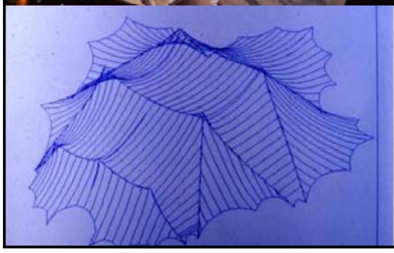
Control of shape, headroom etc

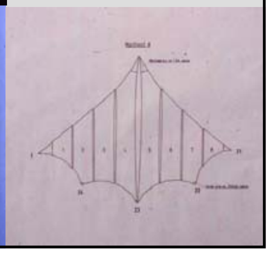
Can help with different load patterns e.g. high snow loading

Baltimore Concert pavilion 1981

Baltimore concert pavilion 1980 – transition to computational methods

1 Stretch fabric model
2 Computer model
3 Layout of cloths





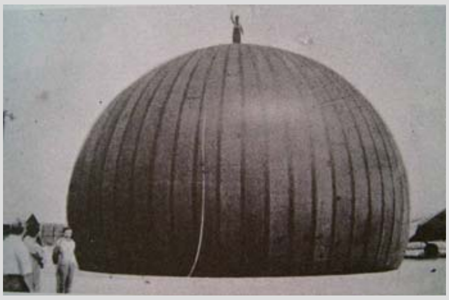
Baltimore Concert Pavilion 1981

Further development 1990 – 2009

Linking patterning with 3D CAD software and cutting machines
Fabric structures become a standardised industrialised process
Custom designed by D&B specialist contractors to architect's ideas
Applications:- canopies, Atrium type roofs and building enclosures

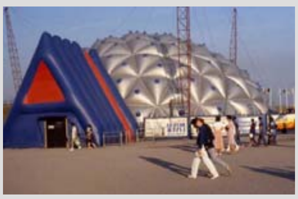
Pneumatic Structures

Originally patented by FW Lanchester in 1917
Concept developed by Walter Bird at Cornell for Radomes in 1955.
The development work involved extensive testing of materials.

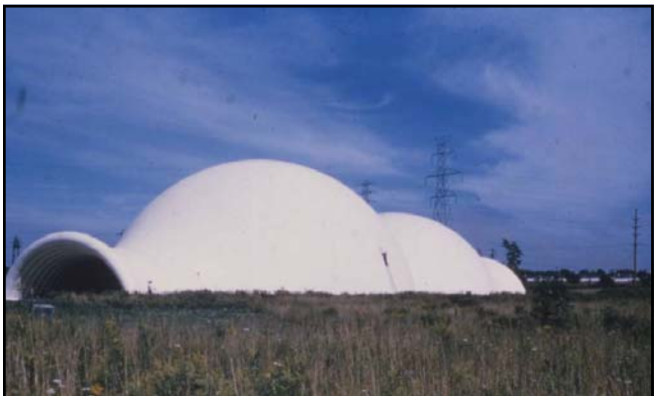


Dew line radome

Hypalon coated nylon



Extensive exploration of pneumatic forms in the 1950s and 60s



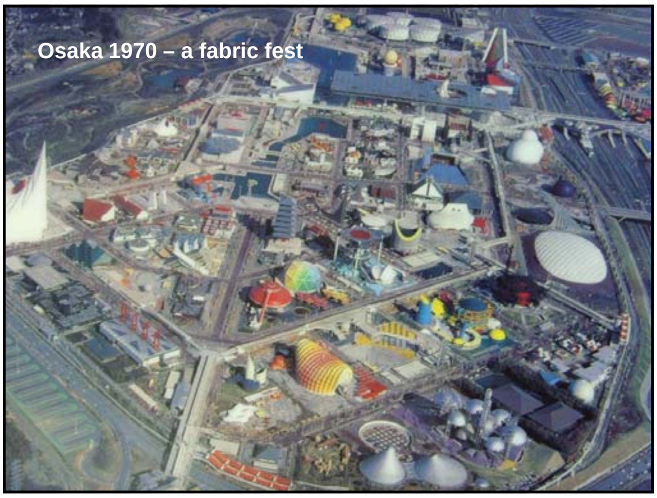
Atoms for peace touring structure - Victor Lundy with Birdair - 1960
Entrance formed by curved airbeams

The dream of a covered town

City in the arctic – Otto 1959

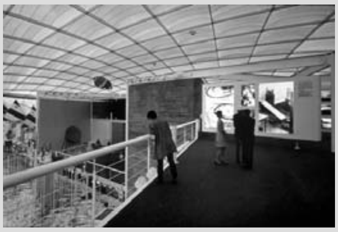
Cable Dome, Walter Bird Ca 1965

City in the arctic – Otto 1971



USA Pavilion at Osaka 1970

Low profile air-supported roof



Pontiac Silver Dome 1975

Minnesota stadium 1981

3 deflations under snow loading in the first year of operation.

Snow drifts on air-supported stadium roof

A deflated dome in its planned down-hanging position.

Safe but damaged

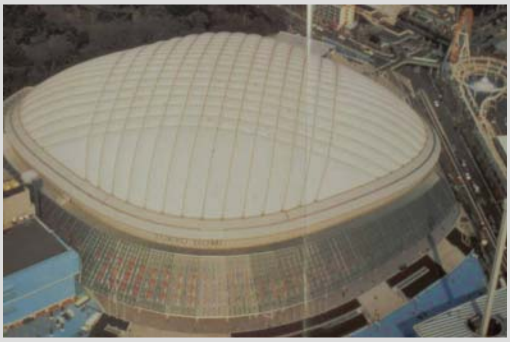
Snow drifts Montreal Olympic stadium Jan 1999

Designs have to take behaviour under environmental loads into account

Fabric structure destroyed by hurricane   Oct 2003

Degradation of PTFE fabric is not obvious and eventually failure is likely

Structures have to be designed to be stable



Tokyo Dome 1988

The last air supported stadium roof. Reduced cable spacing to take high winds and higher internal pressure for snow

Materials for fabric structures

Cotton canvas - Proofed against water and flame; also Acrylic canvas

Kenafine - PU coated Kenaf fibre fabric suitable for short life usage andreadily re-cyclable

PVC coated Polyester
Acrylic and Fluoropolymer top lacquers to reduce dirt retention.

PTFE coated Glassfibre
TiO_2 coated PTFE – provides improved self cleaning.
Tensotherm with Nanogel – provides good insulation

Woven PTFE fibre “Tenara”

ETFE Foil – excellent for environmental control.   Now equal in area to fabric in UK

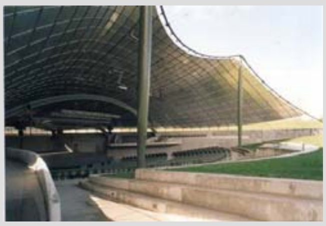
58°N – 1981

A covered city project by Otto + Buro Happold

Air-supported roof + ETFE foil cushions

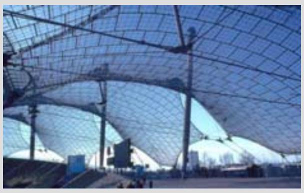
Cable net construction

Raleigh livestock arena – 1952 Fred Severud

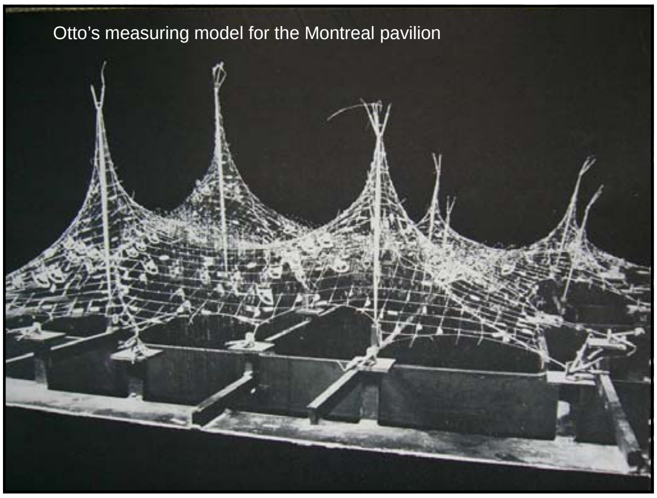


Sidney Myer concert pavilion Melbourne – 1956-8.
Barry Patten, architect + W L Irwin engineers

Cable net construction

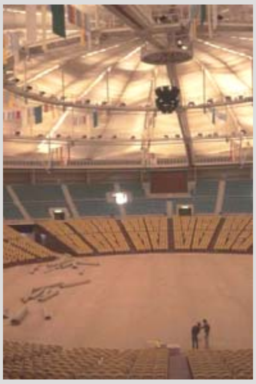


Expo 1967 Montreal,   Munich Olympics 1972



Otto's measuring model for the Montreal pavilion

Jeddah University Sports Hall 1980

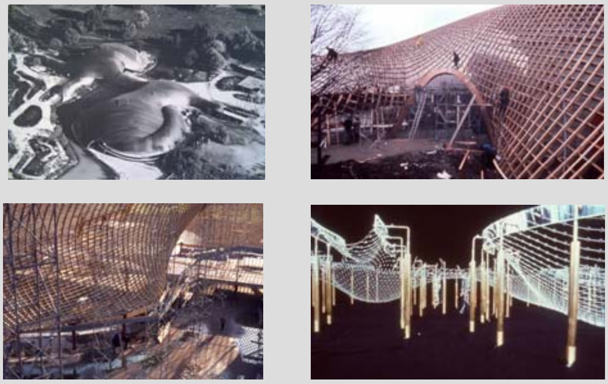


Bicycle wheel structure at
Brussels world fair 1958

Seoul "tensegrity" cable-dome, David
Geiger1988 The alternate for air-supported

Grid Shells

Mannheim Multihalle 1974 - funicular formfinding



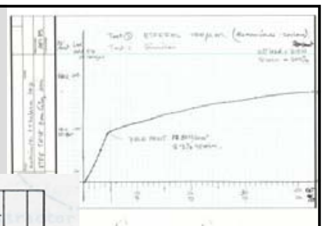
Grid Shells

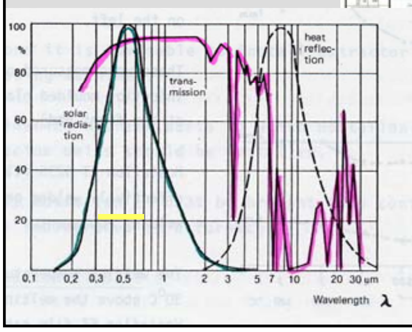
Weald and Downland

Saville Gardens

ETFE foil properties

Low yield point with
high elongation gives
great toughness





Excellent light transmission
into the UV range

good for plant growth etc.

Shading can be provided
by printed patterns

Chelsea and Westminster Hospital 1991 –

First urban application of ETFE foil

Hampshire tennis and Health Centre 1993.

Foil on tensioned cables

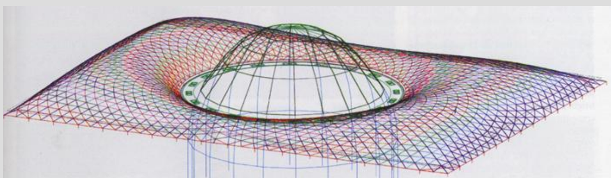
Foil Examples

Foil Examples

Area of ETFE foil roofing is now the same as fabric in Europe

Trends in technology

- Links between **Mathematical form development,** analysis and CAD.
- CAD processing of fabric cutting patterns.
- 3D CAD software for steel modelling, Strucad, XSteel, Autocad BIM
- Automated steel cutting and drilling from plate or sections.
- Fabrication of complex sections of frameworks with high accuracy



British Museum courtyard roof

British Museum

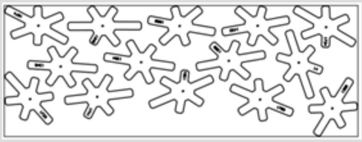
Node detail

Node cut from 200mm plate

Box sections fabricated from plate

Node Cutting

Beam Cutting



Node Cutting Pattern

British Museum nodes

British Museum

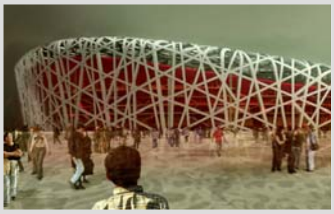
Assembly

Cabot Circus, Bristol

Further examples of mathematical form development

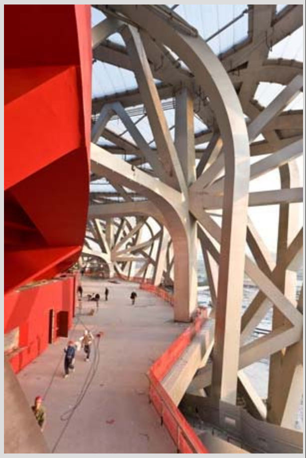
Beijing Aquatic centre

Bubble mathematics



Beijing Stadium a product of 3D CAD

45,000t of steel just for the TV image



2012Olympics Aquatics Centre

120m span with a lot of steel

Trends in procurement

1980

Specialist engineer prepares design with full load analysis and cutting patterns of fabric.

Fabricator makes up membrane with allowances for edge details.

1990

Architect and Engineer prepare schematic design and specifications

Fabric contractor completes design, fabricates and installs

Sometime contractor will prepare design for the architect or client

2000

Contractor becomes a project manager and provides bid-bond

He employs engineers and fabricators as necessary

New technology in CAD etc allows fabrication to move to low cost sources

Trends in procurement

Migration of fabrication work to low cost centres

Fabric contractor prepares patterns and sometimes and sends them electronically to fabricator

3 major contractors have fabrication facilities in low cost centres

Impact on technical staff is bad. The best guys leave and start new business or go elsewhere. Knowledge and experience is lost.

Expert engineers and CAD draftsmen are still required and they are rising to the challenge

Trends in applications

Functions for fabric structures

Climate moderating – shading in high sun areas, rain protection

Covered atria, Railway stations, Walkways, Arrival canopies, covered cities.

Mass housing systems for industrial production

Thermoflex insulation may extend range of applications in cold regions

Styling

Pointy cones out – Undulating surfaces and blobs in.

Equilibrium forms replaced by mathematical

Trends are towards heavy bending structures with add-on moulded cladding. Not lightweight

Trends in applications

ETFE cushions - use has expanded over the last 10 years - now 50%

Sports pools, environmental enclosures, atria, variable shading systems available

Solar thermal energy capture, encapsulated PV cells

Space frames, deployable structures, lattice domes

Energy capture devices

Wide span climate moderating

Hadj Terminal 1980

Shaded environment for millions of pilgrims

Wide span climate moderating

Millennium Dome – now the O_2

300 m diameter Built to provide an environmental enclosure for the Millennium Exhibition.

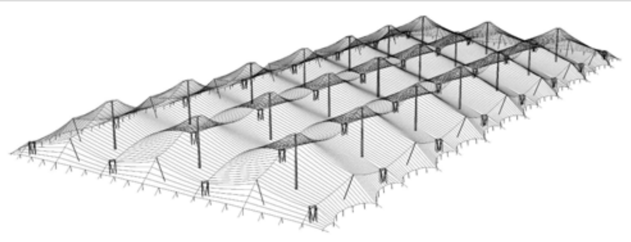
Astana in Kazakhstan – ETFE cushions on a cable net.

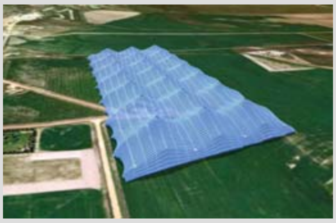
The landmark structure contains a small city centre

Mina Tent City

Fire proof PTFE/glass tents to house about 3 million pilgrims

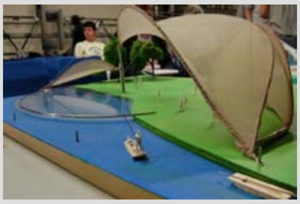
With added insulation the technology might be good for urban slum redevelopment





Cambridge University Engineering student project

600 x 400m modular cover for an arctic city. Cable structure clad in ETFE cushions.



CUED 3rd yr LW design module